Greece 2.0
NATIONAL RECOVERY AND RESILIENCE PLAN

GREENERGY

Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas

(H.F.R.I. Project Number 015376)

Literature review on VF buildings' modeling for combined renovation covering structural, energy, forestry and habitant comfort aspects

Deliverable D3.1 Work package 3

Funding source

"Hellenic Foundation for Research & Innovation (H.F.R.I.)
Greece 2.0
Basic Research Financing Action"

Host Organization

ΔΗΜΟΚΡΙΤΕΙΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΘΡΑΚΗΣ | DEMOCRITUS UNIVERSITY OF THRACE

Democritus University of Thrace (DUTH)

Collaborating Organizations

Aristotle University of Thessaloniki (AUTH)

November 2024

H.F.R.I. Hellenic Foundation for Research & Innovation
Greece 2.0 NATIONAL RECOVERY AND RESILIENCE PLAN
Funded by the European Union NextGenerationEU

The research project is implemented in the framework of H.F.R.I call “Basic research Financing (Horizontal support of all Sciences)” under the National Recovery and Resilience Plan “Greece 2.0” funded by the European Union – NextGenerationEU (H.F.R.I. Project Number: 015376)

Version	Date	Comments-Modifications
1	November 2024	Final Version
2		

Suggested citation:

Rousakis T., Voutetaki M., Vanian V., Fanaradelli T., Zapris A.., 2024. Literature review on VF buildings' modeling for combined renovation covering structural, energy, forestry and habitant comfort aspects. Greenergy-Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas (H.F.R.I. Project Number 015376). Deliverable D3.1 Democritus University of Thrace, Xanthi.

Project Title	Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas
Acronym	GREENERGY
HFRI Project Number	015376
Call identifier	Basic Research Financing (Horizontal support for all Sciences), National Recovery and Resilience Plan (Greece 2.0) / Sub-action 2. Funding Projects in Leading-Edge Sectors – RRFQ: Basic Research Financing (Horizontal support for all Sciences)
Thematic area	ThA1. Physical Sciences, Engineering Sciences and Technology, Environment and Energy
Thematic Field	1.16 Smart Cities
Host Organization	Democritus University of Thrace
Collaborating Institutions	Aristotle University of Thessaloniki
Project starting date	13/3/2024
Project Principal Investigator	**Dr. Theodoros Rousakis**
Affiliation	**Democritus University of Thrace / Department of Civil Engineering**
Email	**trousak@civil.duth.gr**
Telephone	25410 79645, 461 / 6977421569
Deliverable number and title	**D3.1** Literature review on VF buildings' modeling for combined renovation covering structural, energy, forestry and habitant comfort aspects
Related work package	**WP3** - Digital twin model
Authors	Theodoros Rousakis, Maristella Voutetaki, Vachan Vanian, Theodora Fanaradelli, Adamantis Zapris (DUTh)

Τίτλος Έργου	Ανθεκτική Αντισεισμική Ανακαίνιση Κατασκευών από Ωπλισμένο Σκυρόδεμα σε Κάθετο Δάσος
Ακρωνύμιο	GREENERGY
Αριθμός Έργου ΕΛΙΔΕΚ	015376
Δράση	Χρηματοδότηση Βασικής Έρευνας (Οριζόντια υποστήριξη όλων των Επιστημών), Εθνικό Σχέδιο Ανάκαμψης και Ανθεκτικότητας (Ελλάδα 2.0)
Θεματική Περιοχή	Υποδράση 2. Χρηματοδότηση Έργων σε Τομείς Αιχμής – ΤΑΑ: Χρηματοδότηση Βασικής Έρευνας (Οριζόντια υποστήριξη όλων των Επιστημών)
Θεματικό Πεδίο	1.16 Έξυπνες Πόλεις
Φορέας Υποδοχής	Δημοκρίτειο Πανεπιστήμιο Θράκης
Συνεργαζόμενος Φορέας	Αριστοτέλειο Πανεπιστήμιο Θεσσαλονίκης
Ημερομηνία έναρξης Έργου	13/3/2024
Επιστημονικά Υπεύθυνος Έργου	**Δρ. Θεόδωρος Ρουσάκης**
Ίδρυμα / Τμήμα	**Δημοκρίτειο Πανεπιστήμιο Θράκης / Πολιτικών Μηχανικών**
Email	**trousak@civil.duth.gr**
Τηλέφωνα	25410 79645, 461 / 6977421569
Αριθμός και Τίτλος Παραδοτέου	**D3.1** Ανασκόπηση της βιβλιογραφίας για τη μοντελοποίηση των κτιρίων ΚΔ για συνδυασμένη ανακαίνιση, καλύπτοντας πτυχές που αφορούν τη δομή, την ενέργεια, τη δασοκομία και την άνεση των κατοίκων
Σχετική Ενότητα Εργασίας	**ΕΕ3** - Μοντέλο ψηφιακού διδύμου
Συγγραφείς	Θεόδωρος Ρουσάκης, Μαριστέλλα Βουτετάκη, Βαχάν Βανιάν, Θεοδώρα Φαναραδέλλη, Αδαμάντης Ζάπρης (ΔΠΘ)

ACKNOWLEDGEMENTS

This project is carried out within the framework of the National Recovery and Resilience Plan Greece 2.0, funded by the European Union – NextGenerationEU (Implementation body HFRI).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ACRONYMS

ABC	Analysis-Based Classification
ACI	American Concrete Institute
ACMs	Acoustic Comfort Models
ACS	Adaptive Comfort Standard
ANN	Artificial Neural Networks
APDL	ANSYS Parametric Design Language
ARIMA	Autoregressive Integrated Moving Average
ASCE	American Society of Civil Engineers
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BEM	Building Energy Model
BFRP	Basalt Fiber Reinforced Polymer
BIV	Building-Integrated Vegetation
CBE	Center for the Built Environment
CCD	Charge-Coupled Device
CCS	Concrete Cover Separation
CCT	Correlated Color Temperature
CDP	Concrete Damaged Plasticity
CFD	Computational Fluid Dynamics
CFRP	Carbon Fiber Reinforced Polymer
CHP	Combined Heat and Power
CIE	International Commission on Illumination
DAF	Dynamic Amplification Factor
DBC	Dimensionality-Based Classification
DF	Daylight Factor
DGI	Daylight Glare Index
DGP	Daylight Glare Probability
DIC	Digital Image Correlation
DRF	Dynamic Response Factor
EEO	Energy Economy Optimization
EHT	Equivalent Homogeneous Temperature
EMI	Electromechanical Impedance
EMS	Energy Management Systems
FEA	Finite Element Analysis
FRP	Fiber Reinforced Polymer

FRPU	Fiber Reinforced Polyurethanes
GB	Chinese National Standard (Guobiao)
GFRP	Glass Fiber Reinforced Polymer
GTRM	Glass Textile Reinforced Mortar
HVAC	Heating, Ventilation, and Air Conditioning
IAQMs	Indoor Air Quality Models
IC	Intermediate Crack
ICMs	Integrated Comfort Models
IEQ	Indoor Environmental Quality
INODIS	Innovative Decoupled Infill System
ISO	International Organization for Standardization
LAI	Leaf Area Index
LEED	Leadership in Energy and Environmental Design
LES	Large Eddy Simulation
LWS	Living Wall Systems
MC	Material Classification
MMC	Material Behavior Classification
MMC	Material Behavior Classification
NDT	Non-Destructive Testing
NV	Naturally Ventilated
PCS	Personal Comfort Systems
PDE	Partial Differential Equation
PET-FRP	Polyethylene Terephthalate Fiber Reinforced Polymer
PFJ	Polymer Flexible Joint
PIML	Physics-Informed Machine Learning
PM	Polymer Medium stiff
PMV	Predicted Mean Vote
POE	Post-Occupancy Evaluation
PPD	Predicted Percentage Dissatisfied
PS	Polymer Stiff
PSCMs	Psychological and Subjective Comfort Models
PT	Polymer Very Stiff
PUFJ	Polyurethane Flexible Joint
PZT	Lead Zirconate Titanate (Piezoelectric sensors)
QSM	Quantitative Structure Model
RC	Reinforced Concrete

RCM	Reinforced Concrete Model
RHT	Riedel-Hiermaier-Thoma (concrete model)
SHM	Structural Health Monitoring
SPD	Spectral Power Distribution
SR	Structural Renovation
SSCo	Strip of Strong Compression
SSTe	Strip of Strong Tension
STI	Speech Transmission Index
TCMs	Thermal Comfort Models
TRM	Textile-Reinforced Mortar
UGI	Urban Green Infrastructure
UGR	Unified Glare Rating
UHI	Urban Heat Island
URM	Unreinforced Masonry
UTCI	Universal Thermal Climate Index
VCMs	Visual Comfort Models
VCP	Visual Comfort Probability
VF	Vertical Forest
VIV	Vortex-Induced Vibration
VOCs	Volatile Organic Compounds
WBGT	Wet Bulb Globe Temperature
WiAMS	Wireless Autonomous Monitoring System
WoW	Wall of Wind

ΠΕΡΙΛΗΨΗ

Στην παρούσα παραδοτέα έκθεση, συγκεντρώνονται και αξιολογούνται κριτικά οι αναλυτικές μεθοδολογίες και προσομοιώματα για κτίρια Κατακόρυφων Δασών (ΚΔ), με έμφαση στη συνδυαστική ανακαίνιση που αφορά δομικές, ενεργειακές, δασοκομικές και πτυχές άνεσης των ενοίκων. Η έρευνα, που εντάσσεται στο πλαίσιο του έργου GREENERGY, διερευνά καινοτόμες τεχνικές για την ανακαίνιση κατασκευών οπλισμένου σκυροδέματος σε σεισμογενείς περιοχές, ενσωματώνοντας πράσινα υλικά και στοιχεία κατακόρυφου δάσους. Στόχος είναι η βελτιστοποίηση της ανάπτυξης των ΚΔ σε αστικά περιβάλλοντα, η ενίσχυση της ενεργειακής απόδοσης και η βελτίωση της δομικής ανθεκτικότητας. Επιπρόσθετα, συζητείται η ανάπτυξη ενός ψηφιακού διδύμου για τη διευκόλυνση αξιολογήσεων σε πραγματικό χρόνο και μελλοντικών σεναρίων ανακαίνισης.

Λέξεις-κλειδιά: αναλυτικά προσομοιώματα, Κατακόρυφο Δάσος, φυτά, σεισμική ανθεκτικότητα, ενεργειακή απόδοση, δομική ανακαίνιση, οπλισμένο σκυρόδεμα, πράσινα υλικά, ψηφιακό δίδυμο, αστική δασοκομία, άνεση ενοίκων, μεσογειακό

SUMMARY

In this deliverable, the analytical methodologies and models for VF (Vertical Forest) buildings are gathered and critically reviewed, focusing on combined renovation that addresses structural, energy, forestry, and occupant comfort aspects. The research, part of the GREENERGY project, explores innovative techniques for renovating reinforced concrete structures in seismic-prone areas, integrating green materials and vertical forest elements. The goal is to optimize VF growth in urban settings, enhance energy efficiency, and improve structural resilience. Additionally, the development of a digital twin model is discussed to facilitate real-time assessments and future renovation scenarios.

Keywords: Analytical models, Vertical Forest, plant, seismic resilience, energy efficiency, structural renovation, reinforced concrete, green materials, digital twin, urban forestry, occupant comfort, mediterranean

1 INTRODUCTION

GREENERGY goes beyond the leading state of the art concepts in the area that aim mainly to produce nearly zero energy consumption and neutral carbon footprint within built environment in urban areas in order to promote the "green deal" while the real green nature itself is suppressed. Such an approach may satisfy merely mathematical indices and goals. However, it fails to revive natural growth in areas forests were once dominating, i.e. before urbanization. It holds down the decisive, that is natural mechanisms for sustainable environment of high air quality, controlled humidity, satisfaction and comfort for habitants.

Within the framework of GREENERGY a physical 3D model will be tested in the shake table of DUTh lab to set proof of innovative concepts, suitable renovations and VF construction towards digital twin (hybrid) development. The digital twin model to be developed during the following deliverables is going to incorporate and enable real time assessment from a combined structural-energy-human 'health monitoring' aspect and allow for future optimization scenarios.

GREENERGY envisions forest diffusion to alleviate extreme weather conditions impacts in coastal seismic urban regions and to optimize inclusive peoplecentric social engagement towards habitant comfort and satisfaction, through high-density urban forestation.

Retrofit practices in RC buildings often fail to integrate energy and structural upgrades in a way that ensures long-term protection of energy investments from potential disastrous events such as earthquakes. This is primarily due to the fragmented nature of existing basic research, which typically focuses separately on energy efficiency or structural improvements. In that way, several critical construction details are insufficiently addressed. Moreover, these practices overlook the incorporation of green principles, as well as eco-friendly, recyclable, and natural strengthening materials in buildings with structural deficiencies.

GREENERGY envisions forest diffusion to alleviate extreme weather conditions impacts in coastal seismic urban regions and to optimize inclusive people-centric social engagement towards habitant comfort and satisfaction, through high-density urban forestation starting from green- renovated buildings. Based on the poor state of the art in the field of renovation towards vertical forests and the great necessity for their urgent development, GREENERGY aims to really cope with detrimental climate change consequences and advance environmental resilience. In that aspect, **the Digital Twin Modeling of the key performance parameters of the building before and after renovation is crucial. That is modeling of the 3d reinforced concrete structure, of the green retrofits, of the green envelopes, of the forestry and of their interactions towards real-time interoperability with physical model is of paramount importance. The first step is to select the appropriate finite element models for reinforced concrete members, green retrofit materials, green concrete-forestry interface envelopes, for instrumentation locations, for forestry and for their interactions and fixings. Models for energy and comfort related analyses.**

Therefore, GREENERGY addresses the following critical objective:

Literature review on VF buildings' modeling for combined renovation covering structural, energy, forestry and habitant comfort aspects.

2 METHODOLOGY

GREENERGY conducts groundbreaking basic research at building level in order to review barriers in existing renovation approaches that lead to exclusion of forests from cities and detrimental incompatibility with built environment and revolutionize vertical forest (VF) concepts.

The maximum utilization of natural mechanisms through VFs for sustainable environment of high air quality, controlled humidity, satisfaction and comfort for habitants is the main global objective.

It gathers and coordinates approaches and develops the fundamental theoretical, experimental and digital twin framework with respect to structural and energy related drivers in order to allow for efficient renovation as well as continuous monitoring and therefore pave a solid path for harmonic VF growth inside smart cities and interconnection of urban forests in a unified high-quality living environment for citizens.

To meet the objectives of the project and to reach the main target of the development of the VFs in efficiently renovated buildings combining structural, energy and forestry retrofits, various procedures and methodologies are utilized associated with the following components:

The development of digital twin model of the renovated construction to reproduce the unique performance of materials, their interfaces and interactions with distinctive structural, energy and forestry- sensitive parameters. That is modeling of the 3d reinforced concrete structure, of the green retrofits, of the green envelopes, of the forestry and of their interactions towards real-time interoperability with physical model. Development of appropriate finite element models and calibration, especially for innovative green retrofit materials, green concrete-forestry interface envelopes, for instrumentation locations and types, for forestry and for their interactions and fixings (with structural, energy and comfort related mathematical background) require extensive research in TRL 1-3 for various aspects.

The proposed research methodology is capable to address important scientific risks arising during Innovative digital twin model development proposing adequate contingency actions. More specifically, one important scientific risk may arise from the complexities of the numerical computations that represent the backbone of the proposed methodology. To tackle this issue, different nonlinear dynamic models of increased complexity will be investigated and comparative results will be presented to assess the sensitivity of the various influential parameters and enhance the validity of the considered models. Another important scientific risk comes from the difficulties in deriving coupled curves due to the combined effects (forestry, energy and structural). To achieve this, except for the fully coupled approach that considers the combined effects in a single step, an alternative uncoupled approach will be examined where the combined influences will be taken into account in subsequent steps.

This report focuses on the selection of the appropriate finite element models for reinforced concrete members, green retrofit materials, green concrete-forestry interface envelopes, for instrumentation locations, for forestry and for their interactions and fixings. Models for energy and comfort related analyses.

3 LITERATURE REVIEW ON VF BUILDINGS' MODELING

3.1 STATE OF THE ART AND INNOVATION

The main objective is to favor natural mechanisms for sustainable environment of high air quality, controlled humidity, satisfaction and comfort for habitants through suitable Vertical Forests.

Ancient Greek literature acknowledged early enough the importance of the "Vertical Forests" in human society and well-being as "The Hanging Gardens of Babylon" were selected among the well-known "Seven Wonders" of the world (https://en.wikipedia.org/w/index.php?tle=Hanging_Gardens_of_Babylon&oldid=1114135823) (Dalley, 1993) (Reade, 2000) (Foster, 2004).

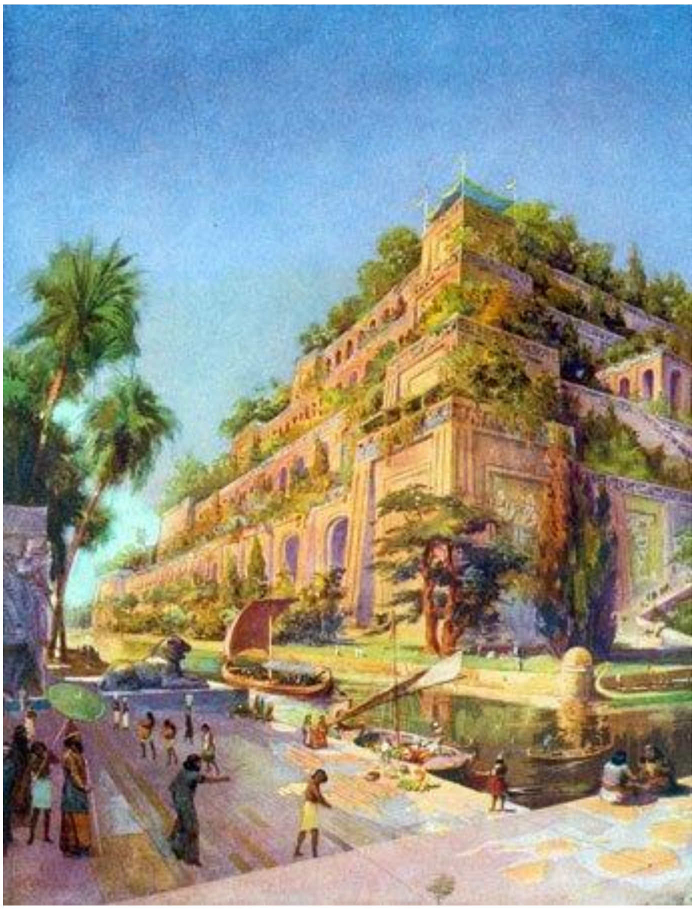


Figure 1 The Hanging Gardens of Babylon, Artist's re-creation, Encyclopedia Britannica https://www.britannica.com/place/Hanging-Gardens-of-Babylon

Contemporary urban environment still lacks the wide spreading of forestry as an integral part of important landmark buildings as well as of broader building complexes with different services. Contrary to the urgent need of scientific and technological developments, only limited research addresses the issue of high-density urban forestation (Marugg, 2018, Helman et al., 2022) besides several contemporary architecture such as Bosco Verticale in Milan (2014, https://www.stefanoboeriarchitetti.net/en/urban-forestry/).

Most of structures in built environment are reinforced concrete ones with brick wall infills. Inherent brittleness requires the use of flexible structural joints to utilize hybridization and other beneficial effects through Polymer Flexible Joints (PFJ). Some special polyurethanes may form flexible joints enabling for extensive redistribution of detrimental stress concentrations in different demanding applications (Kwiecień et al., 2017, Kwiecień et al., 2014, Kwiecień & Zając, 2008, Kwiecień, 2016, Tedeschi et al., 2014). PFJ may repair cracks by injection or fill specially designed structural gaps, to make extremely flexible hinges (with polymers PM and PT) – polyurethane flexible joints (PUFJ). Further, PU may be used to bond composites using flexible adhesives (PS and PT)([Kwiecień, 2016)– fiber reinforced polyurethanes (FRPU). Polyurethanes of various stiffness and deformability (e.g. polymers: PT – stiff, PS – middle stiff and PM – soft). Masonry infill walls in RC buildings may be upgraded through suitable intervention techniques (Yuksel et al., 2006, Ozden et al., 2011, Koutas et al., 2015, Gams et al., 2017, Fardis, 2000). Several analytical studies address the beneficial effects of the suitable infill wall renovation scheme with polyurethane FRP (FRPU) and novel techniques (Rousakis & Tourtouras, 2014, Rousakis, 2016, Rouka et al., 2017). Recently concluded tests in IZIIS seismic table by the PI together with a consortium of 8 universities and 3 private companies have demonstrated and validated the expected unique beneficial effects of the use of novel flexible polymers (INMASPOL SERA TA Horizon project) for retrofitting and repair of large scale structures (Hojdys et al., 2017, Rousakis et al. 2020). Further, the PI has developed advanced analytical models of (digital twin) rc frames and structures within ESPA EDBM103 (MIS: 5050146) Horizon project (Rousakis et al., 2021a, Rousakis et al., 2021b) and INMASPOL (Hojdys et al., 2017).

FRP chords and ropes with, or even without the use of bonding polymers provide a viable renovation alternative (Golias et al., 2021, Karantzikis et al., 2005, Triantafillou et al., 2006, Padanattil & Karingamanna, 2017, Rousakis, 2016, Rousakis et al., 2019). Continuous structural health monitoring HSM through PZT transducers is an efficient method. PZT-based SHM systems, WiAMS, may allow for real-time condition and damage assessment in reinforced concrete structures. The operation and the feasibility of the wireless PZT-based SHM system in concrete members has been widely researched (Providakis et al., 2015, Providakis et al., 2016, Karayannis et al., 2015, Voutetaki et al., 2022, Chalioris et al., 2020, Chalioris et al., 2021, Ai et al., 2018, Ai et al., 2019, Talakokula et al., 2014, Talakokula & Bhalla, 2015, Hou et al., 2017).

GRENERGY will address the gaps in fundamental research concerning: i) the region- and building dependent forestry, ii) the suitable structural joints and anchors or additional constructions and suitable interfaces to accommodate and grow over time forestry on the existing building, iii) the efficient seismic retrofit of the common deficiencies of existing buildings with the forestry additional mass and detailing included, iv) the continuous smart PZT monitoring of the system with digital twin model that allows the investigation of key parameters and examination of different scenarios.

3.2 ABOUT GREEN ROOFS

“A green roof system is installed as an extension of the existing roof which involves, at a minimum, high quality waterproofing, root repellent system, drainage system, filter cloth, a lightweight growing medium, and plants.

Green roof systems may be modular, with drainage layers, filter cloth, growing media, and plants already prepared in movable, often interlocking grids, or loose laid/built-up whereby each component of the system may be installed separately. Green roofs can be defined as "contained" green space on top of a human-made structure. This green space could be below, at, or above grade, but in all cases, it exists separate from the ground. Green roofs can provide a wide range of public and private benefits and have been successfully installed in countries around the world.

In North America, the benefits of green roof technologies are poorly understood, and the market continues to mature, despite the efforts of industry leaders. In Europe however, these technologies have become very well established. This has been the direct result of government legislation and financial support. Such support recognizes the many tangible and intangible public benefits of green roofs. This support has led to the creation of a vibrant, multi-million-dollar market for green roof products and services in Germany, France, Austria, and Switzerland, among others.

Green roof technologies not only provide the owners of buildings with a proven return on investment, but also represent opportunities for significant social, economic, and environmental benefits, particularly in cities." (https://beesl.syr.edu/research/champs-in-building-envelope-systems-champs-bes/ / https://greenroofs.org/about-green-roofs).

3.3 TYPES OF GREEN ROOFS

"Green roofs can be installed on a wide range of buildings, from industrial facilities to private residences. There are two types of green roofs: extensive and intensive."

Table 1 Types of green roofs (https://www.epa.gov/heatislands/using-green-roofs-reduce-heat-islands)

Extensive Green Roofs	Intensive Green Roofs
Tend to be simpler, with hardy plants and a growing medium depth of two to four inches	Tend to be more complex, such as a fully accessible park complete with trees
Require the least amount of added structural support since they are lightweight	Resemble conventional gardens or parks
Need little maintenance once established	Require more structural support since they are heavier
	Require a higher initial investment
	Require more intensive maintenance

"Both types of green roofs consist of the same basic layering components with several barriers to prevent water or root damage to the structure, a drainage layer to aid in water drainage, as well as a growing medium and vegetative layer. The Common Green Roof Layers Figure 2represents the most common design of a green roof, although not all the layers shown are found on every green roof."

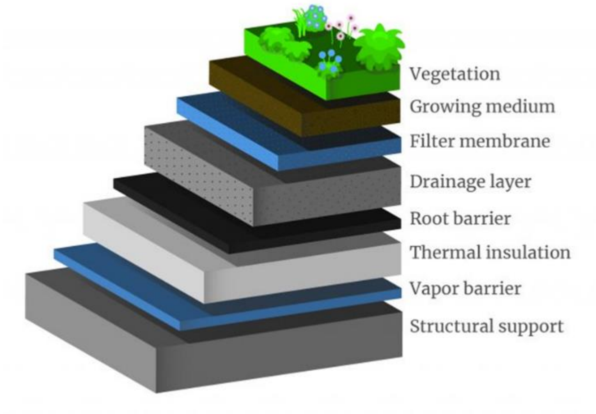


Figure 2 Representative green roof layers: vegetation at the top, then growing medium, filter membrane, drainage layer, root barrier, thermal insulation, vapor barrier, and structural support (ref. https://www.epa.gov/heatislands/using-green-roofs-reduce-heat-islands)

Green Roofs vs. Cool Roofs

“Cool roofs present another option to reduce the heat island effect. Cool roofs are made of highly reflective and emissive materials that remain cooler than traditional materials during peak temperatures. While green roofs often have initially higher costs than cool roofs, green roofs typically have a longer expected life. Both cool and green roofs provide benefits of lower surface and air temperatures, and decreased energy demand. However, green roofs offer added benefits such as reducing and filtering stormwater runoff; absorbing pollutants and carbon dioxide; providing natural habitat; and in the case of intensive green roofs, serving as recreational green space. Cool roofs are best suited for projects with limited budgets and a primary focus on energy savings, while green roofs are preferred when lifecycle costs, public benefits, and broader environmental impacts are of interest. Both options are important strategies for mitigating heat island effects.” (https://www.epa.gov/heatislands/using-green-roofs-reduce-heat-islands)

3.4 PREVIOUS LITERATURE REVIEWS

The article "Numerical Simulation to Assess the Impact of Urban Green Infrastructure on Building Energy Use: A Review" by Zhu et al. (2023) provides a thorough examination of the use of numerical simulations to understand the impact of urban green infrastructure (UGI) on building energy consumption, particularly in the context of increasing urbanization and its contribution to the urban heat island (UHI) effect. The authors aim to address the pressing need for sustainable urban design solutions by reviewing existing numerical models and simulation tools that integrate green infrastructure, such as green roofs, green walls, and site-scale vegetation, into building energy models (BEMs). The review includes researches carried out over the past 35 years and highlights the importance of numerical simulations in the planning and design phases of UGI projects, where evaluating the energy performance of such infrastructures is critical to reducing the energy that is necessary for the buildings.

The paper emphasizes the dual role of UGI in urban environments, particularly its capacity to provide shading and promote evaporative cooling, which helps lower the local air and surface temperatures around buildings. This, in turn, reduces the energy required for air conditioning, particularly during hot seasons. The review details how early simulations focused primarily on

UHI mitigation by large urban green spaces, such as parks and urban forests, while more recent studies have included building-integrated vegetation (BIV), like green roofs and walls, as essential elements in reducing the energy consumption of individual buildings. Through various numerical models, the paper outlines how UGI has been shown to lower the cooling loads of adjacent buildings by up to 10%, depending on the design and arrangement of the green infrastructure.

A large part of the paper includes the review of methodologies used in UGI simulations, noting that current building energy models, such as EnergyPlus and TRNSYS, incorporate modules for green roofs and walls but fail to account for site-scale vegetation (trees, shrubs, etc.) in their assessments. This omission points to a gap in current tools that must be addressed to fully integrate UGI's effects on urban microclimates and energy use. The authors also discuss the coupling of microclimate models with BEMs, which allows for a more detailed assessment of how site-scale vegetation affects heat exchange processes, such as shading, convection, and evapotranspiration. The review encourages greater collaboration between urban climatologists and building physicists to enhance the integration of UGI simulations with BEM tools, particularly through the coupling of urban microclimate models and building-scale energy simulations.

Throughout the review, the authors emphasize the need for more sophisticated and accurate validation of these models using real-world data. Despite advancements in modeling techniques, many studies still rely on oversimplified assumptions or empirical values, which may not fully capture the dynamic and complex interactions between UGI and the urban environment. The paper advocates for more robust data collection efforts, particularly long-term monitoring of green infrastructure's thermal and energy performance across various climates and building types, to better inform future design strategies.

In conclusion, this review offers a comprehensive guide for researchers and practitioners working on integrating UGI into building energy simulations, pointing out both the progress made and the existing gaps in current methodologies. Numerical simulations, in this way, form a critical part in the optimization of design and energy performance of Urban Green Infrastructure (UGI), contributing to the development of more sustainable and energy-efficient urban areas. Future research directions outlined in this paper encourage better tools that would enable an easier inclusion of UGI into the standard Building Energy Modeling (BEM) practices, hence assisting in a more holistic approach toward the reduction of energy use and the impacts of climate change in urban areas.

On the other hand, the research article "The Impact of Greening Systems on Building Energy Performance: A Literature Review" by Raji et al. (2015) developed a critical review of various greening systems, namely, green roofs, vertical greening, green balconies, and sky gardens, giving evidence of potential benefits to enhancing the building energy performance. This study introduces energy consumption and environmental sustainability as two very important emerging global challenges. Buildings are stated to use about a huge percentage of the world's energy and emit a similar share of CO_2 emissions. Amongst systems showing potential to contribute to the reduction of energy demands through enhancement of thermal insulation, shading, and evaporative cooling are greening systems. These systems contribute to mitigating urban heat island effects, managing stormwater, enhancing biodiversity, and essentially improving the aesthetic appeal of cities.

Different greening paradigms are reviewed herein, vis-à-vis the effect of such on temperature regulation, heat transfer, and energy consumption. The review begins with a look at green roofs. Green roofs can be broadly categorized depending on the structural and maintenance requirements as either: extensive, semi-intensive, or intensive systems. Substrate depth, plant species and cover percentage, and moisture contents of the growth medium are major parameters that would define the cooling performance of green roofs. Studies confirm that vegetative roofs help reduce the surface temperatures, while roofs with more significant vegetation density offer more excellent benefits from shading and evaporative cooling. However, despite the fact that green roofs significantly reduce cooling demands during summer periods, they can slightly increase heating demands during winter periods due to reduced solar heat gains.

The next section deals with vertical greening systems that include green facades and living walls. Vertical greening can greatly help reduce energy use by providing shade on building façades, which reduces surface temperatures and prevents heat gain through the building envelope. These systems are very effective in warm climates where the cooling demand is quite high. The outcome of the present study shows that the performance of vertical greening systems is based on factors such as Leaf Area Index (LAI), types of plant species used, and spatial separation between the vegetative layer and the building's façade. Indeed, the shading effect developed from the vertical greening systems might help in reducing solar radiation significantly and hence reduces the cooling loads up to 50% accordingly.

The review also accounts for green balconies and sky gardens, yet these notions receive relatively less consideration by scholars when talking about green roofs and vertical greening. Green balconies-especially with the addition of trees or other vegetation-contribute a lot to the considerable reduction in heat absorption by the building facade and at the same time provide psychological and social benefits for residents. Sky gardens share many benefits with green roofs but is considerably more accessible to residents, more aesthetically pleasing for the building, and generally has more positive effects on the surrounding urban environment.

It concludes that any saving potential of greening systems depends on issues such as building type, geographic location, and architectural design but that greening systems bear huge potentials for the reduction of energy consumption in buildings. The authors further recommend more studies to be done in quantifying long-term benefits of the greening system in different climatic zones and toward developing more comprehensive models with higher accuracy of thermal and energy performance forecast. It allows cities to progress toward a sustainable, energy-efficient, and resilient environment through greening systems incorporated into urban planning and architectural design.

Both reviews further strengthen the fact that has increasingly been recognized: green infrastructure is among the viable solutions to improve building energy performance while mitigating the negative impacts of urbanization, such as the Urban Heat Island (UHI) effect. However, they also emphasize the need for more sophisticated and context-specific simulation models that can accurately predict the energy-saving potential of greening systems across diverse building types and climatic conditions. Furthermore, both papers highlight the importance of interdisciplinary research that combines expertise from fields such as architecture, environmental science, and urban planning to optimize the design and implementation of greening systems. In conclusion, these literature reviews provide valuable insights into the state of research on UGI and greening systems, offering guidance for future studies aimed at enhancing the sustainability and energy efficiency of urban environments.

3.5 STRUCTURAL RENOVATION (SR) MODELS FOR VF BUILDINGS

3.5.1 ANSYS modelling

The analytical models for the characteristic reinforced concrete elements such as columns, slabs etc, may becreated using ANSYS Workbench with the Explicit Dynamics module. Three-dimensional finite element (FE) models may be developed to conduct pseudo-dynamic inelastic analyses. Advanced material models for concrete, steel, and composites, along with their interactions, need careful calibration. (According to PhD by Anagnostou and Fanaradelli)

3.5.1.1 Historical Background

"While it is difficult to quote a date of the invention of the finite element method, the method originated from the need to solve complex elasticity and structural analysis problems in civil and aeronautical engineering. Its development can be traced back to the work by Hrennikoff. (1941) and Courant (1943) in the early 1940s. Another pioneer was Ioannis Argyris. In the Union of Soviet Socialist Republics (USSR), the introduction of the practical application of the method is usually connected with name of Leonard Oganesyan. In China, in the later 1950s and early 1960s, based on the computations of dam constructions, K. Feng proposed a systematic numerical method for solving partial differential equations. The method was called the finite difference method based on variation principle, which was another independent invention of the finite element method. Although the approaches used by these pioneers are different, they share one essential characteristic: mesh discretization of a continuous domain into a set of discrete sub-domains, usually called elements.

Hrennikoff's work (1941) discretizes the domain by using a lattice analogy, while Courant's approach (1943) divides the domain into finite triangular subregions to solve second order elliptic partial differential equations (PDEs) that arise from the problem of torsion of a cylinder. Courant's contribution was evolutionary, drawing on a large body of earlier results for PDEs developed by Rayleigh, Ritz, and Galerkin.

The finite element method obtained its real impetus in the 1960s and 1970s by the developments of J. H. Argyris with co-workers at the University of Stuttgart, R. W. Clough with co-workers at UC Berkeley, O. C. Zienkiewicz with co-workers Ernest Hinton, Bruce Irons (Hinton and Irons 1968) and others at Swansea University, Philippe G. Ciarlet at the Pierre and Marie Curie University and Richard Gallagher with co-workers at Cornell University. Further impetus was provided in these years by available open source finite element software programs. NASA sponsored the original version of NASTRAN, and UC Berkeley made the finite element program SAP IV widely available. In Norway the ship classification society Det Norske Veritas (now DNV GL) developed Sesam in 1969 for use in analysis of ships (Paulsen et al. 2014). A rigorous mathematical basis to the finite element method was provided in 1973 with the publication by Strang and Fix (1973). The method has since been generalized for the numerical modeling of physical systems in a wide variety of engineering disciplines, e.g., electromagnetism, heat transfer, and fluid dynamics (Zienkiewicz et al. (2013), Bathe (2006))." (Source: https://en.wikipedia.org)

3.5.1.2 3D Finite Element Modeling

3.5.1.2.1 FEA workflow

The overall workflow involved when performing any analysis in the Workbench software is listed:

i) Create the Analysis System

ii) Define Engineering Data

iii) Create a Geometry

iv) Define Part Behaviour

v) Define Connections

vi) Apply Mesh Controls and Generate Mesh

vii) Establish Analysis Settings

viii) Define Initial Conditions

ix) Apply Loads and Supports

x) Perform Solution

Implicit" and "Explicit" refer to two types of time integration methods used to perform dynamic simulations. Explicit time integration is more accurate and efficient for simulations involving

- Shock wave propagation
- Large deformations and strains
- Non-linear material behavior
- Complex contact
- Fragmentation
- Non-linear

Figure 3 Explicit Dynamics Analysis Process (Source: ANSYS Training manual).

3.5.1.2.2 Explicit dynamics

The Explicit Dynamics system can perform various modelling such as the nonlinear dynamic behaviour of solids, fluids, and gases, as well as their interaction. Ansys explicit dynamics reproduces efficiently the physics of short-duration events for systems that invlolve highly nonlinear, transient dynamic forces. An explicit dynamics analysis typically includes many different types of nonlinearities, which may stem from the materials (such as hyperelasticity, plastic flows, failure), from contact (such as high-speed collisions and impact) and from the geometric deformation (such as buckling and collapse).

An Explicit Dynamics solution starts with a discretized domain (mesh) with assigned material properties, loads, constraints, and initial conditions (see ANSYS Mechanical User's Guide). When this initial state is integrated with time, motion is produced at the mesh node points, which causes deformation in the mesh elements. Deformation changes volume and density of the material in each element. The material strain rates are derived from the rate of deformation using various element formulations. Then, the material strain rates are used in constitutive laws and derive resultant material stresses, which are transformed back into nodal forces using various element formulations. External nodal forces are computed from boundary conditions, loads and contact (body interaction) and divided by nodal mass to produce nodal accelerations. The integration of the accelerations Explicitly in time produces new nodal velocities and of the nodal velocities produces new nodal positions. The cycle described above is repeated until the calculation end time is reached.

The basic equation of motion solved by an implicit transient dynamic analysis is

$$m\ddot{x} + c\,\dot{x} + kx = F(t)$$

where

The following matrices are included, m for the mass, c for the damping and k for the stiffness matrix. Finally F(t) is the vector for the load.

At any given time, t, this equation can be thought of as a set of "static" equilibrium equations that also take into account inertia forces and damping forces. The Newmark or HHT method is used to solve these equations at discrete time points. The time increment between successive time points is called the integration time step. For linear problems, the implicit time integration is unconditionally stable for certain integration parameters and the time step will vary only to satisfy accuracy requirements. For nonlinear problems, the solution is obtained using a series of linear approximations (Newton-Raphson method), so each time step may have many equilibrium iterations. The solution requires inversion of the nonlinear dynamic equivalent stiffness matrix. Small, iterative time steps may be required to achieve convergence. Convergence tools are provided, but convergence is not guaranteed for highly nonlinear problems.

The basic equations solved by an Explicit Dynamic analysis express the conservation of mass, momentum and energy in Lagrange coordinates. These, together with a material model and a set of initial and boundary conditions, define the complete solution of the problem. For Lagrange formulations, the mesh moves and distorts with the material it models, so conservation of mass is automatically satisfied. The density at any time can be determined from the current volume of the zone and its initial mass:

$$\frac{\rho_0 V_0}{V} = \frac{m}{V}$$

The partial differential equations which express the conservation of momentum relate the acceleration to the stress tensor σ_{ij}:

$$\rho\ddot{x} = b_x + \frac{\partial\sigma_{xx}}{\partial x} + \frac{\partial\sigma_{xy}}{\partial y} + \frac{\partial\sigma_{xz}}{\partial z}$$

$$\rho\,\ddot{y} = b_y + \frac{\partial\sigma_{yx}}{\partial x} + \frac{\partial\sigma_{yy}}{\partial y} + \frac{\partial\sigma_{yz}}{\partial z}$$

$$\rho\,\ddot{z} = b_z + \frac{\partial\sigma_{zx}}{\partial x} + \frac{\partial\sigma_{zy}}{\partial y} + \frac{\partial\sigma_{zz}}{\partial z}$$

Conservation of energy is expressed via:

$$\dot{e} = \frac{1}{\rho}\left(\sigma_{xx}(\dot{\varepsilon_{xx}}) + \sigma_{yy}(\dot{\varepsilon_{yy}}) + \sigma_{zz}(\dot{\varepsilon_{zz}}) + 2\sigma_{xy}(\dot{\varepsilon_{xy}}) + 2\sigma_{yz}(\dot{\varepsilon_{yz}}) + 2\sigma_{zx}(\dot{\varepsilon_{zx}})\right)$$

For each time step, these equations are solved explicitly for each element in the model, based on input values at the end of the previous time step. Only mass and momentum conservation are enforced. However, in well posed explicit simulations, mass, momentum and energy should be conserved. Energy conservation is constantly monitored for feedback on the quality of the solution (as opposed to convergent tolerances in implicit transient dynamics).

The Explicit Dynamics solver uses a central difference time integration scheme (Leapfrog method). After forces have been computed at the nodes (resulting from internal stress, contact, or boundary conditions), the nodal accelerations are derived by dividing force by mass:

$$(\ddot{x_i}) = \frac{F_i}{m} + b_i$$

where

x_i are the components of nodal acceleration (i=1,2,3),

F_i are the forces acting on the nodes,

b_i are the components of body acceleration and

m is the mass of the node

With the accelerations at time n-1/2 determined, the velocities at time n+1/2 are found from

$$x_i^{n+1/2} = x_i^{n-1/2} + (\dot{x_i^n})\Delta t^n$$

Finally, the positions are updated to time n+1 by integrating the velocities

$$x_i^{n+1} = x_i^n + x_i^{n+1/2}\Delta t^{n+1/2}$$

The advantages of using this method for time integration for nonlinear problems are:

- The equations become uncoupled and can be solved directly (explicitly). There is no requirement for iteration during time integration
- No convergence checks are needed since the equations are uncoupled
- No inversion of the stiffness matrix is required. All nonlinearities (including contact) are included in the internal force vector.

FE analysis gives the ability to construct models that take into account geometrical and material nonlinearity or nonlinear interaction between materials in their contact points or surfaces. Also, the effect of several parameters on mechanical behavior of materials or structural elements can be investigated in macrostructural or microstructural level choosing suitable discretization. Reliable FE analysis take into consideration suitable models for materials and their interactions. The models for concrete, steel, and FRP inserted in ANSYS Explicit Dynamics software are presented in the next sections. Comprehensive analytical investigations with ANSYS utilized the experimental tests of RC square and rectangular concrete columns externally confined by FRP materials subjected to axial compressive load, performed by Rousakis and Karabinis (2012), Isleem et al. (2018) and Ilki et al. (2008).

FE analysis may include the following steps (see https://ascelibrary.org/doi/10.1061/%28ASCE%291090-0268%282008%2912%3A5%28531%29) :

1) the geometric characteristics of the members of the model are determined
2) the properties of the materials are defined

3) the connections and contacts among members are assigned
4) the type of discretization of the model as well as the density of discretization is determined depending on the number of seeds in each surface and the suitable meshing technique, always depending on the case of study. The main target of meshing is the compatibility of the nodes between the concrete core and the FRP jacket in order to avoid convergence problems during analysis (see https://www.mdpi.com/2073-4360/12/11/2546).
5) the mode of imposed displacement is defined. Monotonic axial displacement is forced at the top of the column, directly on the concrete core and not at the FRP jacket and
6) the boundary conditions of the model are determined. "Fixed Support" is chosen at the base of the column.

The response of a part is determined by the material properties assigned to the part. Material properties, depending on application, may be linear, non-linear or temperature dependent. Below, the used material models for concrete, steel reinforcement and FRP jacket are presented.

3.5.1.2.3 Concrete Modelling

Concrete is modeled with the Riedel–Hiermaier–Thoma (RHT) model [Riedel et al. (1999), Riedel (2004), Riedel et al (2007)], which is available in ANSYS Autodyn since 2000 as a description of concrete and similar geological materials in highly dynamic loading situations. It is particularly useful for modeling the dynamic loading of concrete. Taking the difference of tensile, compressive strength and strain rate sensitivity into account, the model can better reflect the dynamic mechanical behavior of concrete material. This model takes also into account the porous compaction of concrete. It can also be used for other brittle materials and as a combined plasticity and shear damage model.

Over the last decade, numerous worldwide applications appeared in publications which deal with dynamic load cases such as projectile penetration, contact detonation, internal and external blast loading (Leppanen (2006), Borrvall (2011), Ding et al. (2013), Wang et al. (2017), Heckotter and Sievers (2017)). However, the application of the RHT model requires a set of suitable model parameters without which reliable results cannot be expected. The qualitative overview of the model is presented herein before presenting the mathematical details adopted for the present study.

3.5.1.2.4 Failure surface

The deviatoric stress in the material is limited by a generalized failure surface of the form:

$$f(P, \sigma_{eq}, \theta, \dot{\varepsilon}) = \sigma_{eq} - Y_{TXC}(P) * F_{CAP}(P) * R_3(\theta) * (F)^{RATE(\dot{\varepsilon})}$$

This failure surface can be used to represent the following aspects of the response of geological materials

- Pressure hardening
- Strain hardening
- Strain rate hardening in tension and compression
- Third invariant dependence for compressive and tensile meridians
- Strain softening (shear induced damage)
- Coupling of damage due to porous collapse

The model is modular in nature and is designed such that individual aspects of the material behavior can be turned on and off. This gives the model significant practical usefulness. Further details of how the model represents the various aspects of the material behavior are presented.

3.5.1.2.5 Fracture surface

The fracture surface is represented through the expression:

$$Y_{TXC} = fc'\left[A_{TXC}\left(P^{*} - P^{*}_{span}F_{RATE}\right)^{N_{TXC}}\right]$$

where

- f_c' is the cylinder strength,
- A_{TXC}, N_{TXC} are user defined parameters,
- P^* is pressure normalized with respect to f_c',
- P_{*span} is the normalized hydrodynamic tensile limit, and
- F_{RATE} is a rate dependent enhancement factor.

Additionally, there is an option to truncate the fracture surface to fit through the characteristic points that can be observed experimentally at low pressures, while retaining the flexibility to match data at high pressures. This feature is described in Figure 4.

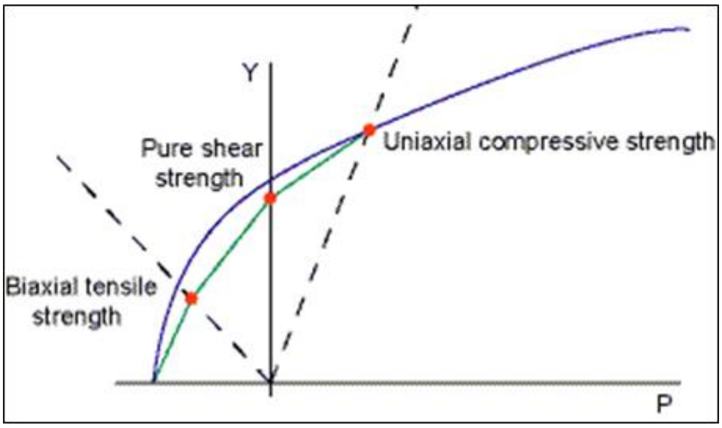


Figure 4 RHT Representation of Compressive Meridian (Source: ANSYS Training manual).

3.5.1.2.6 Tensile and Compressive Meridians

The RHT model can represent the difference between the compressive and tensile meridian in terms of material strength using the term R3. This can be utilized to represent the observed reduction in strength of concrete under triaxial extension, compared with triaxial compression. The third invariant dependence term is formulated using the expression

$$R_3 = \frac{2(1 - Q_2^2)\cos\theta + (2Q_2 - 1)\sqrt{4(1 - Q_2^2)\cos^2\theta - 4Q_2}}{4(1 - Q_2^2)\cos^2\theta + (1 - 2Q_2)^2}$$

where

$$\cos(3\theta) = \frac{3\sqrt{3}J_3}{\frac{3}{2}\sqrt{J_2}}$$

$$Q_2 = Q_{2.0} + BQP^*$$

$$0.5 < Q_2 < 1 \text{ and } BQ = 0.0105$$

The input parameter $Q_{2.0}$ defines the ratio of strength at zero pressure and the coefficient BQ defines the rate at which the fracture surface transitions from approximately triangular in form to a circular form with increasing pressure (Figure 5).

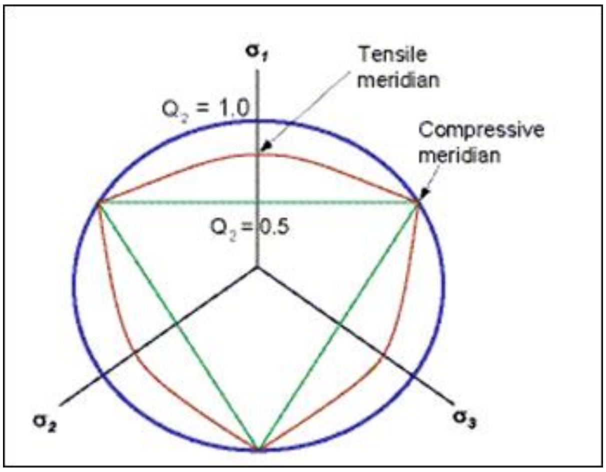


Figure 5 Third invariant dependence (Source: ANSYS Training manual).

3.5.1.2.7 Strain Hardening

Strain hardening is represented in the model through the definition of an elastic limit surface and a "hardening" slope. The elastic limit surface is scaled down from the fracture surface by user defined ratios; (elastic strength/fc) and (elastic strength/ft). The pre-peak fracture surface is subsequently defined through interpolation between the elastic and fracture surfaces using the "hardening" slope, hardening slope: $\left(\frac{G_{elastic}}{G_{elastic}-G_{plastic}}\right)$

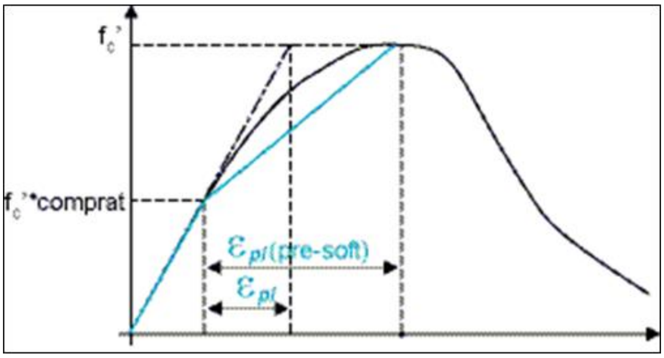


Figure 6 Bi-linear strain hardening function for the case of uniaxial compression (Source: ANSYS Training manual).

$$Y^* = Y_{elastic} + \frac{\varepsilon_{pl}}{\varepsilon_{pl(pre-softening)}}(Y_{fail} - Y_{elastic})$$

where

$$\varepsilon_{pl(pre-softening)} = \frac{Y_{fail} - Y_{el}}{3G} \cdot \left(\frac{G_{elastic}}{G_{elastic} - G_{plastic}}\right)$$

3.5.1.2.8 Shear Damage

Damage is assumed to accumulate due to inelastic deviatoric straining (shear induced cracking) using the relationships

$$D = \sum \frac{\Delta\varepsilon_{pl}}{\varepsilon_p^{failure}}$$

$$\varepsilon_p^{failure} = D_1\left(P^* - P_{spall}^*\right)^{D_2}$$

where D_1 and D_2 are material constants used to describe the effective strain to fracture as a function of pressure. Damage accumulation can have two effects in the model:

1) Strain softening (reduction in strength)

The current fracture surface (for a given level of damage) is scaled down from the intact surface using the expression

$$Y_{fractured}^* = (1 - D)Y_{failure}^* + DY_{residual}^*$$

where

$$Y_{residual}^* = \min[B(P^*)^M, Y_{XTC} * SFMAX]$$

The term YXTC*SFMAX is used to limit the maximum residual shear strength (for completely damaged material) to be a fraction (SFMAX) of the current fracture strength.

2) Reduction in shear stiffness

The current shear modulus is defined through the expression

$$G_{fractured} = (1 - D)G_{elastic} + DG_{residual}$$

3.5.1.2.9 Porous Collapse Damage

The model includes the option to cap (limit) the elastic deviatoric stress under large compressions. This effectively leads to the assumption that porous compaction results in a reduction in deviatoric strength. The final combination of elastic, fracture and residual failure surfaces is shown schematically below in Figure 7:

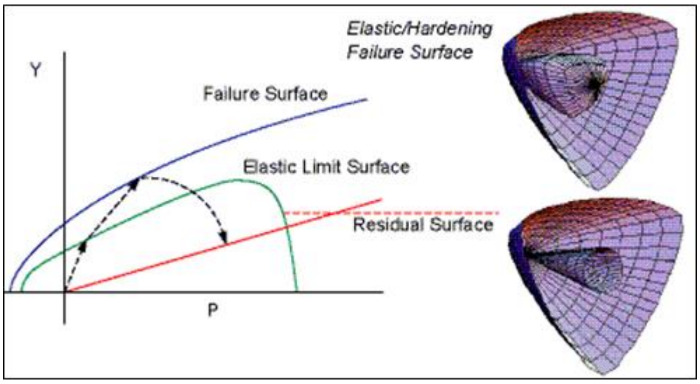


Figure 7. RHT Elastic, Fracture and Residual Failure Surfaces (Source: ANSYS Training manual).

3.5.1.2.10 Strain Rate Effects

Strain rate effects are represented through increases in fracture strength with plastic strain rate. Two different terms can be used for compression and tension with linear interpolation being used in the intermediate pressure regime.

$$F_{RATE} = \begin{cases} 1+\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\alpha} \text{ for } P > \frac{1}{3} f_c \text{ (compression)} \\ 1+\left(\frac{\dot{\varepsilon}}{\dot{\varepsilon}_0}\right)^{\delta} \text{ for } P < \frac{1}{3} f_t \text{ (tension)} \end{cases}.$$

where α is the strain rate factor for compression and δ is the strain rate factor for tension and in tension and in compression.

3.5.1.2.11 Tensile Failure

By default, tensile failure is achieved using a hydrodynamic tensile limit. The maximum tensile pressure in the material is limited to

$$P = \max[D * P_{min}, P(\rho, \theta)]$$

Using this option, no additional user input is required since the value of Pmin is derived from ft, which forms part of the input for the strength model.

After an extensive investigation of existing models and approaches for concrete, the advanced plasticity model for brittle materials Riedel – Hiermaier – Thoma (RHT) was used [Riedel et al. (1999), Riedel (2004), Riedel et al (2007)]. This model is particularly useful for predicting the dynamic loading of concrete (includes a parameter linking velocity to loading). RHT is a combined model of plasticity and shear failure, in which the divergent component of the stress tensor of the material is limited by a generalized failure surface. This model is designed to enable and disable individual aspects of the behavior of the materials and to reproduce the unstable behavior of reinforced columns with insufficient internal steel reinforcement and the local damage of the concrete as well as its bulging. Therefore, this feature is very useful. Data for concrete with cubic strengths of 35 MPa and 140 MPa are included in the library of materials. The model is formulated such that input can be scaled with the cube strength. Thus, the concrete strength is calibrated in order to be formulated into cubic strength. The remaining values are adjusted in proportion to the concrete strength. At the same time, the influence of the factors α (compressive strain rate exponent) and δ (tensile strain rate exponent) of the model was investigated and calibrated, in order not to take into account the influence of the loading speed.

The concrete modeling approach is crucial for the accuracy of the analyzed RC concrete columns [Rousakis (2005), Karabinis et al. (2008), Teng et al. (2015) among others]. This model is suitable for dynamic analyses and its throughout investigation has shown that it has excellent sensitivity to confined concrete, in order to predict the performance of shear capacity and local failures. Dynamic analyses allow the evaluation of mechanical behavior beyond the initial local failures and instabilities of concrete, steel and composite materials, to the failure of the columns while maintaining high levels of reliability. Thus, the phenomenon of the confinement of reinforced concrete columns with composite materials can be studied in greater breadth and depth.

The geometry of the RC columns is accurately reproduced. The models consist of different parts for the concrete (solid body), the longitudinal reinforcements (line body), the stirrups (line body) and the impactor (solid body) for all columns, as well as for the FRP jacket (solid body) for the retrofitted ones.

3.5.1.2.12 Longitudinal and Transverse Steel

If a material is loaded elastically and subsequently unloaded, all the distortion energy is recovered, and the material reverts to its initial configuration. If the distortion is too great a material will reach its elastic limit and begin to distort plastically. In Explicit Dynamics, plastic deformation is computed by reference to the Von Mises yield criterion (also known as Prandtl–Reuss yield criterion). This states that the local yield condition is

$$(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2 = 2\mathrm{Y}^2$$

where Y is the yield stress in simple tension. This expression can be written as follows:

$$(s_1 - s_2)^2 + (s_2 - s_3)^2 + (s_3 - s_1)^2 = 2\mathrm{Y}^2 \text{ or}$$

$$s_1^2 + s_2^2 + s_3^2 = \frac{2\mathrm{Y}^2}{3} \text{ (since } s_1 + s_2 + s_3 = 0)$$

Thus, the onset of yielding (plastic flow), is purely a function of the deviatoric stresses (distortion) and does not depend upon the value of the local hydrostatic pressure unless the yield stress itself is a function of pressure (as is the case for some of the strength models). If an incremental change in the stresses violates the Von Mises criterion then each of the principal stress deviators must be adjusted such that the criterion is satisfied.

$$\frac{\left(\frac{2}{3}\right)^{1/2}\mathrm{Y}}{(s_1^2 + s_2^2 + s_3^2)^{1/2}}$$

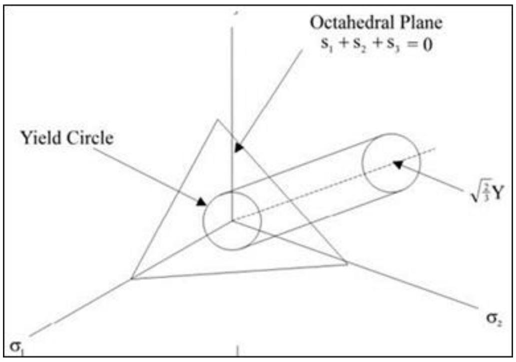


Figure 8. Yield of structural steel (Source: ANSYS Training manual).

3.5.1.2.13 Hardening Rules

The hardening rule describes how the yield surface changes (size, center,shape) as the result of plastic deformation. It determines when the material will yield again if the loading is continued or reversed. This is in contrast to elastic-perfectly-plastic materials which exhibit no hardening -- i.e., the yield surface remains fixed.

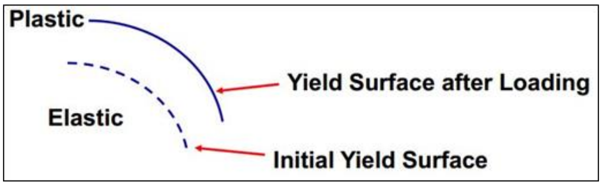


Figure 9. Yield Surface Change (Source: ANSYS Training manual).

3.5.1.2.14 Isotropic Hardening

Isotropic hardening states that the yield surface expands uniformly during plastic flow. The term 'isotropic' refers to the uniform dilatation of the yield surface and is different from an 'isotropic' yield criterion (i.e., material orientation). Plotting the stress-strain curve (Fig. 20) enables an understanding of what occurs during a loading and reverse loading cycle.

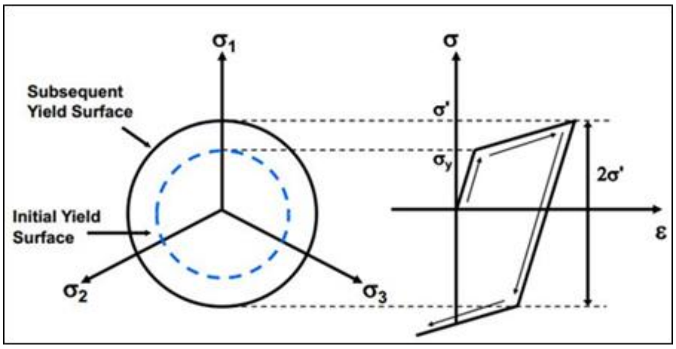


Figure 10. Stress – Strain curve (Source: ANSYS Training manual).

For the simulation of the longitudinal and transverse steel was chosen the "Isotropic Elasticity" model which is suitable for simulating materials subjected to low compressive stresses. At the same time, the "Bilinear Isotropic Hardening" model was used to define the yield stress (Y) as a linear function of plastic strain, ε_p

$$\Upsilon = \Upsilon_0 + A * \varepsilon_p$$

where

- Y_0 Yield Strength
- A Tangent Modulus

3.5.1.2.15 CFRP Jacket

After extensive investigation, the model for structural reinforced polymer composites was suitably calibrated taking into consideration the common properties of epoxy resins used for fiber sheet impregnation and bonding on concrete. Therefore, the analyses may reproduce local damage initiation of the jacket (local fracture) and thus consider the effects of the corner radius of the section. Full bonding of the jacket on concrete was considered in all cases (debonding is not critical for the confinement applications under consideration). As the fibers in the FRP jackets, considered in the present study, were all oriented in the hoop direction, the stiffness (both tensile and compressive) in the axial direction (i.e., the loading direction of the column) was negligibly small. Therefore, the elastic lamina option was used to model an orthotropic elastic material. A local coordinate system was assigned to the FRP jacket, and the hoop direction and the axial direction were adopted as the first principal and second principal material orientations, respectively.

The modulus of elasticity in the axial direction and the shear modulus were both assumed to have lower values than the ones provided by the manufactures for the net fiber sheet, because they take into account the impregnation with the epoxy resin. For example, for the carbon fibers, the manufacturer's elastic modulus was 240000 MPa. The orthotropic elasticity properties used for the analyses were reduced to 59160 MPa for the modulus of elasticity in the directions perpendicularly to global loading (along the direction of carbon fibers). This value is the actual measured elasticity of the composite, using the properties of the fibers in combination with the epoxy resin. The thickness of the jacket was suitably increased to 0.475 per layer, taking into account the thickness of the resin. The modulus of elasticity multiplied by the thickness of the jacket, in both cases (considering the resin or not) gives the same axial rigidity value. Further, the jacket was modeled with the mechanical properties of the resin alone at the direction parallel to global loading. The suitable consideration of the resin besides the reinforcing fibers may reproduce the realistic damage accumulation in the composite jacket.

3.5.1.2.16 Boundary Conditions

When an element consists of several parts, it is necessary to determine the "Connections" connections between the elements. Connections are divided into two categories "Contacts" and "Body Interactions". Without these two functions, the elements would not interact with each other.

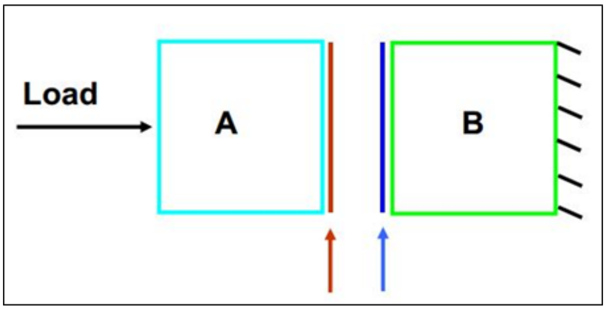


Figure 11. Illustration of the two bi – connection surfaces (Source: ANSYS Training manual).

3.5.1.2.17 Body Interactions

Each "Body Interaction" object activates a body interaction for the bodies scoped in the object. There are four types of Body Interaction:

- Bonded
- Frictionless
- Frictional
- Reinforcement

Every node of the scoped bodies interacts with every face of the scoped bodies. In addition, "Body Interactions" were defined between elements in the connection areas.

After extensive investigation of the appropriate dynamic interactions, two "Body Interactions" were created. In the first, all the elements were selected and the "Frictionless" type was selected. This type simulates friction conditions between all the elements (Fig. 22-a). This allows the materials to work independently and do not fail at the same time, as observed with "Bonded Body Interaction". When the type "Bonded" is selected, all the different materials work as one and fail at the same displacement. For the second "Reinforcement Body Interaction" only the elements that consist the longitudinal and transverse reinforcement were selected and this type models the integration of the reinforcement within the concrete core (Fig. 22-b). It is the most suitable method for the internal steel reinforcement function.

3.5.1.2.18 Connections

Subsequently, connections are applied to the different parts of the model so that they are connected as a unit in sustaining the applied loads for analysis. Herein, two connection features are used, contacts and body interactions.

Contact settings determine how the contacting bodies can move relative to one another. The contact region between concrete and FRP is defined as "bonded" for all retrofitted columns and no sliding or separation between faces or edges is allowed (the contact region is considered as glued). Besides, for the considered applications, debonding is not critical for confinement. The contact area does not change during the application of the load allowing for a linear solution. This approach is in line with other research work [Hany et al. 2016, Kargaran & Kheyroddin 2020]. Moreover, a "bonded' contact region does not allow any penetration. The same applies to the contact region between concrete and steel impactors.

Body interactions object is an automated contact detection feature. The "trajectory" contact settings used, allow to understand where the contact points are in the simulation after an initial coarse mesh run and then refine the contact options and scoping. For all bodies, the body interaction type is defined as "frictionless", that activates frictionless sliding contact between any exterior node or face of the selected bodies. Individual contact events are detected and tracked during the analysis. The contact is symmetric between the bodies. This condition determines the contact between concrete and steel bars. In addition, all elements of the line bodies (internal steel reinforcement), which are contained within any solid body (concrete) in the model, are defined to be converted to discrete reinforcement (using "reinforcement" body interaction type, typically used for RC applications).

3.5.1.2.19 Mesh

3.5.1.2.19.1 Elements

The explicit mesh is followed to form an accurate 3D grid. Solid bodies, concrete and CFRP jacket, are modelled with eight-node hexahedral elements (element type Hex8, Figure 12. a). These elements are preferred for solid bodies. They are well suited to transient dynamic applications including large deformations, large strains, large rotations, and complex contact conditions. The line bodies, steel reinforcement bars, are modelled with 2-node line elements (Figure 12. b), that allow for large displacements and resultant elasto-plastic response.

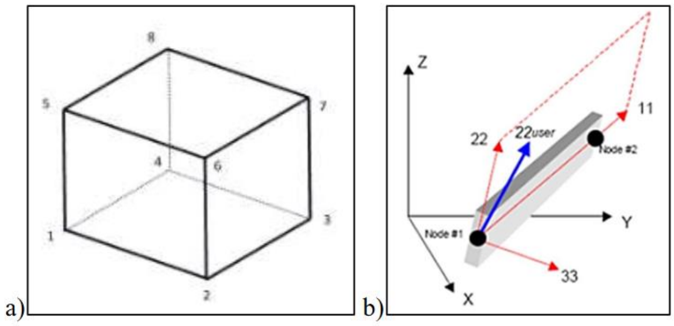


Figure 12. Element type a) 8 node hexahedral and b) 2- node line [ANSYS manual].

3.5.1.2.19.2 Element sizing

As the element size gets smaller, more divisions are generated, and the accuracy is improved. However, the number of elements increases greatly and the required time for one analysis becomes unprofitable for the large-scale model of an RC column. An important note is that the element size of the reinforcement beams (line elements) should be similar or less than that of the volume elements intersected by beams in order to contain a beam node and experience any reinforced beam forces. Based on the mesh convergence study that was conducted, a mesh size of 25mm was chosen (for all individual parts of the model) as the most favourable to provide satisfactory accuracy of the seismic behaviour of RC columns at an acceptable analysis time.

3.5.2 Classification of Reinforced Concrete Model

In the extant literature, numerous references pertain to the modeling of reinforced concrete elements (Park & Paulay, 1975; Mander et al., 1988; Ghali & Neville, 1997). While a comprehensive analysis of all factors influencing reinforced concrete modeling is beyond the scope of this report, we will present a classification of the most salient factors that should be considered when selecting appropriate models. Based on our literature review, we have developed the following classification system for reinforced concrete models, which will be elaborated upon in subsequent sections. The model types will focus on the available framework provided by OpenSees (McKenna et al., 2000; Mazzoni et al., 2006) (as it will be used for later main analyses) and can easily applied to other software too like ANSYS (see 3.5.1.).

This taxonomy (Figure 13) aims to provide a structured framework for understanding and categorizing the diverse approaches to modeling reinforced concrete structures (ACI Committee 318, 2019; EN 1992-1-1, 2004; ASCE 7-16, 2016; CEB-FIP Model Code, 2010). It primarily focuses on the key properties required for the project:

- Material Classification (MC)
- Dimensionality-Based Classification (DBC)
- Material Behavior Classification (MMC)
- Analysis-Based Classification (ABC)

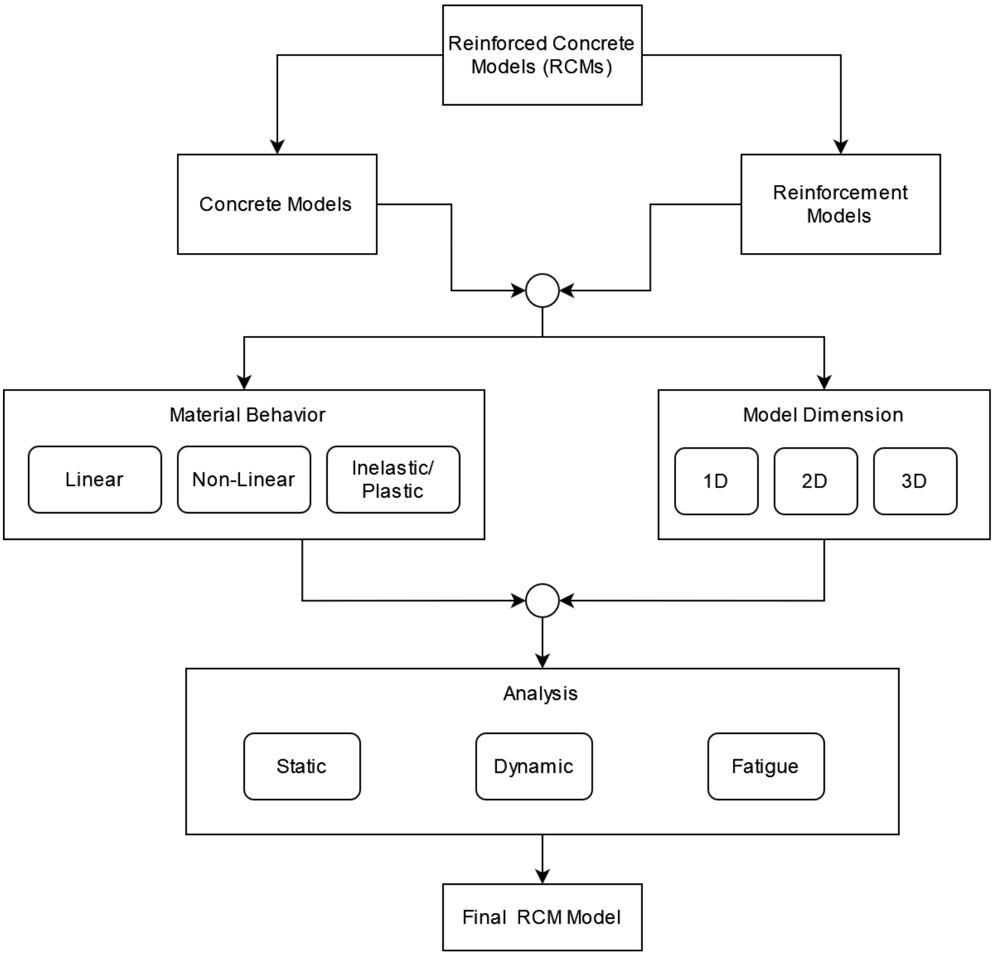


Figure 13 RCMs Classification

3.5.3 Material Classification

From a 'composite' materials point of view, as represented by reinforced concrete, the basic characteristic concerns the junction of two dissimilar materials, namely concrete and steel. This unique combination allows for the exploitation of the benefits associated with each material while at the same time overcoming its respective shortcomings. Concrete-which possesses excellent compressive strength-combines with the outstanding tensile strength of steel to create a structural material which is versatile and durable. It is beyond the scope of this report to delve into an in-depth analysis on the properties of those constituent materials. However, interested readers will find enough relevant references within the literature for a broader understanding of the above text Mehta & Monteiro, 2014; Neville, 1996; Mindess et al., 2003; Galambos & Surovek, 2008; Bruneau et al., 2011. These references provide a deep understanding of the mechanical, chemical, and structural properties of concrete and steel and the interactions between them when joined in reinforced concrete.

3.5.3.1 Dimensionality-Based Classification

Accurate structural modeling constitutes a critical issue in structural engineering for response prediction with respect to various types of loadings and environmental effects. Common textbooks on this subject include Chopra (2012), Zienkiewicz et al. (2005), and Cook et al. (2007). In the modeling process, model dimensionality may have a great influence on the accuracy of the analysis and computational efficiency. The classification of structural models based on dimensionality includes 1D, 2D, and 3D categories. Each type has different levels of complexity and detail, which makes them suitable for specific applications. The following chapter thoroughly describes these types by outlining characteristics, applications, advantages, and disadvantages of each type (Bathe, 1996; Logan, 2012; Reddy, 2006).

3.5.3.1.1 One-Dimensional (1D) Models

1D models simplify structural elements by representing them as line elements (McGuire et al., 2015; Hibbeler, 2017). These models emphasize the dimensionality of length, considering beams, columns, and trusses as elements whose cross-sectional dimensions are much smaller compared to their lengths. This is necessary in analyzing the overall behavior of the structure while avoiding the complexity inherent in the cross-sections of the same structure (Megson, 2014). The underlying assumption in most common 1D modeling is that the stress and strain are uniformly distributed across the cross-section, or that variations are insignificant for the analysis purpose (Beer et al., 2014; Ugural & Fenster, 2011). This simplification proves to be especially advantageous for elongated and slender components in which the length significantly exceeds any cross-sectional dimension. Furthermore, it allows for effective representation of bending, axial, and torsional behaviors without the necessity of accounting for detailed properties of the cross-section.

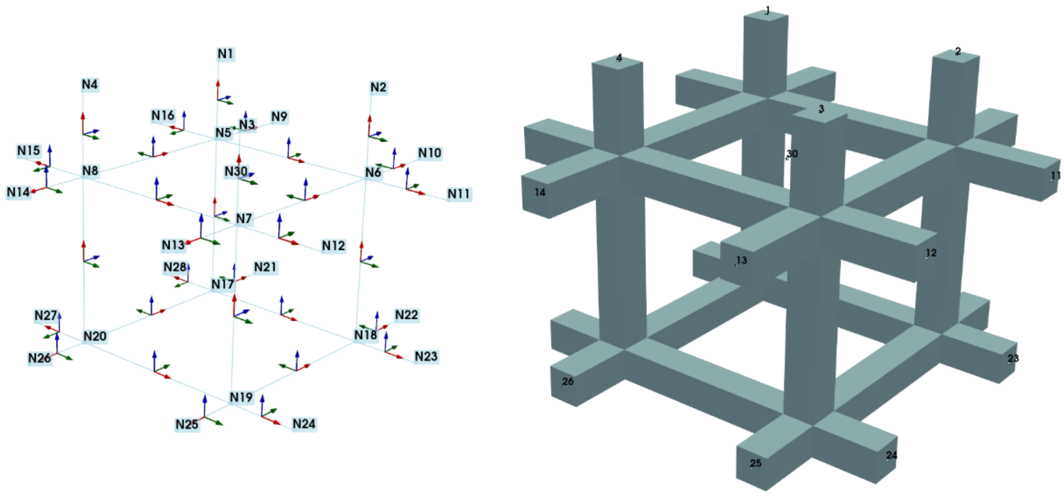


Figure 14 1D representation of RCM vs 3D real structure (draft deliverable 3.2 elaborations)

One-dimensional models find extensive applications in various areas of structural engineering besides RC design. For instance, in wood roof structures, members are typically assumed to be pin-connected and carry only axial forces, either tension or compression (Breyer et al., 2014; Desch & Dinwoodie, 1996; Bodig & Jayne, 1982). This simplification facilitates the calculation of internal forces using methods like the method of joints or the method of sections (Hibbeler, 2015; Hsieh & Mau, 2005).

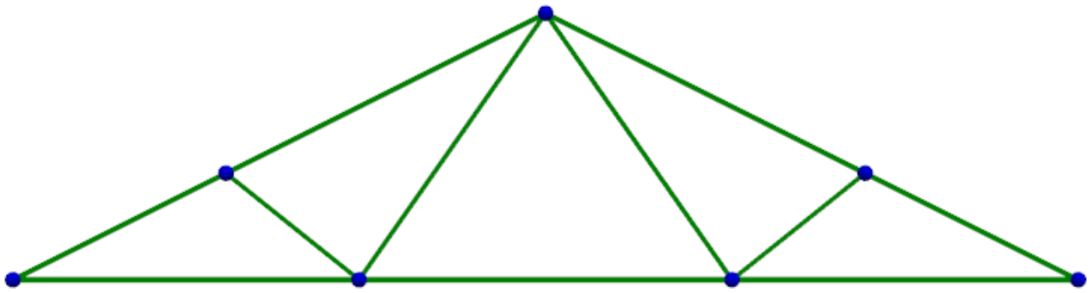


Figure 15 A one dimensional model of wooden roof truss system

Similarly, in RC frame structures, beams and columns are modeled as line elements connected at nodes, allowing for the analysis of bending moments, shear forces, and deflections under various load conditions (Nilson et al., 2010; Wang et al., 2007; MacGregor et al., 2012). This approach is crucial when assessing the load-carrying capacity of multi-story reinforced concrete frame buildings under gravity and lateral loads. During the preliminary stages of structural design, 1D models provide a quick and efficient means to evaluate different design concepts (Salmon et al., 2009; Wang & Salmon, 1998; Nilson & Darwin, 1997). With these, engineers can quickly check whether a proposed structural system has the basic strength and stiffness required, well before time-consuming detailed modelling is invested. For example, they may want to select the preliminary sizes of beams and columns in a new design to rough out material costs. The 1D models are likewise used in performing conceptual comparisons which make different structural schemes considerate so that the most efficient or economical scheme may be selected.

One of the more critical advantages is the computational efficiency of the 1D models since they reduce the number of equations and unknowns for an analysis by rendering the elements one dimension, Cook et al. (2007), Zienkiewicz et al. (2005), and Bathe (1996). Solutions are thereby computed more rapidly and the engineer can try a range of design variations. Also, further simplifying the preparation of data, the requirements of the model for its geometric and material properties are minimal; hence, rapid prototyping and iterative design is enabled. Logan (2012), Reddy (2006), and Megson (2014) add that simplicity in 1D models makes them even more accessible and easy to work with. They are easy to apply by hand calculations or light software; hence, they are very suitable for educational purposes and for professionals who want a quick approximation without using any advanced software. The line element representations will be visually very clear and hence easy for the design team to understand and communicate, which enables easier conceptualization of structural behavior or load paths. In reinforced concrete (RC) Design, Columns and Beams are mainly modelled by 1D elements. One-dimensional beam elements are the simplest type.

3.5.3.1.1.1 Basic Beam Elements

These elements are meant to resist the bending moments and shear forces; axial deformations are considered to be negligible according to Hibbeler (2017) and McGuire et al. (2015). Beams in RC frames carry the loads coming from the slabs and distribute them to columns. Beam elements in general are based on the assumption of plane sections remaining planar and normal to the longitudinal axis after deformation-a behavior applicable to slender members for which shear deformations can be neglected.

3.5.3.1.1.2 Advanced Beam Elements

Known as beam-column elements, these elements combine the effects of axial forces, bending moments, and shear forces (Bathe, 1996; Zienkiewicz et al., 2005; Cook et al., 2007). They are very important in analyzing columns in reinforced concrete (RC) structures that resist significant axial loads coupled with bending due to lateral loads by wind or seismic effects. Frame elements consider flexural and axial deformations, making them more versatile than simple beam elements.

3.5.3.1.2 Two-Dimensional (2D) Models

Two-dimensional models further simplify the structure by modeling it in a plane, taking two dimensions-usually length and height, or length and width-and assume the third dimension is either constant or negligible. Two-dimensional models, according to Logan 2012, Reddy 2006, and Zienkiewicz et al. 2005, find many of their applications in reinforced concrete building structures. These two-dimensional elements include slabs, walls, and plates with one dimension (thickness) significantly smaller than the other two.

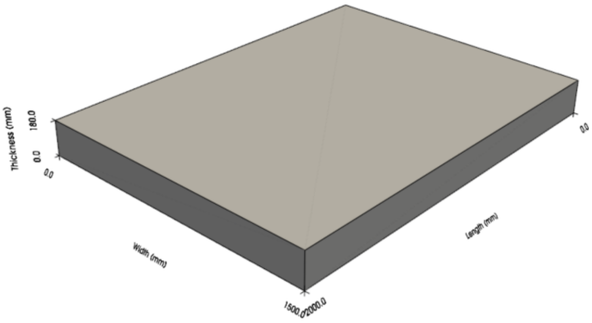


Figure 16 2D RC Slab Model

The 2D models provide more detailed representation of stress and strain distributions across the element's plane, improving the accuracy of predictions related to deflection, cracking, and failure modes (Cook et al., 2007; Bhatt et al., 2014; MacLeod, 1997). They offer a balance between the simplicity of 1D models and the complexity of 3D models, allowing for detailed analysis without excessive computational demands. Although the accuracy in the plane behavior it may not capture behaviors involving significant out-of-plane forces or deformations, which can be critical in some structural scenarios (Hinton & Owen, 1984; Bathe, 1996; Zienkiewicz et al., 2005). One challenging part for accurate representation of these type of elements are the proper boundary conditions and connections to other structural elements, potentially affecting the model’s reliability (Megson, 2014; Weaver & Gere, 1990; Bhatt et al., 2014). Basic 2D element types are Shell Elements.

3.5.3.1.2.1 Shell Elements

Shell element types are suitable for the analysis of curved and flat shallow surfaces such as reinforced concrete (RC) shells, folded plates, and slabs of complex geometry (Logan, 2012; Reddy, 2006; Cook et al., 2007). The shell element is able to capture both in-plane forces coupled with transverse bending moments, hence allowing for detailed analysis for these RC members under combined loadings.

3.5.3.1.3 Three-Dimensional (3D) Models

Three-dimensional models represent structures in all three dimensions of space, giving a most comprehensive study of structures in reinforced concrete buildings. As detailed by Bathe, 1996; Zienkiewicz et al., 2005; Cook et al., 2007, these are models which take into consideration the length, width, and height of structural parts, thus giving the ability to go into details of complex geometries and component interaction.

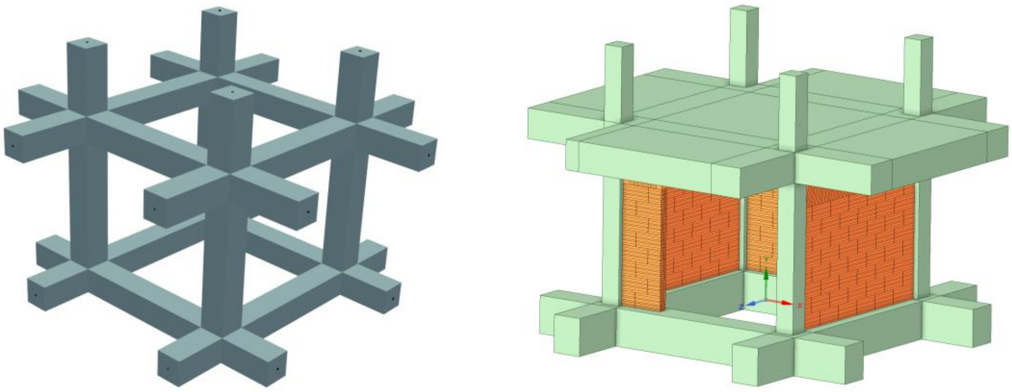


Figure 17 3D RC Models

3.5.3.1.3.1 Solid Elements

Three-dimensional solid elements are used for representing the volume of structural components to capture complicated material stress states. According to Logan (2012), Reddy (2006), and Zienkiewicz et al. (2005), solid elements are employed when the analytical model needs to investigate stress concentrations, local failures, or any zone where the interaction of three-dimensional stresses is predominant. Examples include beam-column joints or connection areas. Due to their inclusion, these elements significantly affect the behaviour of the structure, which cannot be modelled by one-dimensional (1D) or two-dimensional (2D) elements. These techniques, in general, require substantial computational resources and time, which in most cases of large or complicated structures restrict their applications for conventional design procedures (Bathe 1996; Cook et al. 2007; Zienkiewicz et al. 2005).

3.5.3.2 Material Behavior Classification

Material behavior in RCMs (Reinforced Concrete Models) is effectively captured through combinations of linear, nonlinear, and inelastic features as shown by Jirásek & Bažant 2002; Bažant & Planas 1997; and Maekawa et al., 2003. The adoption of purely linear elastic models is based on the assumption that concrete and steel are elastic materials whose states of stress and strain are related in direct proportion up to the time of failure. This simplification is appropriate for initial design considerations and for structures experiencing low stress conditions in which material nonlinearity can be considered insignificant (Hibbeler, 2017; Megson, 2014). Conversely, nonlinear models provide a more advanced methodology by integrating behaviors including concrete cracking, yielding of steel reinforcement, as well as strain hardening and strain softening phenomena (Mander et al., 1988; Park & Paulay, 1975; Sezen & Moehle, 2004). These nonlinear models may consider the energy dissipation and dependence on the load history. Nonlinear models are essential for accurate analysis in high loading level, seismic actions, or assessment of ultimate load-carrying capacity following Fardis 2009, Priestley et al. 2007, and Calvi et al. 2006. The introduction of inelastic properties further refines the material behavior modeling. However, while nonlinear models are able to capture some features of inelasticity, fully inelastic models more comprehensively explain permanent deformations and irreversible changes in material structure by Bažant & Jirásek (2002), Sinha et al. (1964), and Bauschinger (1886). These sophisticated models are crucial to ensure very accurate predictions of structural behavior for extreme loading, detailed seismic assessments, fatigue problems, and progressive collapse scenarios as defined by ASCE/SEI 41-17 (2017); CEB-FIP Model Code (2010). By including inelastic properties, engineers can interpret the post-yield response of the reinforced concrete structure and develop much more resilient and efficient structures. The approach to be chosen will then depend on the scope of the analysis, the importance of the structure, and the available computational resources, balancing simplicity and speed in linear models and accuracy with increased model complexity in nonlinear and inelastic models (Chopra, 2012; Clough & Penzien, 2003).Here is some basic information about the models in OpenSees that may be incorporated during the project. They focus on the RCM elements' uniaxial materials. For more comprehensive information about these materials, users can refer to the official documentation (McKenna,2011; Mazzoni et al., 2006).

3.5.3.2.1 Steel models

3.5.3.2.1.1 Steel01

The Steel01 material model in OpenSees represents a uniaxial bilinear steel material characterized by kinematic hardening and with the possibility of isotropic hardening to simulate nonlinear and inelastic responses under static as well as dynamic loading conditions (Filippou et al., 1983; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.1.2 Steel02

Material Steel02 is based on the Menegotto-Pinto model, enhanced with an isotropic strain hardening rule that accounts for nonlinear and inelastic responses caused by both static and dynamic loadings (Menegotto & Pinto, 1973; Filippou et al., 1983; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.1.3 Steel4

Material Steel4 (uniaxial) combines the kinematic and isotropic hardening mechanisms and provides nonsymmetrical behavior. It gives an ultimate strength limit beyond which the material response may be considered plastic. According to McKenna (2011), and Mazzoni et al. (2006), the model has been commonly used in static and dynamic analyses.

3.5.3.2.1.4 ReinforcingSteel

The ReinforcingSteel material is based on the Chang and Mander model, adding some new functionality for buckling and fatigue based on the Coffin-Manson relationship so that it is suitable for both static and dynamic analyses. It includes isotropic hardening, a descending yield plateau, and the accumulation of plastic strain to further refine simulations with respect to the behavior of reinforcing steel bars. It has characteristic features concerning cyclic degradation and fatigue modeling necessary for simulating the fatigue failure in reinforcing bars highlighted by the studies of Chang and Mander (1994), Mander et al. (1984), McKenna (2011) and Mazzoni et al. (2006).

3.5.3.2.1.5 Dodd_Restrepo

The Dodd_Restrepo steel material implemented in OpenSees represents a uniaxial material model of reinforcing steel developed to simulate cyclic behavior of reinforcement under both tensile and compressive stresses. The model is particularly useful in analyzing the response of steel members under seismic or cyclic loading, considering the Bauschinger effect, strain hardening, and typical strain reversals developed during such loadings. The model is based on the research performed by Dodd and Restrepo in 1995 and was developed to serve as an efficient tool for predicting the cyclic behavior of reinforcing steel with high accuracy in situations involving complex cyclic loading conditions (Dodd and Restrepo-Posada, 1995; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.1.6 RambergOsgoodSteel

The RambergOsgoodSteel material in OpenSees models the nonlinear stress-strain relationship of structural steel using the Ramberg-Osgood relationship, which has become one of the most common ways in earthquake engineering to model the response of steel material under cyclic loading. This will be useful in replicating hysteretic behavior for steel under cyclic loading conditions. It finds application in dynamic and seismic analyses. The Ramberg-Osgood model provides a smooth transition from elastic to plastic behavior and plays a major role in realistically representing the behavior of steel members under repeated load reversals (Bruneau et al., 1997; Ramberg and Osgood, 1943; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.1.7 SteelMPF

SteelMPF in OpenSees represents an advanced version of the Menegotto-Pinto steel model, later updated by Filippou et al. (1983). Generally, this model represents a number of developments compared to other steel models, such as Steel02, for example, with regard to cyclic behavior handling and isotropic hardening, among others. In this regard, it will be quite suitable for complex cyclic loading cases, hence efficient in structures under seismic loading. It finds a wide application in the simulation of Reinforced Concrete (RC) elements, such as walls and columns, under a reversed cyclic loading condition (Filippou et al., 1983; Kolozvari et al., 2015; Menegotto and Pinto, 1973; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.1.8 Steel01Thermal

Material Steel01Thermal in OpenSees represents an upgraded version of the Steel01 material model, especially developed for the temperature-dependent behavior of Eurocode 3. The main area of its application is the thermo-mechanical analysis of the changes within mechanical properties of steel at higher temperatures. That will mainly be beneficial for the simulations regarding fire within civil structure applications. This material model can be utilized for both beam and column elements under thermal analyses, especially in the case of thermal expansion evaluation or heat that is considered to affect structural integrity. This material model is normally used in fire engineering studies to investigate the performance of steel structures at high temperatures (EN 1993-1-2, 2005; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.2 Concrete

3.5.3.2.2.1 Concrete01

The Concrete01 material models a uniaxial concrete object following the Kent-Scott-Park model with no tensile strength and features degraded linear unloading/reloading stiffness. It is typically used to simulate the nonlinear, inelastic behavior of concrete under compressive loads, making it applicable for both static and dynamic analyses (Kent & Park, 1971; McKenna,2011; Mazzoni et al., 2006).

3.5.3.2.2.2 Concrete02

The Concrete02 material is a uniaxial concrete material model with linear tension softening that is generally adopted for the simulation of nonlinear behavior under both static and dynamic loading conditions. It incorporates provisions for tension softening, compressive unloading/reloading stiffness, and damage developed by Yassin 1994, McKenna, 2011; Mazzoni et al., 2006.

3.5.3.2.2.3 Concrete04

Concrete04 is a uniaxial OpenSees material model, where the Popovics model is considered for concrete in tension and compression, while the degrading linear unloading/reloading stiffness is considered by Karsan-Jirsa's model. The Concrete04 model can be used for nonlinear and inelastic analysis because this model traces the development of damage under cyclic loadings. The citations are Popovics, 1973, Karsan & Jirsa, 1969, Mander et al., 1988, McKenna, 2011, and Mazzoni et al., 2006).

3.5.3.2.2.4 Concrete06

Concrete06-a uniaxial concrete material that models both compressive and tensile responses with nonlinear tension stiffening and compressive curves based on the Thorenfeldt curve-is one of the most commonly used materials for both static and dynamic analyses while modeling complex behaviors like tension cracking and compression damage. This work is basically based on Popovics 1973, Belarbi & Hsu 1994, Palermo & Vecchio 2003, McKenna 2011, and Mazzoni et al. 2006.)

3.5.3.2.2.5 Concrete07

The Concrete07 material that has been implemented in OpenSees is based on the model developed by Chang and Mander in 1994. It is primarily applied for the simulation that involves confined and unconfined concrete under cyclic loading and includes simplified protocols for unloading and reloading in contrast to previously developed models. It is a versatile model that can represent nonlinear and inelastic response in both static and dynamic conditions for reinforced concrete elements with ease (Chang & Mander, 1994; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.2.6 Concrete01WithSITC

Material Concrete01WithSITC improved from the material of Concrete01, takes into consideration "Stuff In The Cracks" (SITC), defining the effect of microcrackings regarding to stiffness loss in concrete under cyclic loading. This model describes nonlinear inelastic behavior, and it allows for dynamic and static analysis of the damage (Stanton & McNiven, 1979; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.2.7 ConfinedConcrete01

The OpenSees material model ConfinedConcrete01 represents a nonlinear concrete formulation that was developed in confined concrete, including details regarding transverse reinforcement and external Fiber Reinforced Polymer (FRP) wraps. It is intended for performance modeling of confined concrete under both static and dynamic loading conditions. The methodology follows an incremental procedure to determine the stress-strain response considering variables like Poisson's ratio and the provided confinement due to transverse reinforcement and FRP wraps. This modeling approach is very useful for carrying out dynamic analyses in which confined concrete represents an essential component of the structure (Attard & Setunge, 1996; Braga et al., 2006; D'Amato, 2009; D'Amato et al., 2012; Karsan & Jirsa, 1969; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.2.8 ConcreteD

ConcreteD is a one-dimensional element constitutive model of concrete implemented in OpenSees, with its basis on the concrete design code of China. Compressive and tensile behaviors of concrete have been modelled by employing individual parameters of plasticity (GB 50010-2010, 2010; Karsan & Jirsa, 1969; Ren, 2010; Wu et al., 2006; Zeng, 2012; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.2.9 FRPConfinedConcrete

The FRPConfinedConcrete material implemented in OpenSees is a material which is specifically developed to simulate the behavior of concrete encased in Fiber Reinforced Polymer (FRP) jackets. This material models quite effectively the nonlinear stress-strain characteristic of FRP-confined concrete, which is a common practice to reinforce concrete columns for strength enhancement under axial and cyclic loadings. The material is suitable for both static and dynamic analyses. It has quite great effectiveness in simulating the behavior of FRP-wrapped circular columns. Following the model of Lam and Teng 2009, the representative stress-strain curve of this material was assumed to be composed of two parts: a parabolic curve followed by a line. It also assumes a hysteretic performance to correctly model crushing, considering a modified tension performance based on a model from Yassin 1994. Besides giving the ultimate stress/strain, FRP jacket properties can be specified according to the users' requirements. The present model can be more appropriate in the case of static and dynamic load analyses of structures, particularly for a concrete member strengthened with FRP wraps. (Megalooikonomou et al., 2012; Karsan and Jirsa, 1969; Megalooikonomou, 2019a; Megalooikonomou and Monti, 2015; Megalooikonomou, 2019b; Megalooikonomou and Papavasileiou, 2019; Megalooikonomou, 2023; Gallardo-Zafra and Kawashima, 2009; Kumar and Mosalam, 2015; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.2.10 FRPConfinedConcrete02

FRPConfinedConcrete02 represents a concrete material in OpenSees for FRP-confined concrete, modelling the basic stress-strain characteristics of such material, given the current attention to this material for static and dynamic applications. This material defines the envelope of the compressive stress-strain response by an initial parabolic segment followed by a linear segment. Accordingly, hysteretic rules in compression are developed based on well-established models, and therefore these hysteretic rules are suitable for both dynamic cyclic loading and static conditions. (Bisby and Ranger, 2010; Lam and Teng, 2003; Lam and Teng, 2009; Lin, 2016; Lin and Teng, 2015; Lin et al., 2012; Saadatmanesh et al., 1997; Teng et al., 2015; Yassin, 1994; Zhao and Sritharan, 2007; McKenna, 2011; Mazzoni et al., 2006).

3.5.3.2.2.11 ConcreteCM

ConcreteCM (Kolozvari et al., 2015) is a uniaxial hysteretic model developed by Chang and Mander (1994) to simulate the behavior of both confined and unconfined concrete under cyclic loading. It can capture nonlinear inelastic behavior and includes progressive stiffness degradation and crack closure effects. It was determined by Belarbi and Hsu, 1994; Chang and Mander, 1994; Kolozvari et al., 2015; Mander et al., 1988; Orakcal, 2004; Tsai, 1988; McKenna, 2011; and Mazzoni et al., 2006 that the constitutive relationship was applicable in both static and dynamic situations.

3.5.3.2.2.12 TDConcrete

The OpenSees model of TDConcrete is a time-dependent model that tries to simulate the variation in concrete material behavior with time, taking into account creep and shrinkage, among others, based on the recommendations from ACI 209R-92. These are analyzed by investigating the compressive and tensile behaviors of concrete. To date, the TDConcrete model has been basically used in static analyses, where concrete shows time-dependent behavior under different load conditions (ACI Committee 209, 1992; Knaack and Kurama, 2018; Knaack, 2013; Knaack, 2023).

3.5.3.2.2.13 TDConcreteEXP

The time-dependent behavior of the OpenSees model is called TDConcreteEXP, which is concrete-like material, considering the empirical behavior of creep and several others from the long-term effects. The material will serve mainly for modeling purposes, especially concerning the study of time-dependent behavior in Reinforced Concrete. Static analysis is similarly possible, and its explicit proposition is proposed to serve applications dealing with concrete durability under time-dependent loads. The present material primarily emphasizes long-term consequences such as creep, as outlined in (ACI 209R-92), while it does not specifically address fatigue or dynamic responses. It is optimally applicable to static scenarios that involve behaviors dependent on time (ACI Committee 209, 1992; Knaack and Kurama, 2018; Knaack, 2013; Knaack, 2023).

3.5.3.2.2.14 TDConcreteMC10

The OpenSees material TDConcreteMC10 is a time-dependent concrete model accounting for creep and shrinkage of concrete. Its basis is Model Code 2010 for both creep and shrinkage functions. Further, this material will be especially applicable to long-term analysis and time-dependent deformation, including those resulting from creep and shrinkage (Fib Model Code, 2010; Knaack and Kurama, 2018; Knaack, 2013; Knaack, 2023).

3.5.3.2.2.15 TDConcreteMC10NL

The TDConcreteMC10NL material in OpenSees framework is an evolution of the TDConcreteMC10 model by the inclusion of nonlinear behavior. The TDConcreteMC10NL implementation is similar to the basic version, TDConcreteMC10, considering time-dependent effects such as creep and shrinkage, but in nonlinear formulation, it is used to solve more involved problems related to concrete cracking and softening in tension and compression. This approach becomes even more useful in the case of long-term simulation of concrete structures for analyses involving nonlinear behaviors due to their loading history. Hence, fib Model Code, 2010; Knaack and Kurama, 2018; Knaack, 2013; Knaack, 2023).

3.5.3.3 Analysis-Based Classification

In the context of modeling reinforced concrete RC building structures, the nature of the analysis conducted becomes pivotal to effective prediction of structural performance under different loading scenarios as pointed out by Chopra, 2012; Clough & Penzien, 2003. Classification by analysis groups categorizes models by the nature of the loads imposed and the structural responses considered. The main types of analysis relevant to the study are:

1) Static Analysis
2) Dynamic Analysis
3) Fatigue Analysis

3.5.3.3.1 Static Analysis

Static analysis estimates the structural response of the RC members under repeated loads applied monotonically and remaining constant or varied quasi-statically with time; dead and live loads are examples. According to Gere & Timoshenko, 1997; Hibbeler, 2017 and Megson, 2014, in a static analysis, it is usually assumed that the structure is under a state of static equilibrium; thus, the effects of the inertia and damping are neglected. Static analysis is essential in RC design; it basically provides information about internal forces, moments and deflections. It enables one to size the structural members for the structure to meet safety and serviceability criteria in terms of relevant codes and standards such as ACI Committee 318 (2019), EN 1992-1-1 (2004) and ASCE 7-16 (2016).

3.5.3.3.2 Dynamic Analysis:

Dynamic analysis deals with those problems of the structure's performance under time-varying or impact loads that generate great inertial forces such as earthquakes, wind gusts, or machinery vibrations. Examples are Chopra, 2012; Clough & Penzien, 2003; Krawinkler, 1996. The current analysis includes the mass, damping, and stiffness properties of the structure and, thus, covers the acceleration and deceleration effects. Dynamic analysis should be performed for all RC structures located in seismic areas or for those structures sensitive to dynamic excitations. By performing this type of analysis, an engineer can predict various responses, such as resonant vibrations, dynamic magnification, and potential modes of failure under dynamic conditions (Fardis, 2009; Priestley et al., 2007; Calvi et al., 2006).

3.5.3.3.3 Fatigue Analysis:

Fatigue analysis assesses the performance and durability of reinforced concrete The fatigue test characterizes the performance and durability of the RC structures subjected to cyclic or the repetitive load in a sustained period may be progressively deteriorated and ultimately failed due to such stress, which is below the ultimate strength of the material. Such cases were observed by Sinha et al. (1964), Zhang et al. (2017), and Gergely & Lutz (1968). The second kind of analysis deals with microcrack accumulation and deterioration in concrete and reinforcing steel due to cyclic loadings stemming from traffic on bridges or from repeated loading from some kind of industrial machinery. When such loading conditions arise, the important method to estimate the expected life of RC structures involves fatigue analysis because it enables the designing of elements that can bear a predetermined number of load cycles with only limited loss in the structural integrity.

3.5.3.4 Tabulations of RCMs

The tabulation is based on the OpenSees framework models that may be used during this project.

Table 2 Type of FEM elements available in OpenSees for RCMs
Note: "-" indicate additional steps may be required

Element	Element Dimension			Material			Analysis		
	1D	2D	3D	Linear	Non-Linear	Inelastic /Plastic	Static	Dynamic	Fatigue
Zero-Length Element	✓	-	-	✓	✓	✓	✓	✓	✓
Truss Element	✓			✓	✓	-	✓	✓	✓
Beam-Column Element	✓			✓	✓	✓	✓	✓	✓
Joint Element	✓	-	-	✓	✓	✓	✓	✓	-
Link Element	✓	-	-	✓	✓	✓	✓	✓	✓
Quadrilateral Element		✓		✓	✓	✓	✓	✓	-
Triangular Element		✓		✓	✓	✓	✓	✓	-
Brick Element			✓	✓	✓	-	✓	✓	-
Tetrahedron Element			✓	✓	✓	-	✓	✓	-

Table 3 Type of FEM steel materials available in OpenSees for RCMs
Note: "-" indicate additional steps may be required

Material	Type			Analysis		
	Linear	Non-Linear	Inelastic /Plastic	Static	Dynamic	Fatigue
Steel01	✓	✓	✓	✓	✓	-
Steel02	✓	✓	✓	✓	✓	-
Steel4	✓	✓	✓	✓	✓	-
ReinforcingSteel	✓	✓	✓	✓	✓	✓
Dodd_Restrepo	✓	✓	✓	✓	✓	✓
RambergOsgoodSteel	✓	✓	✓	✓	✓	-
SteelMPF	✓	✓	✓	✓	✓	-
Steel01Thermal	✓	✓	✓	✓	✓	-

Table 4 Type of FEM concrete materials available in OpenSees for RCMs
Note: "-" indicate additional steps may be required

Material	Type			Analysis		
	Linear	Non-Linear	Inelastic /Plastic	Static	Dynamic	Fatigue
Concrete01	✓	✓	✓	✓	✓	-
Concrete02	✓	✓	✓	✓	✓	-
Concrete04	✓	✓	✓	✓	✓	-
Concrete06	✓	✓	✓	✓	✓	-
Concrete07	✓	✓	✓	✓	✓	✓
Concrete01WithSITC	✓	✓	✓	✓	✓	-
ConfinedConcrete01	✓	✓	✓	✓	✓	-
ConcreteD	✓	✓	✓	✓	✓	-
FRPConfinedConcrete	✓	✓	✓	✓	✓	-
FRPConfinedConcrete02	✓	✓	✓	✓	✓	-
ConcreteCM	✓	✓	✓	✓	✓	-
TDConcrete	✓	✓	-	✓	-	-
TDConcreteEXP	✓	✓	-	✓	-	-
TDConcreteMC10	✓	✓	✓	✓	-	-
TDConcreteMC10NL	✓	✓	✓	✓	-	-

3.5.4 Retrofit Models

3.5.4.1 Literature Review for Finite Element Modeling

Since the literature review was focused on spotting those models apt for Finite Element Modeling (FEM) analysis, it was relevant to perform an appropriate standardization and to provide a quick overview of the results. Therefore, two different kinds of summaries of the source papers were produced.

1. **Text Summary**: The text summary is the reasoned, written summary of each paper considered within the literature. It shows an overview yet highly representative expression of the content of each paper, whereby the reader can appreciate the central ideas in quick time.

2. **Tree-View Summary**: A tree view summary represents the key information from each paper in an orderly, hierarchical fashion. It provides an instantaneous and clear visual picture of the essence of what it is that the paper contributes. In this format, material can be directly compared from various papers, increasing productivity by presenting complex information in a more palatable format. Here's a detailed explanation of each component: ·

- **Objective**: The main goal or purpose of the study (1-2 sentences).
- **Methodology**: A brief explanation of how the research was carried out.
- **Key Findings**: Major findings or identification of the revelations obtained through this research.
- **Conclusions**: Major ideas or interpretations of findings.

- **Limitations and Future Work**: This involves limitations in this survey and suggestions for the future.
- **Significance**: The importance of the study, or relevance, to the discipline.

These summaries, both in textual and tree view format, are intended to quick understanding and efficiency, not to replace the original research papers. Readers are encouraged to view these summaries as starting resources or quick references, referring back to the original documents for further detail in conceptual explanations and methodologies applied.

3.5.4.2 Textile-Reinforced Mortar (TRM)

3.5.4.2.1 "Multiscale Numerical Analysis of TRM-Reinforced Masonry under Diagonal Compression Tests" (Gulinelli et al. 2020)

Text Summary

This paper presents, by way of example, a multiscale numerical analysis of TRM-strengthened masonry walls subjected to diagonal compression tests. Diagonal compression tests of unreinforced and TRM-reinforced masonry panels along with tests for material characterization were carried out according to ASTM E519-2007 in the experimental procedure.

A finite element model was developed using Abaqus, employing a simplified micro-modeling approach. The model represented masonry units as 3D continuum elements, interface joints as 3D cohesive elements, and TRM layers as 2D shell elements with homogenized properties. The TRM-wall interface was modeled using 3D cohesive elements, while anchors were represented by 1D beam elements (see Figure 18).

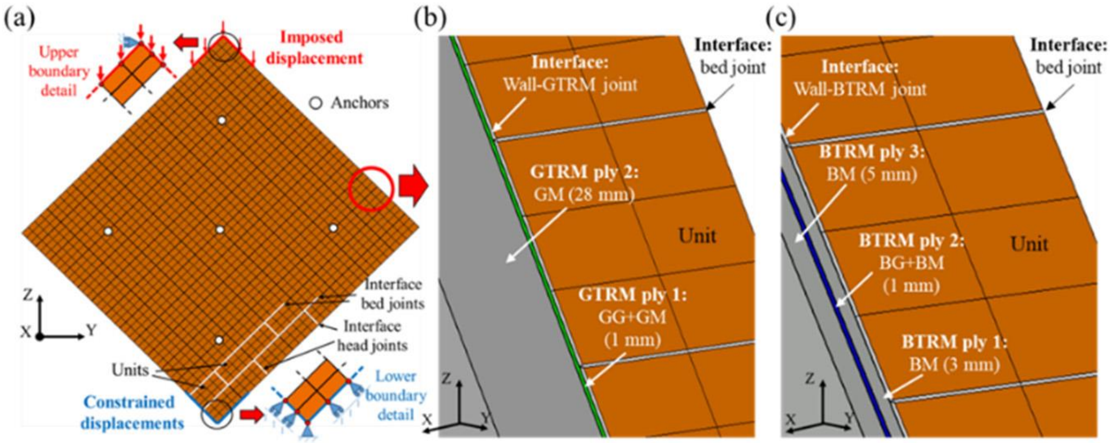


Figure 18 Numerical model layout; representation of the (b) GTRM–wall interactions (image and caption are from Gulinelli et al. 2020)

Material properties were defined based on experimental data, with masonry units treated as linear elastic, mortar joints following a traction-separation law with damage, and TRM layers as homogenized orthotropic elastic materials. The model underwent quasi-static, displacement-controlled loading to simulate experimental conditions.

The numerical results showed good agreement with experimental data, accurately predicting peak loads, stiffness, and failure modes for both unreinforced and TRM-reinforced walls (see Figure 19). The model successfully captured the two-phase behavior observed in glass TRM systems and provided insights into the strengthening effects of different TRM techniques.

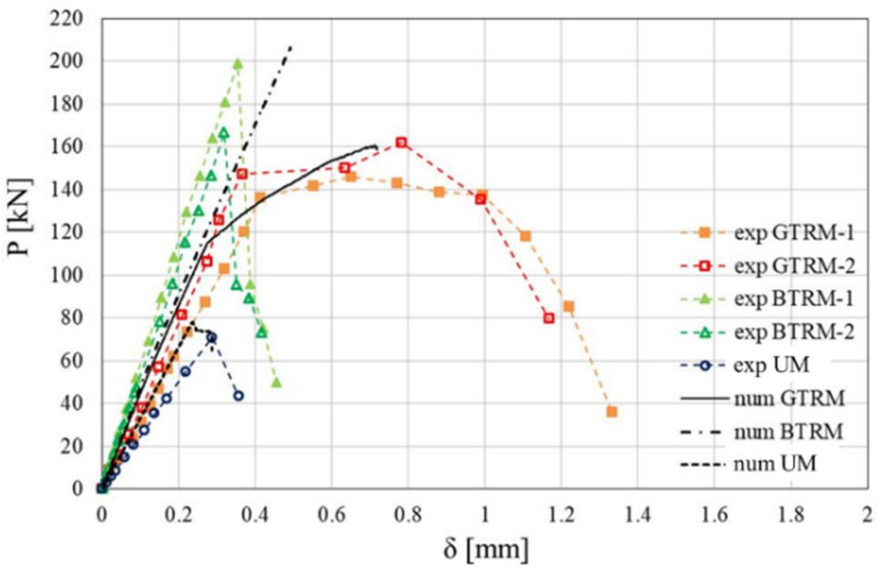


Figure 19 Comparison of experimental and numerical results: vertical load vs vertical displacement. (image and caption are from Gulinelli et al. 2020)

Despite its success, the model had limitations in simulating post-peak softening behavior and reproducing diagonal tension failure for basalt TRM systems. Future work could focus on improving damage models, incorporating nonlinear material behavior for masonry units, and refining TRM homogenization techniques.

This research provides a valuable tool for understanding and optimizing seismic retrofitting techniques for historical masonry buildings in earthquake-prone regions. The validated model can be used to explore various design options and predict the performance of TRM-strengthened structures, contributing to the development of more effective strengthening solutions.

Tree-View Summary

Objective: To develop and validate a finite element model for simulating the behavior of masonry walls strengthened with textile-reinforced mortar (TRM) under diagonal compression tests.

Methodology:

Experimental Testing:

- Diagonal compression tests on unreinforced and TRM-reinforced masonry panels
- Material characterization tests for masonry components and TRM materials
- Triplet tests for mortar-brick interface properties

Numerical Model Development:

- Simplified micro-modeling approach in Abaqus
- Masonry units modeled as 3D continuum elements
- Interface joints modeled with 3D cohesive elements
- TRM layers modeled as 2D shell elements with homogenized properties
- TRM-wall interface modeled with 3D cohesive elements
- Anchors modeled as 1D beam elements

Material Properties:

- Masonry units: Linear elastic
- Mortar joints: Traction-separation law with damage
- TRM: Homogenized orthotropic elastic
- Interfaces: Cohesive behavior with damage initiation and evolution

Load Case:

- Quasi-static displacement-controlled loading
- Boundary conditions simulating experimental setup

Analysis:

- Dynamic analysis to handle nonlinearity
- Monitoring of load-displacement response and damage patterns

Key Findings:

- Good agreement between numerical and experimental load-displacement curves
- Accurate prediction of peak loads and stiffness for both unreinforced and TRM-reinforced walls
- Successful simulation of different failure modes (joint sliding, TRM debonding)
- Reproduction of two-phase behavior observed in glass TRM system

Conclusions:

- The simplified micro-modeling approach effectively captures global behavior of TRM-strengthened masonry
- Cohesive elements successfully simulate interface damage and failure mechanisms
- The model provides insights into the strengthening effects of different TRM systems

Limitations and Future Work:

- Limited ability to simulate post-peak softening behavior
- Difficulty in reproducing diagonal tension failure mode for basalt TRM system
- Need for more advanced homogenization techniques for TRM layers
- Potential improvements in damage models for cohesive elements
- Incorporation of nonlinear material models for masonry units

Significance: This study presents a novel multiscale approach for modeling TRM-strengthened masonry, providing a valuable tool for understanding and optimizing seismic retrofitting techniques. The validated model can be used to explore various design options and predict the performance of TRM-strengthened structures, contributing to the development of more effective and efficient strengthening solutions for historical masonry buildings in earthquake-prone regions.

3.5.4.2.2 "Experimental and analytical investigation on bond between Carbon-FRCM materials and masonry" (D'Ambrisi et al. 2012)

Text Summary

D'Ambrisi et al. have investigated the performance of Carbon-FRCM material for masonry strengthening. This new methodology tries to overcome some drawbacks that always appear when FRP materials are used, such as poor fire resistance and low vapor impermeability.

The test campaign includes double shear tests with different bond lengths in order to investigate the bonding properties between Carbon-FRCM and masonry substrates. The main results confirm that, for large slip values, debonding occurs at the fibers/matrix interface, thus confirming the effectiveness of Carbon-FRCM as an external strengthening technique for masonry.

The authors present a local bond-slip relationship that better captures the structural behavior of retrofitted masonry members, which can be developed by exploiting experimental outcomes. As such, this analytical tool constitutes the base for further design and verification of Carbon-FRCM-strengthened masonry members.

The research emphasizes the capabilities of Carbon-FRCM materials in the conservation and enhancement of historical masonry structures, especially in accordance with contemporary seismic code regulations. Although additional investigation is required regarding the long-term effectiveness and different types of masonry, this study makes a substantial contribution to the advancement of more compatible and effective methods for the reinforcement of architectural heritage preservation.

Tree-View Summary

Objective: The interaction of FRCM materials - essentially comprising a carbon net incorporated within a cement-based matrix - is investigated here with masonry surfaces.

Methodology:

Experimental Setup:

- Double shear tests
- Various bond lengths tested

Analytical Approach:

- Calibration of local bond-slip relation using experimental results

Material Properties:

- Carbon net embedded in cement-based matrix (Carbon-FRCM)
- Masonry substrate

Analysis:

- Evaluation of debonding behavior
- Assessment of Carbon-FRCM effectiveness as external reinforcement

Key Findings:

- Debonding occurs at the fibers/matrix interface after considerable fibers/matrix slip
- Carbon-FRCM materials are effective as external reinforcements for masonry structures
- A local bond-slip relation was established based on experimental results

Conclusions:

- Carbon-FRCM materials show promise for strengthening masonry structures
- The bond-slip relation is crucial for modeling structural behavior of strengthened masonry elements
- Debonding mechanism in Carbon-FRCM differs from traditional FRP materials

Limitations and Future Work:

- Further investigation needed on long-term performance and durability
- Additional studies required for different types of masonry and loading conditions
- Development of design guidelines for Carbon-FRCM strengthening of masonry structures

Significance: This study provides valuable insights into the bonding behavior of Carbon-FRCM materials with masonry, which is crucial for the effective strengthening of historical masonry structures. The findings contribute to the development of more efficient and compatible strengthening techniques for preserving architectural heritage.

3.5.4.2.3 "Numerical modelling of flexural performance of textile reinforced mortar strengthened concrete beams" (Cao et al. 2024)

Text Summary

This study develops and validates a finite element model for textile reinforced mortar (TRM) strengthened reinforced concrete (RC) beams. The researchers used LS-DYNA software to create a 3D nonlinear model, incorporating advanced material models for concrete, steel, and textile reinforcement. They conducted four-point bending tests on various beam configurations to validate the model (see Figure 21).

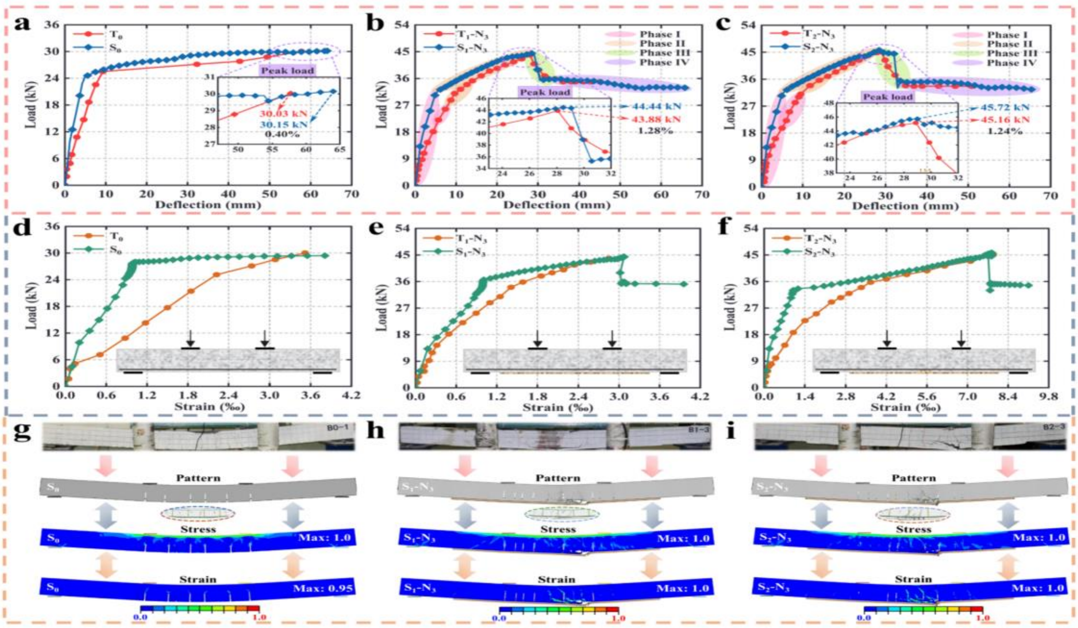


Figure 20 Comparison between experimental test and simulation results: (a-c) Load-deflection curve; (d-f) Mid-span strain curve of tensile steel; (g-i) Comparison offailure mode between experimental test and simulation models: (g) S0; (h) S1-N3; (i) S2-N3.(image and caption are from Cao et al. 2024)

The finite element model accurately predicted the flexural behavior and failure modes of TRM-strengthened RC beams (see Figure 20). A parametric study revealed that increasing the number of textile layers enhanced the beams' stiffness and flexural capacity, while longer textile lengths improved ultimate flexural strength and ductility. Interestingly, textile mesh sizes beyond 17.5 mm × 17.5 mm had minimal effect on flexural load capacity but increased ductility.

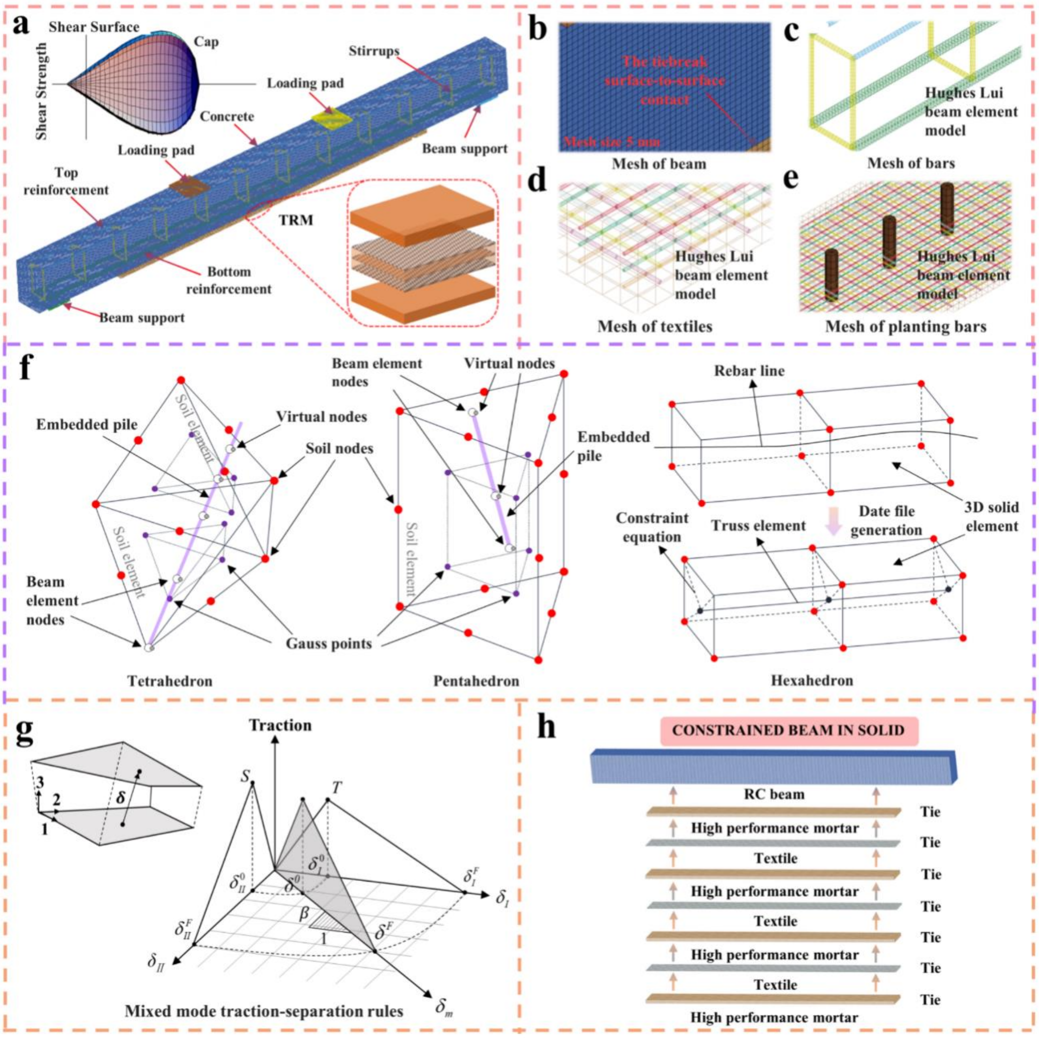


Figure 21 Details of FE model establishment: (a) TRM-strengthened RC beam model and Cap model; (b) RC beam matrix and TRM mesh division; (c) Division of steel reinforcement; (d) Mesh division of textiles; (e) Mesh division of integrated steel implants; (f) The implanting methods of steel in different elements; (g) Mixed modetraction-separation rules; (h) Schematic of three-textile-layer TRM-strengthened RC beam model; (i-k): Three FE model diagrams: S0, S1-N3, and S2-N3. (image and caption are from Cao et al. 2024)

The researchers also developed an analytical model for predicting the flexural strength of TRM-strengthened RC beams, which showed good agreement with the finite element results. This study provides valuable insights for optimizing TRM-strengthened RC beams and offers a reliable numerical tool for predicting their performance in practical applications. Future work should focus on refining contact modeling and exploring multi-scale approaches for better representation of micro-mechanics.

Tree-View Summary

Objective: To develop and validate a finite element model for predicting the flexural behavior of textile reinforced mortar (TRM) strengthened reinforced concrete (RC) beams and conduct a parametric study to evaluate various design parameters.

Methodology:

Experimental Program:

- Fabrication of unreinforced RC beams and two types of TRM-strengthened RC beams
- Four-point bending tests to evaluate flexural strength

Finite Element Model Development:

- 3D nonlinear FE model using LS-DYNA software
- Material modeling for concrete, mortar, steel reinforcement, and textile
- Contact modeling between various components
- Damage and failure criteria implementation

Material Properties:

- Concrete: MAT_CSCM_CONCRETE model
- Steel: MAT_PIECEWISE_LINEAR_PLASTICITY model
- Textile: Bilinear elastic-plastic constitutive method

Load Case:

- Accelerated loading method using explicit dynamics algorithm
- Forced displacement applied to beam top

Analysis:

- Model validation against experimental results
- Parametric study on number of textile layers, textile length, and mesh size
- Development of analytical model for predicting flexural strength

Key Findings:

- The developed FE model accurately predicted the flexural behavior and failure modes of TRM-strengthened RC beams.
- TRM strengthening increased flexural strength but decreased ductility of RC beams.
- Increasing the number of textile layers enhanced pre-cracking stiffness, post-cracking stiffness, and flexural capacity.
- Longer textile length positively affected ultimate flexural strength and ductility.
- Textile mesh size beyond 17.5 mm × 17.5 mm had minimal effect on flexural load capacity but increased ductility.

Conclusions:

- The proposed FE model effectively simulates the flexural behavior of TRM-strengthened RC beams.
- TRM strengthening significantly improves the flexural performance of RC beams.
- The developed analytical model reasonably predicts the flexural strength of TRM-strengthened RC beams.

Limitations and Future Work:

- Refine contact modeling between textile and mortar, and between TRM and RC beams.
- Investigate more detailed modeling of the textile mesh structure and its interaction with the mortar matrix.
- Explore multi-scale modeling approaches for better micro-mechanics representation.

Significance: This study provides valuable insights into the design and optimization of TRM-strengthened RC beams, offering a reliable numerical tool for predicting their flexural performance and guiding practical engineering applications.

3.5.4.2.4 "Numerical Modeling of Shear Behavior of URM Strengthened with FRCM or FRP Subjected to Seismic Loading" (Thomoglou et al. 2018)

Text Summary

This study presents a numerical modeling approach for analyzing unreinforced masonry (URM) walls strengthened with fabric reinforced cementitious mortar (FRCM) or fiber-reinforced polymer (FRP) under seismic loading. The researchers employ a micro-modeling technique using 3D finite element analysis in ANSYS (see Figure 22). The model incorporates Solid186 elements for bricks and mortar, Shell181 elements for reinforcement, and considers material interfaces and non-linear properties.

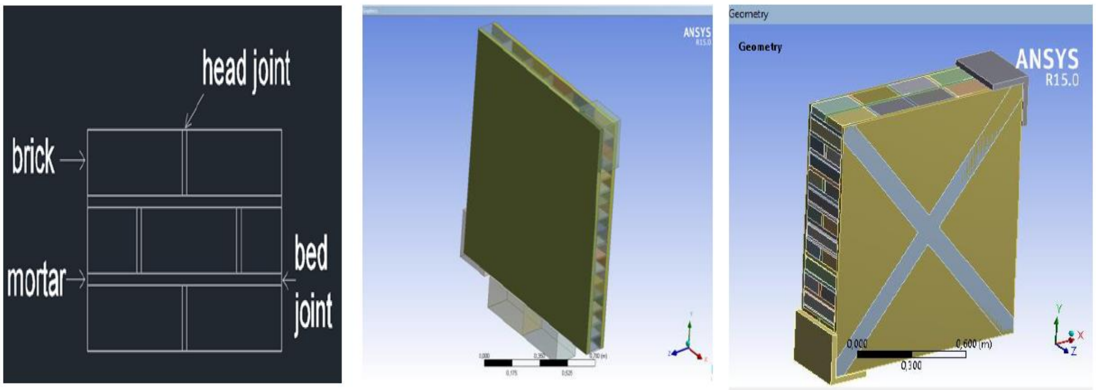


Figure 22 Detail of micro-modeling of the masonry elements (left), modeling of FRCM (middle) and FRP reinforcement of unreinforced masonry (right). (image and caption are from Thomoglou et al. 2018)

The analysis focuses on diagonal compression tests, simulating seismic loading conditions. Results show that FRP and FRCM strengthening significantly increase the shear capacity of URM walls. The finite element model predictions closely match experimental results, validating the approach's reliability. Local shear stresses in the masonry center are found to be close to the average shear stress calculated using ASTM E519 / E519M standards.

The study concludes that 3D finite element modeling provides accurate predictions of strengthened URM wall behavior and is effective for parametric studies of design parameters. However, existing design relations are found to be conservative for FRCM reinforcement. The research contributes to improved design and assessment methods for seismic retrofitting of masonry structures, though further investigation into different reinforcement configurations is recommended for future work.

Tree-View Summary

Objective: To analyze unreinforced masonry (URM) walls strengthened with external composite reinforcement subjected to diagonal compression using 3D finite elements.

Methodology:

Modeling Approach:

- Micro-modeling technique
- 3D finite element analysis using ANSYS

Model Creation:

- Solid186 elements for bricks and mortar
- Shell181 elements for FRP/FRCM reinforcement
- Interface modeling between materials

Material Properties:

- Non-linear material properties considered
- Specific properties from experimental studies (Babaeidarabad et al., 2013; Ferretti et al., 2015)

Load Case:

- Diagonal compression tests
- Static loading applied

Analysis:

- Static structural analysis
- Shear stress and strain evaluation

Key Findings:

- FRP and FRCM strengthening significantly increase shear capacity of URM walls
- Local shear stresses in masonry center close to average shear stress
- FE model predictions closely match experimental results
- Existing design relations are conservative for FRCM reinforcement

Conclusions:

- FE modeling provides accurate predictions of URM wall behavior
- Micro-modeling approach allows detailed analysis of local behavior
- 3D FE analysis is effective for parametric studies of design parameters

Limitations and Future Work:

- High computational effort required for micro-modeling
- Need for more experimental data for model validation
- Further investigation of different reinforcement configurations

Significance: This study provides a reliable numerical approach for analyzing strengthened URM walls, contributing to improved design and assessment methods for seismic retrofitting of masonry structures.

3.5.4.2.5 "Integrated Seismic and Energy Retrofitting System for Masonry Walls Using Textile-Reinforced Mortars Combined with Thermal Insulation: Experimental, Analytical, and Numerical Study" (Karlos et al. 2020)

Text Summary

This study investigates an innovative system combining textile-reinforced mortar (TRM) and thermal insulation for simultaneous seismic and energy retrofitting of masonry walls. The researchers employed experimental testing, analytical modeling, and numerical simulations to evaluate the system's performance.

Out-of-plane cyclic loading tests on brick masonry wallettes and bond-slip tests were conducted to assess the system's behavior. Finite element analysis using ANSYS software was performed, utilizing a macro-modeling approach for masonry and insulation, with shell elements representing TRM. The analytical model employed simplified cross-section analysis based on classical bending theory (see Figure 23, Figure 24 and Figure 25).

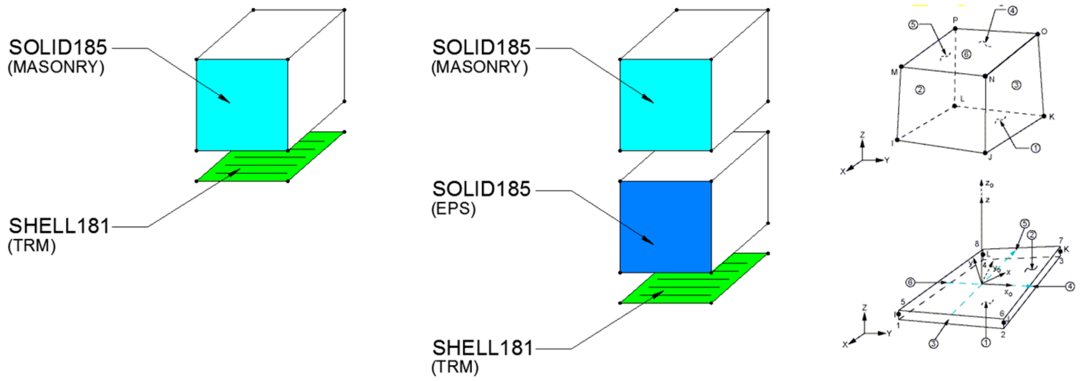


Figure 23 Schematic of the reinforced specimen arrangement using ANSYS SOLID185 andSHELL181 elements. (image and caption are from Karlos et al. 2020)

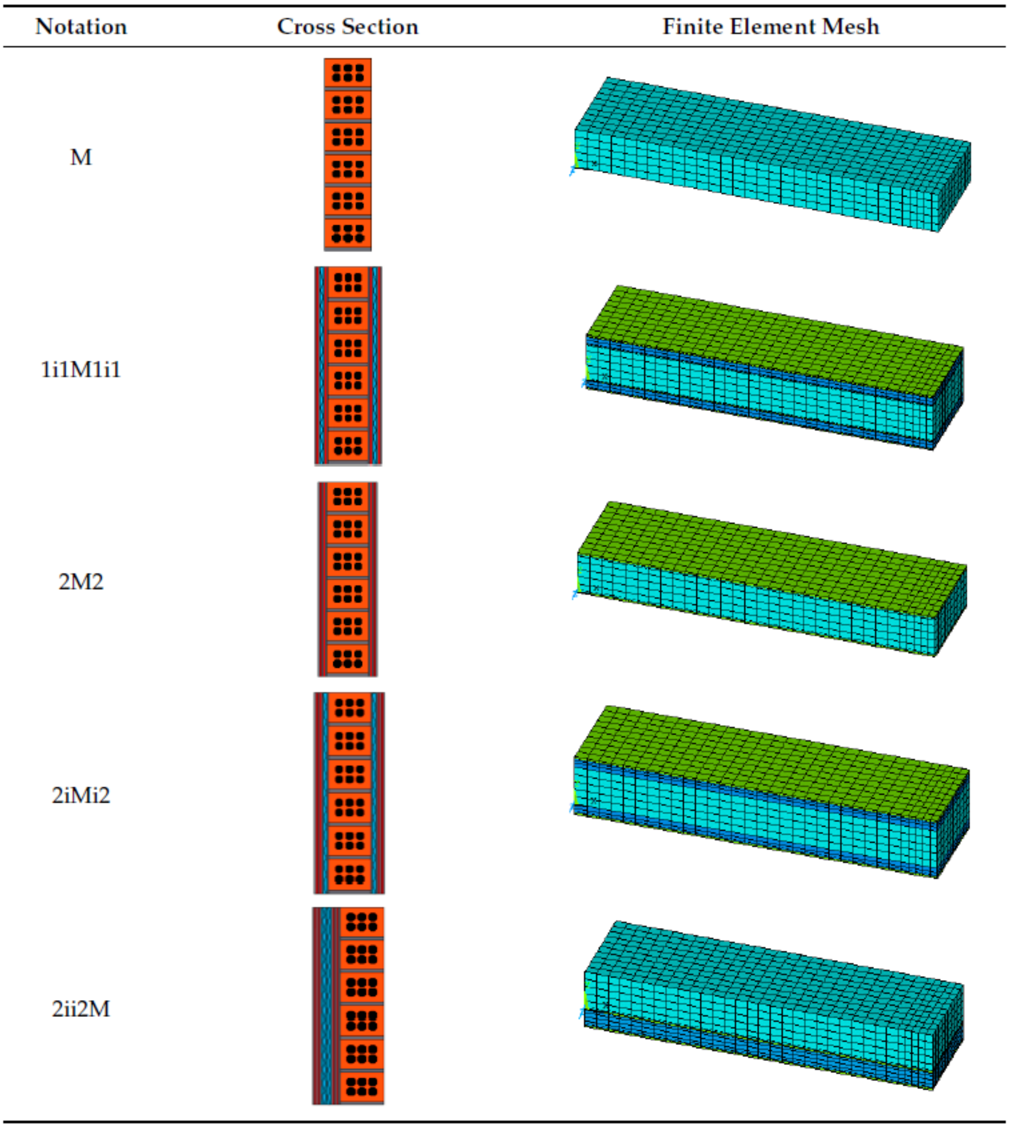


Figure 24 Out-of-plane loaded specimens and finite element models. (image and caption are from Karlos et al. 2020)

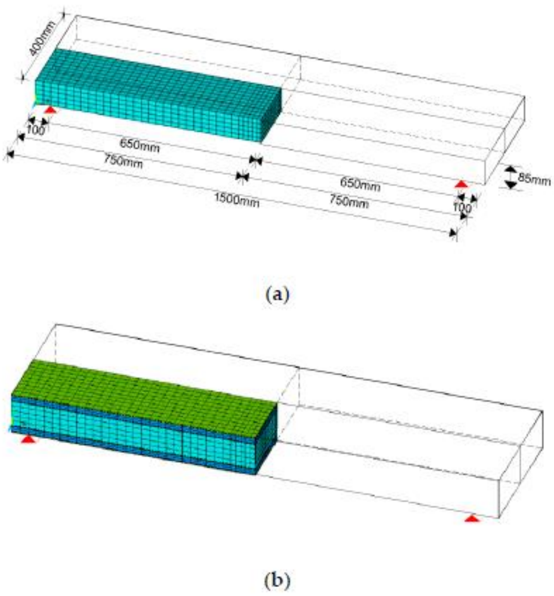


Figure 25 (a) Schematic arrangement and geometry of control specimen and (b) model for specimen2iMi2.Figure 12. (a) Schematic arrangement and geometry of control specimen and (b)model for specimen 2iMi2. (image and caption are from Karlos et al. 2020)

Results showed that the combined TRM/insulation system significantly improved the out-of-plane strength and deformation capacity of masonry walls. Positioning TRM outside the insulation increased effectiveness compared to TRM alone. The prevailing failure mode was TRM tensile failure with fiber rupture.

Both analytical and numerical models demonstrated good agreement with experimental results, indicating their potential for future optimization studies. The research highlights the system's effectiveness in addressing seismic vulnerability and energy efficiency of existing masonry buildings, potentially contributing to more sustainable and resilient urban environments.

Future work should focus on incorporating damage criteria in FEA, extending the model to capture in-plane and combined loading scenarios, and investigating full-scale wall and building system performance.

Tree-View Summary

Objective: To investigate an innovative system combining textile-reinforced mortar (TRM) and thermal insulation for simultaneous seismic and energy retrofitting of masonry walls.

Methodology:

Experimental Testing:

- Out-of-plane cyclic loading tests on brick masonry wallettes
- Bond-slip tests on masonry specimens with TRM and insulation
- Digital image correlation (DIC) for displacement measurements

Analytical Modeling:

- Simplified cross-section analysis based on classical bending theory

- Consideration of multiple failure modes (TRM tension, masonry compression, debonding)

Numerical Simulation:

- Finite Element Analysis using ANSYS software
- Macro-modeling approach for masonry and insulation
- Shell elements for TRM with orthotropic behavior

Material Properties:

- Masonry: Cast-Iron model with asymmetric tension/compression behavior
- Insulation: Cellular material model
- TRM: Multi-linear kinematic hardening model

Load Case:

- Out-of-plane cyclic loading
- Monotonic loading for numerical simulations

Key Findings:

- Combined TRM/insulation system significantly improved out-of-plane strength and deformation capacity of masonry walls
- Positioning TRM outside the insulation increased effectiveness compared to TRM alone
- Prevailing failure mode was TRM tensile failure with fiber rupture
- Analytical and numerical models showed good agreement with experimental results

Conclusions:

- The proposed system effectively combines seismic and energy retrofitting for masonry walls
- Proper bonding between layers is crucial for system performance
- Simple analytical and numerical models can capture basic response characteristics

Limitations and Future Work:

- Incorporate damage criteria in FEA to better model post-peak behavior
- Extend the model to capture in-plane and combined loading scenarios
- Perform parametric studies to optimize the system
- Investigate full-scale wall and building system performance

Significance: This study presents a novel approach to address both seismic vulnerability and energy efficiency of existing masonry buildings, potentially leading to more sustainable and resilient urban environments.

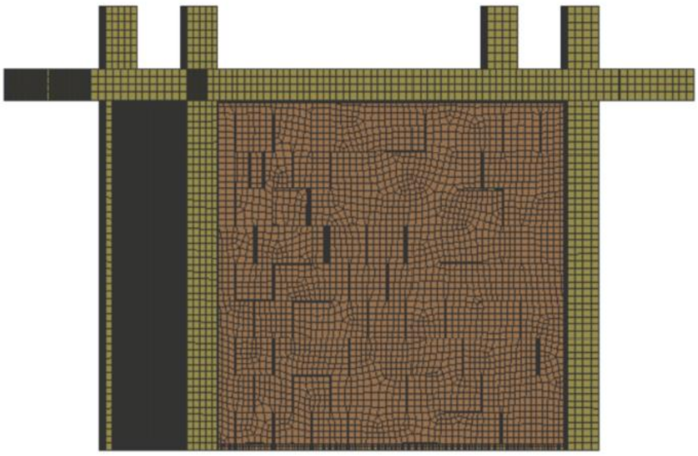
3.5.4.3 Seismic Joints and Infill Strengthening

3.5.4.3.1 “3D FEA of Infilled RC Framed Structures Protected by Seismic Joints and FRP Jackets” (Rousakis et al. 2021)

Text Summary

This study presents a comprehensive analysis of 3D finite element models for reinforced concrete (RC) frames with infilled walls, incorporating innovative seismic protection techniques. The research focuses on the use of polyurethane flexible joints (PUFJ) and fiber-reinforced polyurethane (FRPU) jackets to enhance the seismic performance of these structures.

The authors developed 3D pseudo-dynamic finite element models using ANSYS Workbench's Advanced Explicit Dynamics framework. They modeled bare RC frames, infilled frames with PUFJ, and retrofitted frames with FRPU jackets (see Figure 26). The models employed the RHT concrete model and elastic material models for PUFJ and FRPU. Pseudo-dynamic analyses with controlled monotonic displacement were conducted to evaluate the structures' behavior



(a)

Figure 26 (a) Mesh of the RC structure, of the damaged brick infill and of the external FRPU retrofit (image and caption are from Rousakis et al. 2021)

Key findings revealed that FRPU jackets maintained infill integrity up to 3.6% drift, while PUFJ-protected infilled structures exhibited ductile behavior up to 3.7% drift. The infilled structure with PUFJ developed three times higher maximum acceleration than the bare structure. FRPU retrofit increased initial stiffness and maintained higher base shear capacity.

The analysis shows that the experimental responses are reasonably well predicted by the 3D FE models and that the seismic performances of the infilled RC frames were effectively enhanced by the PUFJ and FRPU techniques. This study provides valuable insight into new seismic protection strategies that may be further explored in enhancing seismic resilience in both existing and new structures. Future work may consider combined retrofit techniques, multi-story structures, and out-of-plane loading effects.

Tree-View Summary

Objective: The paper is aimed at the development and analysis of 3D finite element models of the RC frame with infilled walls, including advanced seismic protection techniques using polyurethane flexible joints and fiber-reinforced polyurethane jackets.

Methodology:

Model Development:

- 3D pseudo-dynamic FE models using ANSYS Workbench
- Advanced Explicit Dynamics framework
- Models for bare RC frame, infilled frame with PUFJ, and retrofitted frame with FRPU

Material Modeling:

- RHT concrete model for concrete behavior
- Elastic material models for PUFJ and FRPU
- Steel reinforcement modeled as linear elements

Geometry and Elements:

- Solid elements for concrete and infill walls
- Linear elements for reinforcement
- Surface bodies for FRPU jackets
- 8-node reduced integration hexahedral elements

Boundary Conditions and Loads:

- Fixed boundary conditions for column and infill supports
- Pseudo-dynamic analysis with controlled monotonic displacement at the top

Analysis:

- Comparison of analytical results with experimental data from shake table tests
- Investigation of bare RC frame, infilled frame with PUFJ, and retrofitted frame with FRPU

Key Findings:

- FRPU jackets maintained infill integrity up to 3.6% drift
- PUFJ-protected infilled structure showed ductile behavior up to 3.7% drift
- Infilled structure with PUFJ developed 3 times higher maximum acceleration than bare structure
- FRPU retrofit increased initial stiffness and maintained higher base shear capacity

Conclusions:

- 3D FE models accurately predicted experimental responses
- PUFJ and FRPU techniques effectively improved seismic performance of infilled RC frames
- Combined retrofits can manipulate infill engagement and control damage accumulation

Limitations and Future Work:

- Further investigation of combined retrofit techniques
- Analysis of multi-story structures
- Consideration of out-of-plane loading effects

Significance: Importantly, it also provides critical insight into the effectiveness of some new seismic protection methodologies for infilled reinforced concrete frames that can provide effective ways to enhance seismic resilience in existing and new constructions.

3.5.4.3.2 "Dynamic Modeling and Analysis of RC Frames Filled With URM Panels Protected With Flexible Connectors" (Vanian et al. 2024)

Text Summary

This study focuses on developing dynamic models of reinforced concrete (RC) frames with unreinforced masonry (URM) infills, protected by innovative interventions. The researchers used Finite Element Method (FEM) with Ansys-Autodyn and Abaqus software to model various specimens, including one-bay, one-level frames and a seismic table specimen. They employed different material models for concrete, reinforcement, masonry, and protective systems like fiber-reinforced polyurethane (FRPU) and polyurethane flexible joints (PUFJ) (see Figure 27 and Figure 28).

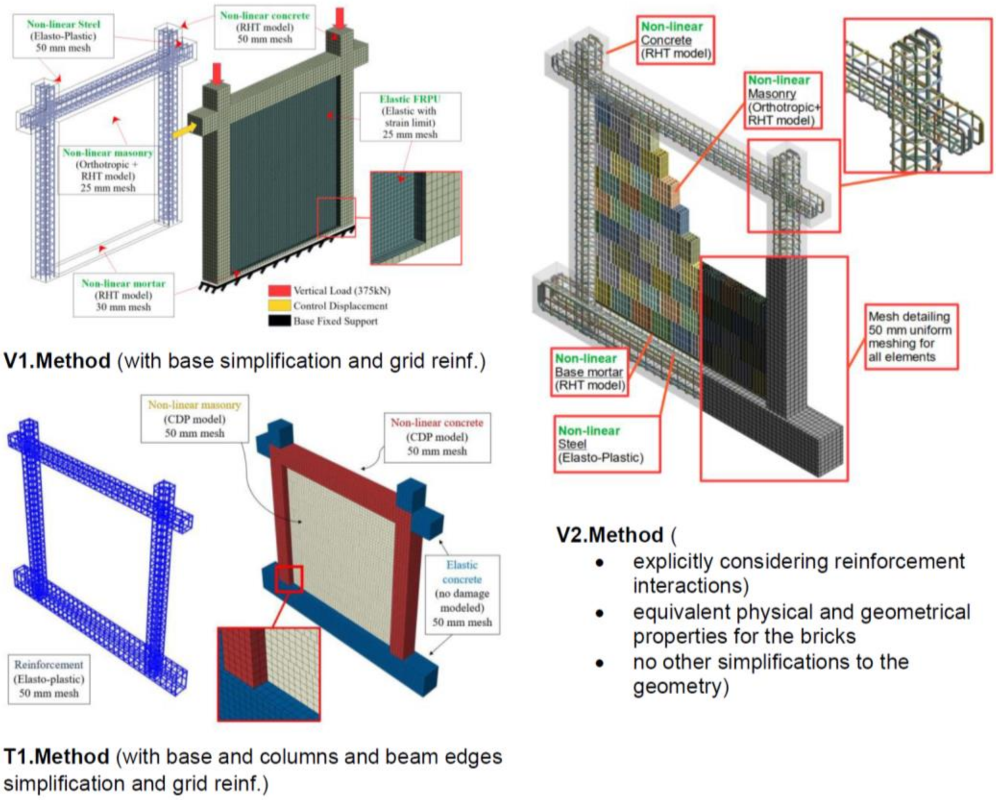


Figure 27 Numerical modeling details for all methods (one-bay, one-level specimens) a) (image and caption are from Vanian et al. 2024)

The study compared experimental and numerical results, showing good agreement for specimens responses. The researchers found that proper calibration of material models, detailed geometry representation (especially for masonry units), and consideration of contact interfaces are crucial for improving model accuracy. They also demonstrated that calibrated data from simplified models could be extrapolated to more detailed models without recalibration when the main assumptions remain the same.

Key findings include the positive effects of PUFJ and FRPU interventions on enhancing ductility and out-of-plane resistance of walls. The study also highlighted the significant influence of infill walls on buildings' dynamic characteristics. Future work should focus on refining loading protocols, investigating detailed failure patterns, and exploring long-term effects of the protective interventions.

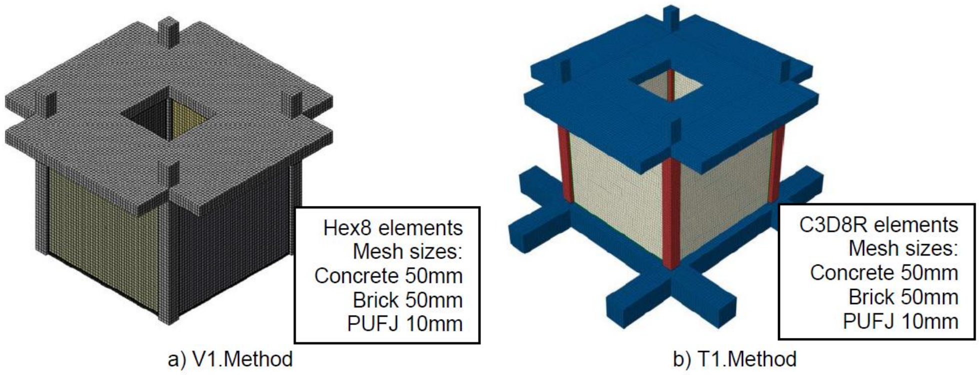


Figure 28 Numerical discretization (mesh) for V1.Method a) and T1.Method b) (seismic table specimen) (image and caption are from Vanian et al. 2024)

This research contributes valuable insights to improving seismic performance predictions and design strategies for earthquake-resistant structures with masonry infills.

Tree-View Summary

Objective: To develop reliable dynamic models of reinforced concrete (RC) frames filled with unreinforced masonry (URM) panels, protected with innovative interventions.

Methodology:

Specimen Preparation:

- One-bay, one-level frames: bare, filled with common URM, and strengthened with FRPU
- INMASPOL project: one-story, 4-column, 3D frame with top slab, filled with URM and protected with PUFJ

Numerical Modeling:

- V1 and V2 Methods: Ansys-Autodyn
- T1 Method: Abaqus
- Element types: 8-node 3D elements for concrete, masonry, base mortar, and PUFJ; line elements for reinforcement

Material Properties:

- Concrete: RHT Concrete model (V1, V2), CDP model (T1)
- Reinforcement: Bilinear stress-strain curve
- Masonry: Orthotropic material limit with RHT concrete strength (V1, V2), CDP method and Traction-Separation Law (T1)
- FRPU: Rule of mixture (ROM)
- PUFJ: Mooney-Rivlin model

Load Cases:

- One-bay, one-level specimens: Constant axial load and imposed horizontal top displacement (pushover V1 and V2) and (reversal T1)
- Seismic table specimen: (V1) Top Displacement, (T1) Shake table testing protocol portion

Analysis:

- Explicit dynamic solver
- Comparison of experimental and numerical results
- Parametric study of PUFJ thickness

Key Findings:

- Both numerical methods (V1 and T1) show good agreement with experimental results for bare frame responses
- Method V2 provides improved results compared to Method V1 due to more equivalent assumptions
- Increasing PUFJ thickness may provide more ductile behavior for the protected system
- Proper brick unit modeling plays a crucial role in damage pattern generation

Conclusions:

- Calibrated data from simplified models can be extrapolated to more detailed models without recalibration
- PUFJ and FRPU solutions enhance ductility features and out-of-plane resistance of walls
- Infill walls have a considerable influence on the dynamic characteristics of buildings

Limitations and Future Work:

- Further research needed on equivalent loading protocols with correction factors
- Investigation of more detailed failure patterns and damage accumulation analyses
- Exploration of the long-term effects of PUFJ and FRPU interventions

Significance: This study provides valuable insights into modeling RC frames with URM infills and innovative protection systems, contributing to improved seismic performance predictions and design strategies for earthquake-resistant structures.

3.5.4.3.3 "Seismic Protection of RC Buildings by Polymeric Infill Wall-Frame Interface" (Akyildiz et al. 2021)

Text Summary

This study investigates the use of PolyUrethane Flexible Joints (PUFJ) in reinforced concrete (RC) buildings with infill walls to improve seismic performance (see Figure 29 and Figure 30). The researchers developed finite element models using Abaqus, comparing three building types: Bare Frame (BF), Traditional Mortar (TM), and PUFJ. They employed the Concrete Damaged Plasticity model for concrete and masonry, and a Mooney-Rivlin hyperelasticity model for PUFJ. The analysis included static, modal, and dynamic simulations using a modified Duzce 1999 earthquake record.

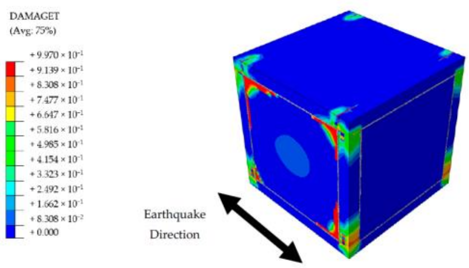


Figure 29 Damage distribution on the PUFJ Building. (image and caption are from Akyildiz et al. 2021)

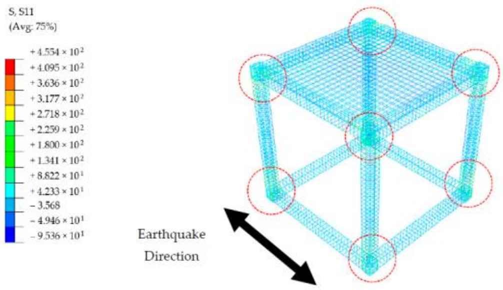


Figure 30 Reinforcement stresses belong to BF Building [MPa]; circles indicate the highest stress concentrations (image and caption are from Akyildiz et al. 2021)

Results showed that PUFJ implementation significantly enhanced the overall structural performance during seismic loading. The PUFJ building exhibited minimal frequency reduction after the earthquake, while the TM building experienced severe bonding failures between infill walls and RC frames. The BF building showed the highest displacement values but lower acceleration forces.

The study concludes that PUFJ offers a promising solution for seismic protection of infilled RC frames, contributing to lateral load-carrying capacity with reasonable drift ratios. This approach has potential applications in both new constructions and retrofitting existing structures in seismic zones. Future research should focus on different masonry materials, wall configurations, and long-term performance of PUFJ under various environmental conditions.

Tree-View Summary

Objective: It deals with the flexibility of joints in masonry infilled walls that are framed with RC in order to enhance their seismic performance.

Methodology:

Model Development:

- Small-scale micro-models for calibration
- Large-scale macro-models for full building analysis
- Three building types: Bare Frame (BF), Traditional Mortar (TM), and PolyUrethane Flexible Joint (PUFJ)

Material Modeling:

- Concrete Damaged Plasticity (CDP) model for concrete, bricks, and mortar
- Mooney-Rivlin hyperelasticity model for PUFJ
- Cohesive surface model for material interfaces

Analysis Procedures:

- Static analysis for gravity loads
- Modal analysis for natural frequencies
- Dynamic analysis for seismic loading

Load Cases:

- Gravity loads
- Seismic acceleration based on modified Duzce 1999 earthquake record

Software:

- Abaqus for FEM analysis

- SAP2000 for preliminary seismic record generation

Key Findings:

- PUFJ implementation improved overall structural performance during seismic loading
- TM building experienced severe bonding failures between infill walls and RC frames
- PUFJ building showed minimal frequency reduction after seismic loading
- BF building exhibited the highest displacement values but lower acceleration forces

Conclusions:

- PUFJ implementation enhances seismic performance of RC buildings with infill walls
- Flexible joints contribute to lateral load-carrying capacity with reasonable drift ratios
- PUFJ approach offers a promising solution for seismic protection of infilled RC frames

Limitations and Future Work:

- Further research on different masonry materials and types of bricks
- Review of various wall configurations and openings
- Long-term performance and durability of PUFJ under various environmental conditions conditions

Significance: This current study identifies PUFJ as capable of serving as an efficient method for Economically enhance the seismic performance of the RC buildings having infill walls. Both for new constructions and retrofitting of the existing structures in seismic zones.

3.5.4.3.4 "Damage reduction system for masonry infill walls under seismic loading" (Butenweg and Marinković 2018)

Text Summary

This paper presents the design and performance evaluation of a new INODIS-Innovative Decoupled Infill System to enhance the seismic resilience of masonry infill walls in RC structures. It is based on decoupling the infill by means of U-shaped elastomers from the frame in order to prevent adverse interaction at the interface under earthquake loading.

Experimental and numerical modeling investigations were combined in this research to determine the effectiveness of the system. (see Figure 31). Full-scale tests on RC frames with masonry infills were conducted under in-plane, out-of-plane, and combined loading conditions. A micromodeling approach using ABAQUS software was employed to simulate the behavior of frames with traditional infills and those with the INODIS system.

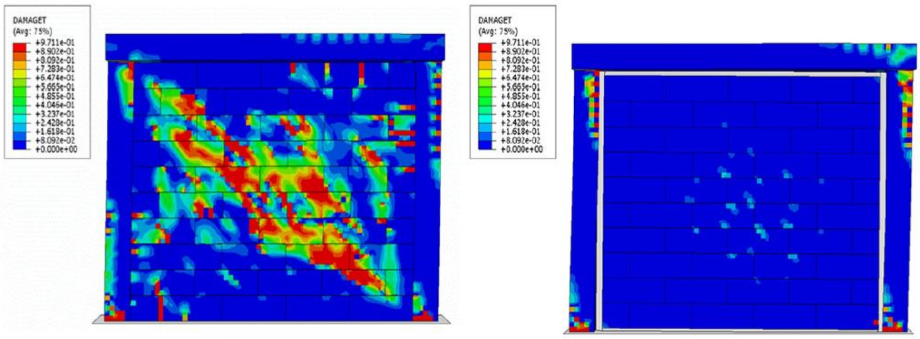


Figure 31Tensile damage distribution obtained with the numerical model for traditionally infilled frame (A) and INODIS system (B) (image and caption are from Butenweg and Marinković 2018)

Results show that the INODIS system significantly increases the deformation capacity of infilled frames, reduces stiffness and base shear, and delays the activation and damage of the infill. The system also improves energy dissipation and provides more stable hysteretic behavior.

The study concludes that the INODIS system effectively transforms masonry infills into true non-structural components, improving overall seismic performance. Future work includes developing a practical design concept for elastomer selection and investigating sound isolation and fire protection aspects.

This research overcame an important shortfall in existing practices in construction and might lead to safer building construction in seismic-prone areas around the world. The methodology fully aligns with the recommendations of Eurocode 8, regarding the consideration of the infill wall effect in seismic design.

Tree-View Summary

Objective: The objective is to design and assess the INODIS system for decoupling masonry infills from reinforced concrete frames to enhance their seismic performance.

Methodology:

System Development:

- Design of U-shaped elastomers
- Selection of appropriate elastomer materials
- Development of installation process

Experimental Testing:

- Material property tests for elastomers
- Small specimen tests for elastomeric connections
- Full-scale tests on RC frames with masonry infills

Numerical Modeling:

- Development of micromodel using ABAQUS
- Calibration with experimental results
- Extension to AAC masonry infills

Load Cases:

- In-plane cyclic loading
- Out-of-plane pressure loading
- Combined in-plane and out-of-plane loading

Analysis:

- Comparison of traditional infill vs. INODIS system
- Evaluation of damage patterns and load-displacement curves

Key Findings:

- INODIS system significantly increases the deformation capacity of infilled frames
- Reduction in stiffness and base shear for frames with INODIS system
- Delayed activation and reduced damage to infill with INODIS system
- Improved energy dissipation and more stable hysteretic behavior

Conclusions:

- INODIS system effectively decouples masonry infills from RC frames
- Seismic performance is improved for both in-plane and out-of-plane loading
- The system transforms infills into true non-structural components
- Energy dissipation is distributed, reducing overall seismic action

Limitations and Future Work:

- Development of practical design concept for elastomer selection
- Optimization of construction process
- Investigation of sound isolation and fire protection aspects

Significance: INODIS provides an answer to the seismic vulnerability enhancement of reinforced concrete frames with masonry infills by proposing a new generation of construction methodologies. Limiting damage, INODIS increases structural performance and is likely to lead to safer building design in earthquake-prone areas in every part of the world.

3.5.4.3.5 "Innovative seismic isolation of masonry infills using cellular materials at the interface with the surrounding RC frames "(Tsantilis and Triantafillou 2018)

Text Summary

The present research proposes a new seismic isolation of masonry infill walls from the adjacent RC frames by using cellular materials at the interface. The tests carried out by the researchers were on five 1/3-scaled single-storey single-bay RC frames with hollow clay brick masonry panels, representing fully and partially infilled frames with different interface conditions and tested them under in-plane cyclic loading without any vertical loads.

The key finding is that cellular material joints eliminate frame-infill interaction for small to medium drifts, preventing infill damage during low to moderate earthquakes. At larger drifts, infills become activated, increasing the structure's strength and stiffness. The study identifies joint position and thickness as critical design parameters, with fully isolated infills activating at lateral displacements approximately four times the joint thickness, while side-isolated infills activate at displacements equal to the joint thickness.

The researchers developed an analytical modeling approach using single-strut elements for infills and nonlinear springs for cellular material joints, implemented in OpenSees software (see Figure 32). This model showed good agreement with experimental results and was used for parametric studies on three-storey three-bay RC frames with different infill configurations under nonlinear dynamic analysis.

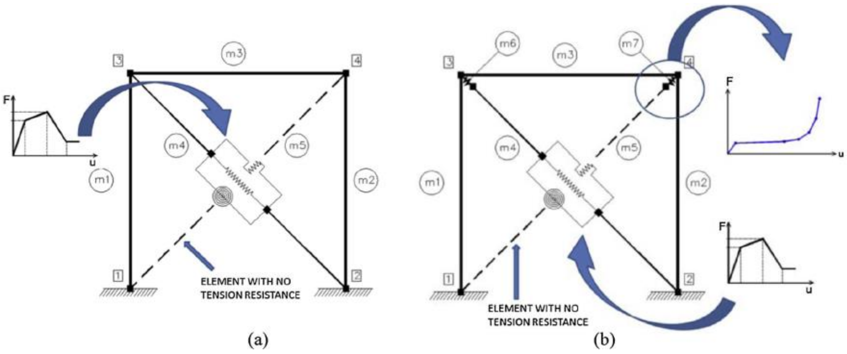


Figure 32 Models for (a) conventionally infilled frames and (b) infills with cellular material joints at the frame-infill interface. (image and caption are from Tsantilis and Triantafillou 2018)

While the proposed technique shows promise in mitigating infill wall damage during earthquakes, further research is needed to address out-of-plane resistance and optimize the concept through full-scale testing and additional parametric investigations. Overall, this study introduces a novel approach to improve the seismic performance of infilled RC frames, with potential applications in numerical simulations and design of RC structures with isolated infills.

Tree-View Summary

Objective: To investigate an innovative technique for seismic isolation of masonry infill walls from surrounding RC frames using cellular materials at the interface.

Methodology:

Experimental Program:

- Five 1/3 scaled single-storey, single-bay RC frames with hollow clay brick masonry panels
- Three fully infilled frames with different interface conditions
- Two partially-infilled frames

Testing Procedure:

- In-plane cyclic loading
- No vertical loads applied

Material Properties:

- Concrete: 26 MPa average cube compressive strength
- Steel reinforcement: 526 MPa yield stress for deformed bars, 277 MPa for plain stirrups
- Masonry: Fired clay bricks with varying compressive strengths
- Cellular material: Foamed polyethylene with 80 kg/m³ density

Modeling Approach:

- Single-strut elements for infills
- Nonlinear springs for cellular material joints
- Implementation in OpenSees software

Parametric Study:

- Three-storey three-bay RC frames with different infill configurations
- Nonlinear dynamic analysis using Thessaloniki 1978 earthquake record

Key Findings:

- Cellular material joints eliminate frame-infill interaction for small to medium drifts
- Infills get activated at larger drifts, increasing strength and stiffness
- Joint position and thickness are critical design parameters
- Fully isolated infills activate at lateral displacements ≈ 4 times joint thickness
- Side-isolated infills activate at lateral displacements ≈ joint thickness

Conclusions:

- Proposed technique prevents infill damage for low to moderate earthquakes
- Infills contribute to structural performance during strong seismic events
- Analytical modeling approach shows good agreement with test results

Limitations and Future Work:

- Out-of-plane resistance of isolated infills needs investigation
- Full-scale testing on 3D structures required
- Additional parametric studies needed for optimization

Significance: This study introduces a novel approach to mitigate infill wall damage during earthquakes while maintaining their beneficial contribution to structural performance under severe seismic events. The proposed modeling technique can be used for numerical simulations and design of RC structures with isolated infills.

3.5.4.4 Fiber-Reinforced Polymer (FRP)

3.5.4.4.1 "Analytical modelling of plastic behaviour of uniformly FRP confined concrete members" (Rousakis et al. 2008)

Text Summary

This paper describes a new approach to model the elastoplastic behavior of FRP confined concrete. The authors have developed a strain-hardening Drucker-Prager model which can simulate hardening as well as softening material response. They have focused on determining permanent deformations from experimental observations as well as theoretical elastic response of confined concrete. In this study, the limitations of the existing analytical models have been identified, especially those concerning the determination of axial strains of FRP confined concrete. Given this problem, the authors are proposing a method through which permanent strains-plastic-can be derived from monotonic loading tests and deliver basic information that is much needed in order to model more accurately. Key results show that FRP-confined concrete exhibits different behavior compared to plain concrete during increasing cycles of compressive loading and unloading. In this paper, the model developed gives reasonable agreement with the experimental observation; it was validated through a comparison with published data and other analytical models. The significance of the research is related to the potential enhancements in the accuracy of FRP-confined concrete behavior modeling, which thus may enable more reliable design and analysis involving this material. However, there are still challenges in accurately carrying out load-unload test cycles to record plastic strain variation without the effects of fatigue. This paper will add to the knowledge base by providing a fresh look into the modeling of FRP-confined concrete and addressing previous shortcomings, thus forming the basis for further research into the subject area.

Tree-View Summary

Objective: To present a method for assessing and calibrating the elastoplastic behaviour of FRP confined concrete.

Methodology:

Data Acquisition:

- Evaluation of permanent deformations from experimental observations
- Theoretical elastic response of confined concrete

Model Creation:

- Development of a strain-hardening Drucker-Prager model
- Production of closed-form expressions relating model parameters to material properties

Material Properties:

- FRP confined concrete
- Plain concrete (for comparison)

Load Case:

- Increasing compressive load-unload cycles

Analysis:

- Calculation of permanent (plastic) strains from monotonic loading experiments
- Estimation of elastic strain rates using elastic relations of concrete

Key Findings:

- FRP confined concrete exhibits different response compared to plain concrete under increasing compressive load-unload cycles
- Initial stages of inelastic concrete response show unloading curve slope equal to the modulus of elasticity of concrete
- The developed model simulates both hardening and softening material response

Conclusions:

- The proposed method allows for the assessment and calibration of elastoplastic behaviour of FRP confined concrete
- The model shows reasonable agreement with experimental observations
- The predictive ability of the model is verified through comparisons to numerous published experimental data and analytical models

Limitations and Future Work:

- Difficulties in accurate load-unload test cycles, especially at the exact failure point of FRP confined concrete
- Challenges in reliable recording of plastic strain variation without creating significant fatigue effects

Significance: This study provides a new approach to modeling FRP confined concrete behavior, addressing limitations in existing models, particularly in predicting axial strains. The proposed method and model could lead to more accurate design and analysis of FRP confined concrete structures.

3.5.4.4.2 "3D Finite-Element Analysis of Substandard RC Columns Strengthened by Fiber-Reinforced Polymer Sheets" (Karabinis et al. 2008)

Text Summary

This study presents a 3D finite element analysis of substandard reinforced concrete (RC) columns strengthened with fiber-reinforced polymer (FRP) sheets. The researchers developed an advanced Drucker-Prager-type plasticity model for concrete, incorporating a non-associated flow rule and discrete 3D modeling of steel reinforcement. The FRP jacket was modeled as a quadrilateral lamina element with orthotropic properties (see Figure 33) Using ABAQUS software, the model was validated against experimental results for both plain and reinforced concrete columns. The study focused on the prevention of premature bar buckling in low-strength RC columns through FRP confinement.

Key findings include the effectiveness of FRP sheets in preventing bar buckling, even at low volumetric ratios. The research revealed that section geometry and steel reinforcement significantly influence stress distribution in the FRP jacket. Stress in the FRP at failure ranged from 90% (plain concrete) to 60% (reinforced concrete) of its tensile strength.

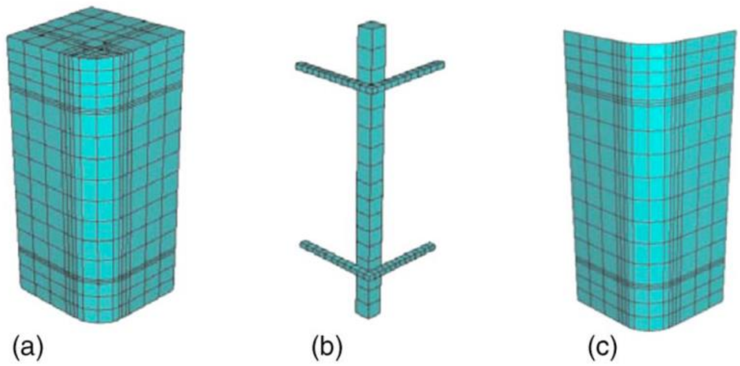


Figure 33 a Discretization of concrete; b steel reinforcement; and cFRP jacket for the reinforced concrete member from Karabinis and Rousakis 2006 (image and caption are from Karabinis et al. 2008)

The study provides valuable insights for improving structural retrofitting techniques, highlighting the complex interactions between concrete, steel reinforcement, and FRP confinement. Future work should address more detailed modeling of the FRP jacket and explore a wider range of variables affecting column behavior.

Tree-View Summary

Objective: To investigate the mechanical behavior of reinforced concrete columns with premature bar buckling, strengthened by FRP sheets, using 3D finite element analysis.

Methodology:

Model Development:

- Advanced Drucker-Prager-type plasticity model for concrete
- Non-associated flow rule
- 3D discrete modeling of steel reinforcement

- Quadrilateral lamina element for FRP jacket

Material Properties:

- Concrete: Plasticity parameters estimated using closed-form relations
- Steel: Full hardening response assumed
- FRP: Orthotropic, linearly elastic up to failure

Analysis:

- ABAQUS finite element software
- Newton's solution method

Validation:

- Comparison with experimental results for plain and reinforced concrete columns

Stress Analysis:

- Investigation of stress concentrations in concrete core and FRP jacket

Key Findings:

- FRP confinement, even in low volumetric ratios, can prevent bar buckling in substandard RC columns.
- Geometry of the section and presence of steel reinforcement significantly affect stress distribution in FRP jacket.
- Stress in FRP at failure ranges from 90% (for plain concrete columns) to 60% (for reinforced columns) of its tensile strength.
- Sharp stress variations along section perimeter or height lead to lower average FRP stress at failure.

Conclusions:

- The proposed model accurately predicts behavior of FRP-confined concrete columns.
- FRP confinement enhances mechanical behavior of low-strength RC columns by preventing bar buckling.
- Section geometry and steel reinforcement significantly influence stress distribution in FRP jacket.

Limitations and Future Work:

- Need for more detailed modeling of FRP jacket (resin layers, bond characteristics)
- Further parametric studies on variables like steel properties, tie spacing, concrete properties, and FRP properties
- Investigation of FRP confinement detailing and cross-section ovalization schemes

Significance: This study provides valuable insights into the behavior of FRP-strengthened substandard RC columns, offering a foundation for improved design and analysis methods in structural retrofitting

3.5.4.4.3 "3D Finite Element Pseudodynamic Analysis of Deficient RC Rectangular Columns Confined with Fiber Reinforced Polymers under Axial Compression" (Fanaradelli and Rousakis 2020)

Text Summary

This study presents a comprehensive 3D finite element analysis of reinforced concrete (RC) columns confined with fiber-reinforced polymer (FRP) jackets and composite ropes under axial compression (see Figure 34). The research employs a pseudodynamic approach to simulate monotonic, repeated, and cyclic loading conditions typical in seismic applications. The Riedel-Hiermaier-Thoma (RHT) model is used for concrete, capturing inelastic behaviors and damage redistribution, while steel reinforcement and FRP jackets are modeled in detail.

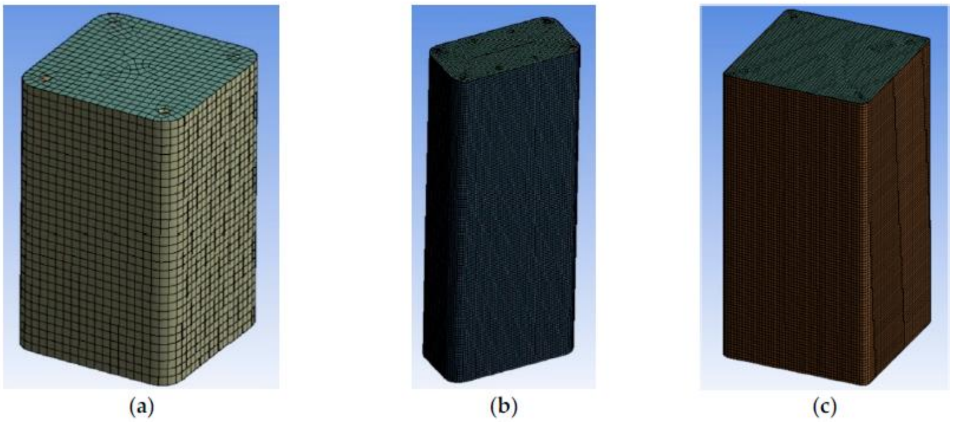


Figure 34 Mesh of specimens: (a) Series BS1C/BS2C by [2]; (b) Series R2.0H2CL by [28] and (c) Series LSR-R-1-3 by [20]. (image and caption are from Fanaradelli and Rousakis 2020)

These finite element models simulate the experimentally observed stress-strain behavior quite accurately for the wide ranges of column configurations such as square and rectangular sections of different concrete strengths and corner radii, with various FRP properties. This analysis also allows highlighting significant variations of FRP jacket strains and steel reinforcement deformations consistent with local damage and failure mechanisms.

Among others, key findings include: the identification of the critical interaction of local concrete damage with FRP fracture and the limited dependence of the quality of reinforcement in terms of column axial capacity and deformability. The applications within the second part show the versatility of the modeling approach to composite rope-confined columns.

This research contributes to the understanding of the behavior of FRP-confined RC columns under axial loading, providing useful insight into the improvement of design models in seismic applications. Future work should focus on further investigating the concrete-FRP damage interactions and experimental validation of local strain measurements.

Tree-View Summary

Objective: To study axial mechanical behavior with RC columns that are square and of a rectangle section, confined with FRP jackets and continuous composite ropes through 3D finite element pseudodynamic analysis.

Methodology:

Model Development:

- Used ANSYS Explicit Dynamics software
- Implemented Riedel-Hiermaier-Thoma (RHT) model for concrete
- Applied Von Mises yield criterion for steel reinforcement
- Utilized orthotropic elastic material model for FRP jackets

Material Properties:

- Calibrated concrete model to eliminate loading rate effects

- Considered effects of epoxy resins in FRP jackets
- Used bilinear isotropic hardening model for steel

Geometry and Meshing:

- Modeled square and rectangular RC columns
- Used hexahedral and tetrahedral solid elements for concrete and FRP
- Applied beam elements for steel reinforcement

Loading and Boundary Conditions:

- Applied monotonic axial displacement at column top
- Used "Fixed Support" at column base

Analysis:

- Conducted pseudodynamic analyses
- Performed parametric studies on steel reinforcement quality

Key Findings:

- FE models accurately reproduced experimental stress-strain behavior
- Significant variation in FRP jacket strains and steel reinforcement deformations observed
- Local concrete damage and FRP fracture interaction identified as critical
- Steel reinforcement quality marginally affected column axial capacity and deformability

Conclusions:

- Pseudodynamic 3D FEA can capture complex behavior of FRP-confined RC columns
- Advanced modeling techniques give insight into local damage and failure mechanisms.
- Parametric studies reveal the influence of steel reinforcement properties on column performance

Limitations and Future Work:

- Further investigation needed on concrete-FRP damage interaction
- Experimental validation required for local strain measurements in FRP and steel
- Extension of model to dynamic loading conditions

Significance: This article provides a comprehensive analysis to realize the behavior of FRP-confined RC columns, discussing all the critical design parameters and providing suggestions for improved design models in seismic applications.

3.5.4.4.4 "Modeling Strategies of Finite Element Simulation of Reinforced Concrete Beams Strengthened with FRP: A Review" (Naser et al. 2021)

Text Summary

This paper gives an overall review of the finite element modeling techniques in the analysis of FRP-strengthened reinforced concrete beams. Further, the authors, M. Z. Naser, Rami Antoun Hawileh, and Jamal Abdalla provide insight into element type, material modeling, bond-slip behavior, and varied loading conditions, as depicted in Figure 35.

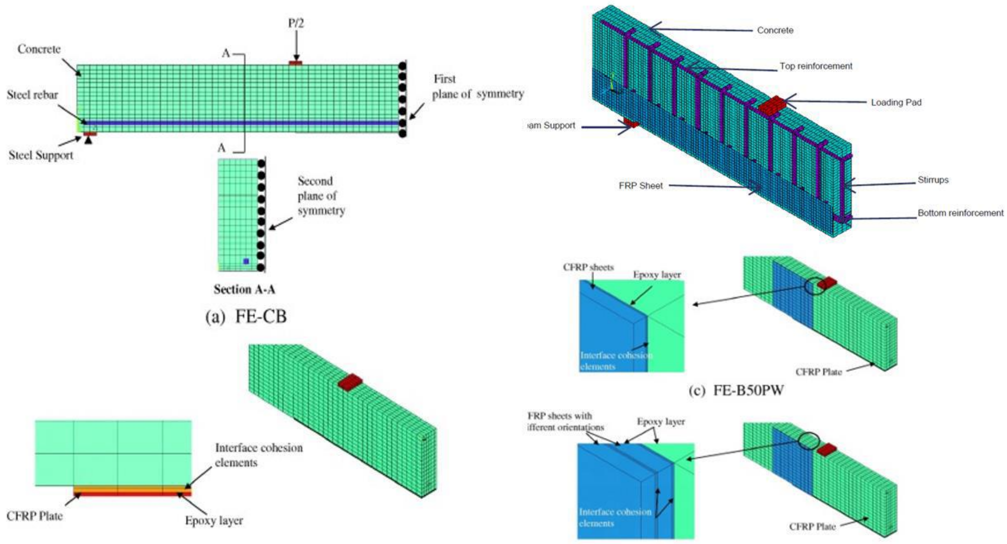


Figure 35 Typical finite element (FE) models developed in ANSYS for fiber-reinforced polymer (FRP)-strengthened Reinforced Concrete Beams (RC beams) showing different components. (image and caption are from Naser et al. 2021)

The review covers some of the key aspects of FE modeling in 3D brick elements for concrete, spar/link elements for the reinforcement, and shell elements for FRP sheets. It underscores the significance of appropriate material models, including those developed by William and Warnke.model of concrete and orthotropic elastic model of FRP. This paper also discusses Bond-slip models, their numerical implementation within FE analyses.

The authors develop the importance of consideration of different loading conditions. such as monotonic, cyclic, and fire loading. They provide a rationale behind nonlinear analysis techniques, and use of automatic time stepping to enhance convergence. Additionally, the test case hasaddresses the problems of FRP debonding modelling and provides temperature-dependent Properties in fire analysis. T

his study identifies FEM as a inexpensive alternative to experimental methods. Testing requires painstaking thought about many variables to produce an accurate result. It defines areas that would require further research include improved modeling of debonding of FRP, long-term behaviour of FRP-strengthened structures. In other words, the review is a great source regarding scholar and professional considerations in developing accurate FE models of FRP-strengthened concrete beams by following guidelines such as given by ACI 440.2R-17 and FIP provisions.

Tree-View Summary

Objective: To present an in-depth analysis of the finite element modeling approach. reinforced concrete beams strengthened with Fiber Reinforced Polymer (FRP).

Methodology:

Element Selection:

- Concrete: 3D brick elements
- Steel/FRP rebars: Spar/link elements
- FRP sheets/plates: Shell elements
- Bonding agents: Solid brick elements
- Bond interface: Spring elements or embedded region constraint

Material Modeling:

- Concrete: William and Warnke's model, CDP, or smeared crack models
- Steel: Linear elastic-perfectly plastic model
- FRP: Orthotropic elastic model

Bond-Slip Modeling:

- CEB-FIP model
- Lu et al. model
- Nabaka et al. model

Loading Conditions:

- Monotonic and cyclic loading
- Fire loading (thermal-structural transient analysis)

Analysis Techniques:

- Nonlinear analysis with Newton-Raphson method
- Automatic time stepping for convergence
- Thermal analysis followed by structural analysis for fire conditions

Key Findings:

- Proper element selection and material modeling are crucial for accurate simulations
- Bond-slip behavior significantly affects the performance of FRP-strengthened beams
- Cohesive elements improve the simulation of debonding phenomena
- Temperature-dependent properties are essential for fire analysis
- Validation with experimental results is necessary for model accuracy

Conclusions:

- FE modeling provides an economical alternative to experimental testing
- Accurate simulation requires consideration of various factors, including material nonlinearity and bond behavior
- Different modeling approaches are needed for various loading conditions (ambient, seismic, fire)

Limitations and Future Work:

- Need for more experimental data on FRP-concrete bond behavior
- Improved modeling of FRP debonding under complex loading conditions
- Further research on long-term behavior and durability of FRP-strengthened structures
- Development of more accurate fire resistance models for FRP-strengthened elements

Significance: This review, therefore, acts like a comprehensive guide to the development of finite element models by researchers and practitioners for the case of FRP-strengthened concrete beams with maximum accuracy, meanwhile underlining the most recent state-of-the-art on modeling techniques.

3.5.4.4.5 “Finite Element Simulation of FRP-Strengthened Thin RC Slabs” (Assad et al. 2022)

Text Summary

This study investigates the flexural behavior of high-strength thin reinforced concrete (RC) slabs externally strengthened with fiber-reinforced polymer (FRP) laminates using finite element (FE) analysis. The researchers developed a 3D nonlinear FE model using ANSYS software (see Figure 36), incorporating various element types to represent concrete, steel reinforcement, FRP sheets, and interfacial behavior. The mode l was validated against

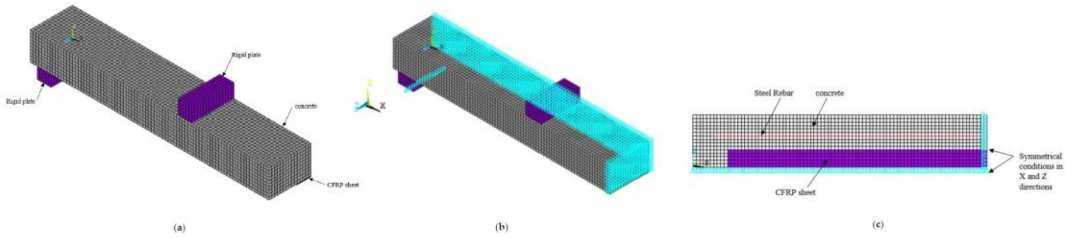


Figure 36 Developed FE model components in ANSYS: (a) 3D view; (b) boundary conditions;(c) bottom view. (image and caption are from Assad et al. 2022)

experimental data before conducting a parametric study examining different FRP types (CFRP, GFRP, BFRP, and PET-FRP) and concrete compressive strengths (50, 70, and 90 Mpa).Key findings include good agreement between FE model results and experimental data, with a maximum 5.7% difference in ultimate loads. CFRP-strengthened slabs exhibited the highest flexural capacity, while GFRP, BFRP, and PET-FRP strengthened slabs showed similar behavior. The effect of concrete compressive strength on strengthened slabs' behavior was moderate. This research provides valuable insights into the effectiveness of different FRP types for strengthening thin high-strength RC slabs and offers a validated FE modeling approach for future studies. The results may help engineers select appropriate reinforcement options. materials and the design of FRP-strengthened thin reinforced concrete slabs in practice.

Tree-View Summary

Objective: The bending performance of high-strength thin RC is investigated. slabs externally strengthened with fiber-reinforced polymer (FRP) laminates through numerical Simulation.

Methodology:

Model Development:

- Created 3D finite element (FE) model using ANSYS software
- Simulated four-point bending test setup
- Utilized symmetry to model quarter of the slab

Element Types:

- Concrete: SOLID65 element
- Steel reinforcement: LINK180 element
- FRP sheets and rigid plates: SOLID185 element
- Interfacial behavior: INTER205 element

Material Properties:

- Concrete: Nonlinear compressive and tensile stress-strain relationships
- Steel: Elastic-perfectly plastic model
- FRP: Linear elastic orthotropic material properties

Bond-slip Model:

- Used Nakaba et al.'s model for FRP-concrete interface

Validation:

- Compared FE results with experimental data from literature
- Verified load-deflection behavior and ultimate loads

Parametric Study:

- Investigated different FRP types (CFRP, GFRP, BFRP, PET-FRP)
- Varied concrete compressive strengths (50, 70, 90 MPa)

Key Findings:

- FE model results showed good agreement with experimental data (max 5.7% difference in ultimate loads)
- CFRP-strengthened slabs exhibited highest flexural capacity
- GFRP, BFRP, and PET-FRP strengthened slabs showed similar behavior
- Concrete compressive strength had moderate effect on strengthened slabs' behavior

Conclusions:

- Developed FE model accurately predicts behavior of FRP-strengthened RC slabs
- CFRP most effective for strengthening thin high-strength RC slabs
- Concrete compressive strength has limited impact on strengthened slabs' performance

Limitations and Future Work:

- Study limited to single FRP layer configuration
- Need for experimental validation of parametric study results
- Investigation of multi-layer FRP configurations
- Exploration of different loading conditions and slab geometries

Significance: This study provides a validated FE modeling approach for FRP-strengthened thin RC slabs and offers insights into the effectiveness of different FRP types and concrete strengths. The findings can guide engineers in selecting appropriate strengthening materials for thin high-strength RC slabs.

3.5.4.4.6 "Finite Element Modeling of Debonding Failures in FRP-Strengthened Concrete Beams Using Cohesive Zone Model" (Al-Saawani et al. 2022)

Text Summary

This study develops a finite element model to simulate debonding failures in FRP-strengthened concrete beams using ABAQUS software (see Figure 37). The researchers implemented a concrete damaged plasticity model for concrete, an elastic perfectly plastic model for steel, and a cohesive zone model to represent debonding interfaces. The model was calibrated and validated against experimental results from seven FRP-strengthened beams with varying shear span-to-depth ratios.

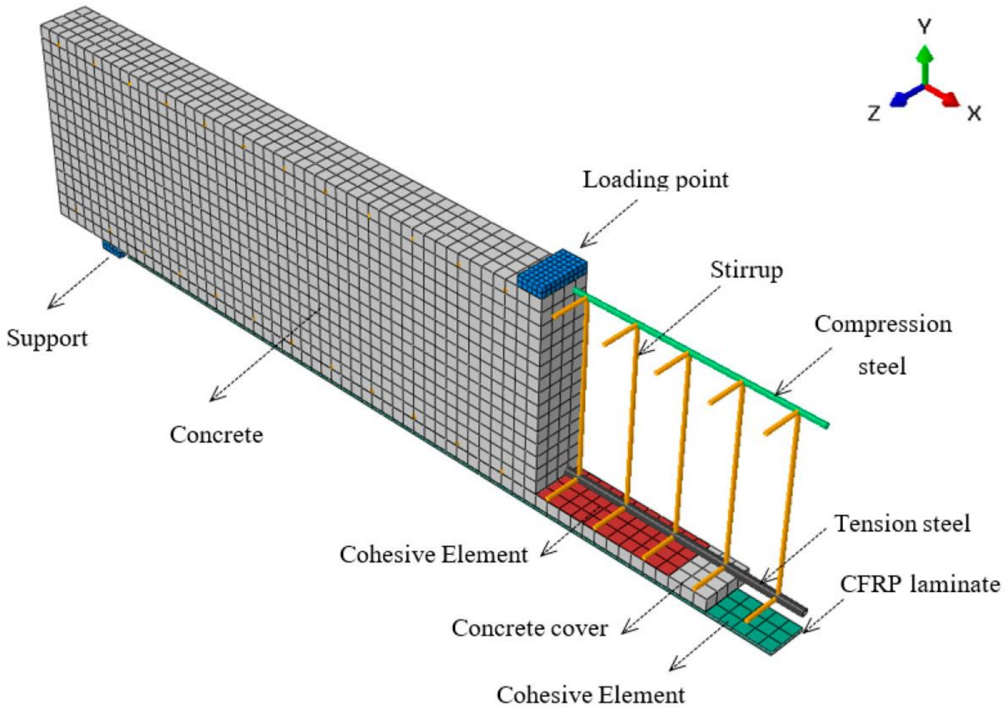


Figure 37 Geometry and elements used in the FE simulation. (image and caption are from Al-Saawani et al. 2022)

Key findings include accurate prediction of debonding failure modes and capacities, improved predictions by adjusting bond-slip model parameters, and confirmation of the effect of shear span-to-depth ratio on debonding failure type. The study also revealed that increasing stirrup spacing reduces load capacity, especially for concrete cover separation failure.

The developed model provides a valuable tool for simulating flexural behavior and predicting critical debonding failures in FRP-strengthened beams. It offers insights into the effects of various parameters on structural performance, potentially aiding in the optimization of strengthening systems. Future studies may expand the model to different FRP types, configurations, and loading conditions to further improve its applicability and accuracy.

Tree-View Summary

Objective: Develop the finite element model using ABAQUS software to simulate the two critical debonding failures in FRP-strengthened beams.

Methodology:

Model Development:

- Used 3D nonlinear FE model in ABAQUS
- Implemented concrete damaged plasticity model for concrete
- Used elastic perfectly plastic model for steel reinforcement
- Applied cohesive zone model for debonding interfaces

Material Properties:

- Concrete: CDP model parameters, compressive and tensile behavior
- Steel: Elastic modulus, Poisson's ratio, yield stress

- FRP: Linear elastic behavior, lamina properties

Debonding Failure Modeling:

- IC debonding: Cohesive elements at FRP-concrete interface
- CCS failure: Cohesive elements between tension steel and concrete cover

Model Calibration:

- Adjusted bond-slip model parameters (τmax, Gcr)
- Developed new equations for CCS failure interface properties

Validation:

- Compared with experimental results from 7 FRP-strengthened beams
- Analyzed load-deflection curves, CFRP strains, and crack patterns

Key Findings:

- FE model accurately predicted debonding failure modes and capacities
- Reducing τmax to 50% and increasing Gcr to 500 J/m2 improved predictions
- Shear span-to-depth ratio (av/ds) affects debonding failure mode
- Increasing stirrup spacing reduces capacity for CCS failure
- IC debonding location shifts with increased stirrup spacing

Conclusions:

- Developed FE model simulates flexural behavior and predicts critical debonding failures
- Model validated against experimental results for various av/ds ratios
- FE analysis confirmed effect of av/ds on debonding failure type
- Increasing stirrup spacing reduces load capacity, especially for CCS failure

Limitations and Future Work:

- Limited to specific beam geometries and loading conditions
- Further validation needed for different FRP types and configurations
- Investigate effect of other parameters (e.g., FRP thickness, concrete strength)

Significance: It represents the most complete FE model to predict debonding failures in FRP-strengthened beams and forms a very useful tool for designers and researchers to optimize the strengthening system for the most accurate predictions of structural performances.

.

3.5.4.5 Green Concrete and Other Composites

3.5.4.5.1 "Experimental Study and Finite Element Analysis on the Flexural Behavior of Steel Fiber Reinforced Recycled Aggregate Concrete Beams" (Guan et al. 2022)

Text Summary

This study investigates the flexural behavior of steel fiber reinforced recycled aggregate concrete (SFRAC) beams through experiments, finite element analysis (FEA), and analytical modeling. Nine beam specimens were tested under four-point bending, varying steel fiber content, recycled aggregate ratio, and concrete strength. 3D FEA models were developed using ABAQUS, employing the Concrete Damaged Plasticity model for concrete behavior (see Figure

38). A new approach was presented for analyzing the flexural capacity considering the influence of steel fibers and recycled aggregates.

Key findings show that SFRAC beams exhibit improved ductility and crack control compared to plain concrete. Flexural capacity increased with steel fiber content and concrete strength but decreased with higher recycled aggregate content. The FEA models and proposed analytical method demonstrated good agreement with experimental results.

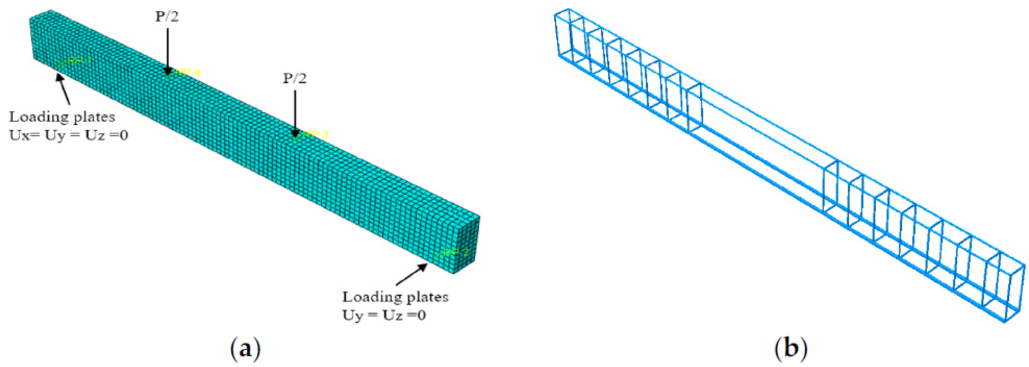


Figure 38 The FEA model. (a) Concrete and boundary consideration, (b) rebar cage. (image and caption are from Guan et al. 2022)

This research provides valuable insights for designing sustainable concrete structures using recycled materials. The developed models offer tools for engineers to predict and optimize SFRAC beam performance. Future work should address fatigue behavior and refine FE modeling techniques. The study follows relevant Chinese and international standards for concrete testing and design.

Tree-View Summary

Objective: To investigate the flexural behavior of steel fiber reinforced recycled aggregate concrete (SFRAC) beams through experimental testing, finite element analysis, and analytical modeling.

Methodology:

Experimental Testing:

- Nine SFRAC beam specimens tested
- Varied parameters: steel fiber volume fraction, recycled aggregate replacement ratio, concrete strength
- Four-point bending tests conducted
- Measured load-deflection, strain, crack development

Finite Element Analysis:

- 3D models created in ABAQUS
- Used solid elements for concrete, truss elements for reinforcement
- Applied Concrete Damaged Plasticity model
- Conducted mesh sensitivity analysis
- Validated against experimental results

Material Properties:

- Used constitutive models for SFRAC in compression and tension

- Adopted bilinear model for steel reinforcement

Analytical Modeling:

- Developed new calculation method for flexural capacity
- Based on stress-strain relationships and section equilibrium

Considered effects of steel fibers and recycled aggregates

Key Findings:

- SFRAC beams showed improved ductility and crack control compared to plain concrete
- Flexural capacity increased with steel fiber content and concrete strength
- Flexural capacity decreased with increasing recycled aggregate content
- FEA model predictions agreed well with experimental results
- Proposed analytical model showed good accuracy in predicting flexural capacity

Conclusions:

- Steel fibers enhance flexural performance of recycled aggregate concrete beams
- FEA can effectively predict SFRAC beam behavior
- Proposed analytical model provides accurate flexural capacity predictions

Limitations and Future Work:

- Only static loading considered; need to study fatigue behavior
- Limited number of test specimens
- Further refinement of FE modeling techniques needed

Significance: This study provides valuable insights into the structural behavior of SFRAC beams, offering design guidance for sustainable concrete structures using recycled materials. The developed analytical and numerical models can aid engineers in predicting and optimizing SFRAC beam performance.

3.5.4.5.2 "Microstructure-Free Finite Element Modeling for Elasticity Characterization and Design of Fine-Particulate Composites" (Luo 2022)

Text Summary

This study introduces a microstructure-free finite element modeling (MF-FEM) approach for characterizing and designing fine-particulate composites. The research demonstrates that for small inclusion-to-RVE size ratios, composite properties are independent of inclusion shape and size (see Figure 39). This finding allows for the development of a simplified modeling approach that eliminates the need for complex geometric representation of microstructures.

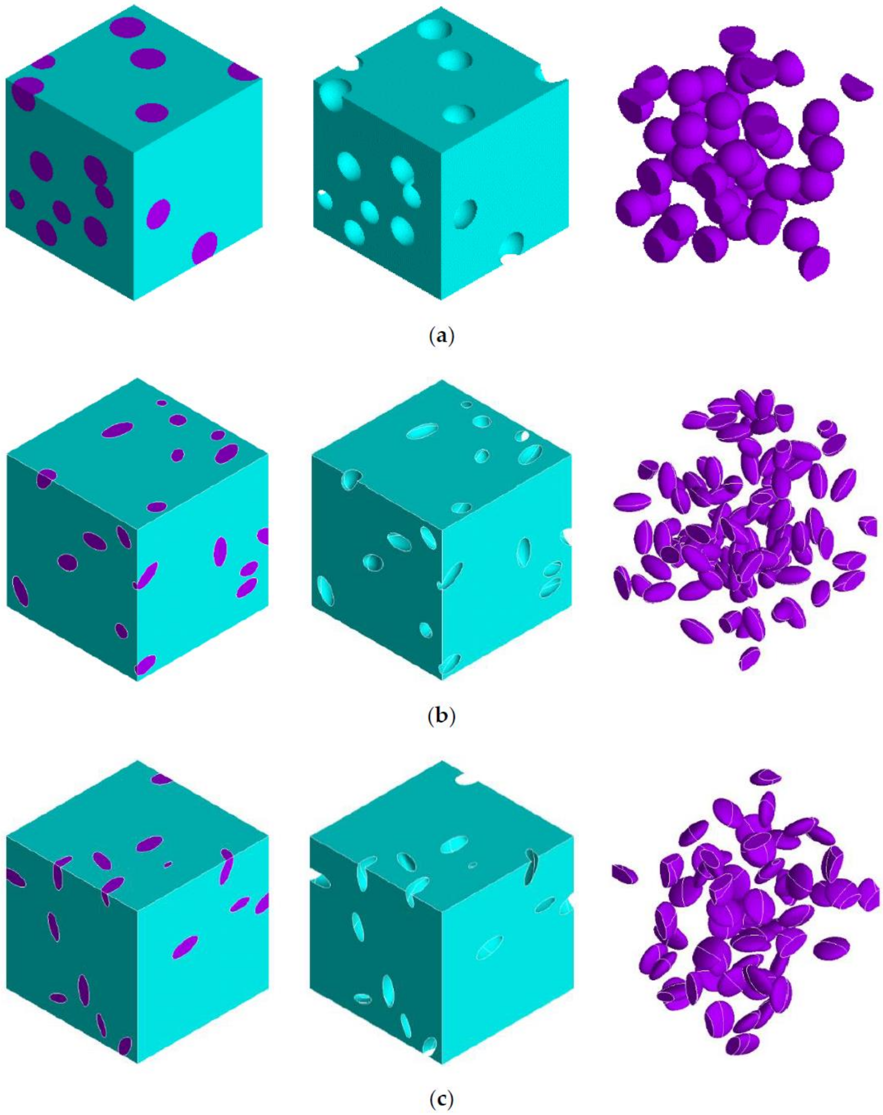


Figure 39 Composite RVEs with inclusions of different shapes: (a) spherical inclusions; (b) almondshapedinclusions (aspect ratio = 2); (c) pill-shaped inclusions (aspect ratio = 2). (image and caption are from Luo 2022)

The MF-FEM method uses uniform brick elements, randomly assigning some as inclusions based on the desired volume fraction. This approach significantly simplifies the modeling process, reduces computational complexity, and allows for easier modeling of high volume-fraction composites. The study validates the MF-FEM against experimental data and compares it with traditional microstructure-based FEM (MB-FEM) and popular micromechanics models.

Results show excellent agreement between MF-FEM and MB-FEM predictions, as well as good alignment with experimental data, especially for composites with similar phase properties. However, some deviations are observed for composites with high contrast in phase properties. The research concludes that MF-FEM can effectively replace MB-FEM for predicting macroscopic composite properties, offering a more efficient tool for material engineers in the design of novel composites. Future work should focus on further validation and exploring the method's applicability to other types of composites.

Tree-View Summary

Objective: To develop and validate a microstructure-free finite element modeling (MF-FEM) approach for characterizing and designing fine-particulate composites.

Methodology:

Model Development:

- Created cubic RVE models with varying inclusion shapes and sizes
- Developed MF-FEM approach using uniform brick elements
- Randomly assigned elements as inclusions based on desired volume fraction

Comparative Analysis:

- Compared MF-FEM results with traditional microstructure-based FEM (MB-FEM)
- Analyzed effect of inclusion-to-RVE size ratio on composite properties

Validation:

- Validated MF-FEM against experimental data for WC-cobalt alloy and glass-polyester composites
- Compared results with popular micromechanics models (e.g., Voigt-Reuss bounds, Hashin-Shtrikman bounds)

Property Calculation:

- Used mean-field homogenization theory to calculate composite properties
- Determined Young's modulus, shear modulus, and Poisson's ratio from average stresses and strains

Key Findings:

- Composite properties are independent of inclusion shape and size for small inclusion-to-RVE size ratios (< 0.04)
- MF-FEM predictions show excellent agreement with MB-FEM results
- MF-FEM predictions align well with experimental data, especially for composites with similar phase properties
- MF-FEM shows some deviation from experimental data for composites with high contrast in phase properties

Conclusions:

- MF-FEM can effectively replace MB-FEM for predicting macroscopic composite properties
- MF-FEM simplifies the modeling process and reduces computational complexity
- MF-FEM allows for easier modeling of high volume-fraction composites

Limitations and Future Work:

- MF-FEM cannot predict stress distribution in phase materials
- Further validation needed for composites with high contrast in phase properties
- Investigation of MF-FEM applicability to other types of composites

Significance: This study introduces a simplified yet effective approach for modeling particulate composites, potentially streamlining the design process for material engineers and opening new avenues for composite material development.

3.5.4.5.3 "Behavior of RC Beam Retrofitted Using Ultra High-Performance Concrete Under Impact Loads" (Al-Osta, 2019)

Text Summary

This study investigates the behavior of reinforced concrete (RC) beams retrofitted with Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) under impact loads using finite element modeling. The researchers developed a 3D finite element model using ABAQUS software, employing the Concrete Damage Plasticity Model for concrete materials and an elastic-perfectly plastic model for steel reinforcement (see Figure 40) The model was validated using experimental results from static load tests.

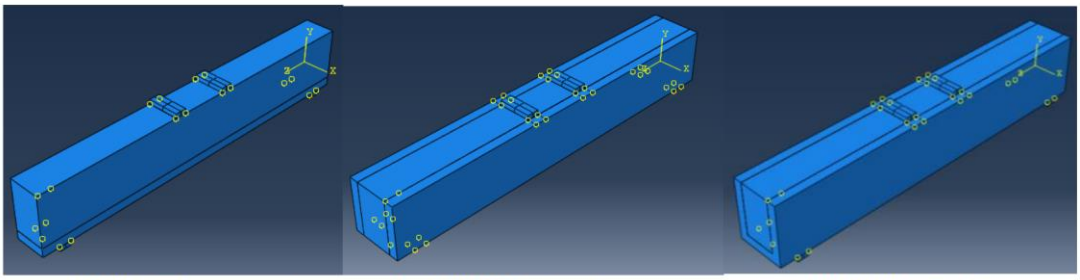


Figure 40 Geometry of models.(image and caption are from Al-Osta, 2019)

The study examined various UHPFRC strengthening configurations, including bottom-side, two-side, and three-side applications with different layer thicknesses. Impact loads were simulated by applying an equivalent initial velocity of 2500 mm/s to the beam mid-span.

Key findings reveal that UHPFRC strengthening effectively reduces mid-span deflections under impact loads, with three-side strengthening showing the highest reduction. A 20 mm bottom layer of UHPFRC decreased mid-span deflection by 15%, while three-side strengthening with 20 mm UHPFRC reduced it by 37%. The model also accurately predicted energy conservation during impact.

This research provides valuable insights into improving structural resilience against extreme loading conditions. However, limitations include the lack of experimental data for impact scenarios and the need for more complex material models. Future work should focus on investigating strain rate effects and exploring different impact velocities and loading conditions.

Tree-View Summary

Objective: To investigate the behavior of reinforced concrete (RC) beams retrofitted with Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) under impact loads using finite element modeling.

Methodology:

Model Development:

- 3D finite element model using ABAQUS software
- Validation using experimental results from static load tests

Material Modeling:

- Concrete Damage Plasticity Model (CDPM) for normal concrete and UHPFRC

- Elastic-perfectly plastic model for steel rebars and stirrups

Element Types:

- 3D eight-noded linear brick elements for concrete and UHPFRC
- 2-noded linear 3D truss elements for steel rebars and stirrups

Contact Modeling:

- Perfect bond between UHPFRC and normal concrete

Loading Conditions:

- Impact load applied as an equivalent initial velocity of 2500 mm/s

Parametric Study:

- Different thicknesses of UHPFRC layers
- Various strengthening configurations (bottom side, two-side, and three-side)

Key Findings:

- UHPFRC strengthening reduced mid-span deflections under impact loads.
- Three-side UHPFRC strengthening showed the highest reduction in mid-span deflection.
- Increasing UHPFRC layer thickness further decreased mid-span deflection.
- The model accurately predicted energy conservation during impact.

Conclusions:

- UHPFRC strengthening is effective in improving RC beam performance under impact loads.
- A 20 mm bottom layer of UHPFRC can reduce mid-span deflection by 15%.
- Three-side strengthening with 20 mm UHPFRC can reduce mid-span deflection by 37%.
- The FEM accurately predicts the behavior of UHPFRC-strengthened RC beams under impact loads.

Limitations and Future Work:

- Lack of experimental data for impact load scenarios
- Need for more complex material models to capture UHPFRC behavior accurately
- Investigation of strain rate effects on material properties
- Exploration of different impact velocities and loading conditions

Significance: This study provides valuable insights into the behavior of UHPFRC-strengthened RC beams under impact loads, which is crucial for improving the resilience of structures against extreme loading conditions. The developed FEM can be used as a tool for designing and optimizing UHPFRC strengthening systems for RC beams subject to impact loads.

3.5.4.5.4 "Finite Element Analysis on Structural Behaviour of Geopolymer Reinforced Concrete Beam Using Johnson-Cook Damage in ABAQUS" (Mortar et al. 2022)

Text Summary

This study investigates the structural behavior of geopolymer reinforced concrete beams under blast loading using finite element analysis (FEA) in ABAQUS (see Figure 41). The researchers conducted air blast explosion tests on geopolymer concrete beams and developed a corresponding FEA model using the Johnson-Cook Damage model and Concrete Damaged Plasticity model.

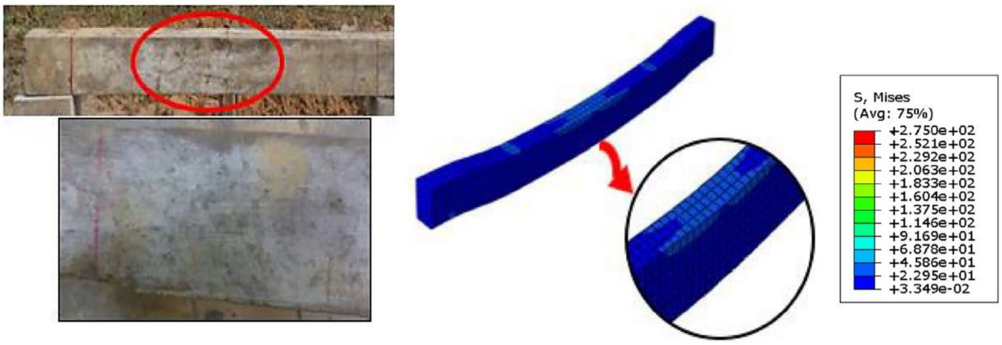


Figure 41 Deformation of GCRB 1 after blasting on experimental and simulation (image and caption are from Mortar et al. 2022)

The experimental setup involved 100mm x 100mm x 1100mm geopolymer concrete beams subjected to air blast explosions with varying standoff distances. The FEA model utilized C3D8R elements with reduced integration and implemented the Johnson-Cook Damage model to simulate blast effects.

Key findings reveal that decreasing the scaled distance from 0.298 to 0.149 kg/m³ increased the deformation percentage of the beams. Higher scaled distances resulted in more elastic behavior with internal cracking, while lower scaled distances led to compressive and tensile failures near the blast source. Shear cracks were attributed to impact and reflective waves.

The study concludes that the Johnson-Cook plasticity model effectively simulates blast damage on geopolymer materials. The research provides valuable insights into the behavior of geopolymer reinforced concrete under blast loading, contributing to the development of more resilient and sustainable construction materials for high-risk environments. Future work should focus on comparing geopolymer concrete's blast resistance to conventional concrete and exploring different reinforcement configurations for improved performance.

Tree-View Summary

Objective: To analyze the behavior of Si-Al geopolymer concrete beams reinforced with steel bars under impulsive loads and high-velocity impacts using finite element analysis.

Methodology:

Experimental Setup:

- Geopolymer concrete beams (100mm x 100mm x 1100mm)
- Air blast explosion tests with varying standoff distances
- Emulex explosive charge (0.30 kg)

Finite Element Model:

- ABAQUS software used for simulation
- Johnson-Cook Damage model implemented
- C3D8R elements with reduced integration

Material Properties:

- Geopolymer concrete: Concrete Damaged Plasticity model

- Steel reinforcement: Perfectly plastic-elastic model

Load Case:

- Air blast explosion simulated
- Varying scaled distances: 0.298, 0.224, and 0.149 kg/m³

Analysis:

- Explicit dynamic analysis
- Stress distribution and crack development studied

Key Findings:

- Decreasing scaled distance from 0.298 to 0.149 kg/m³ increased deformation percentage
- Higher scaled distances resulted in more elastic behavior with internal cracking
- Lower scaled distances led to compressive and tensile failures near the blast source
- Shear cracks attributed to impact and reflective waves

Conclusions:

- Johnson-Cook plasticity model effectively simulates blast damage on geopolymer materials
- Failure modes include compressive and tensile cracks, especially at lower scaled distances
- Analyzing structural behavior at different scaled distances helps determine damage levels and crack modes

Limitations and Future Work:

- Further investigation of geopolymer concrete's blast resistance compared to conventional concrete
- Exploration of different reinforcement configurations for improved blast resistance
- Study of long-term performance of geopolymer concrete after blast exposure

Significance: This study provides valuable insights into the behavior of geopolymer reinforced concrete under blast loading, contributing to the development of more resilient and sustainable construction materials for high-risk environments.

3.5.4.5.5 "Numerical Analysis Exterior RC Beam-Column Joints with CFRP Bars as Beam's Tensional Reinforcement under Cyclic Reversal Deformations" (Kytinou et al. 2022)

Text Summary

This study investigates the use of carbon fiber-reinforced polymer (CFRP) bars as longitudinal reinforcement in reinforced concrete (RC) beam-column joints under cyclic loading. The research combines experimental testing of full-scale specimens with finite element (FE) modeling using Abaqus software (see Figure 42). The FE model incorporates nonlinear material behavior, including the Concrete Damaged Plasticity model for concrete and a surface-based cohesive approach for CFRP-concrete bond behavior calibrated with pull-out test results.

The test results have shown that the derived FEM model efficiently predicted the load-carrying capacity, load-deflection behavior, modes of failure, and energy dissipation characteristic of CFRP-RC joints. Importantly, CFRP-RC joints exhibited improved energy dissipation compared with conventional steel-reinforced joints and retained substantial residual strength beyond the slippage of the CFRP bars. These test results tend to indicate that

CFRP bars could serve as an alternative for conventional steel reinforcement in earthquake-vulnerable RC structures. Complete understanding of the post-failure behavior of the CFRP-RC joints and development of appropriate design guidelines call for further research. This paper provides useful insight into the growing literature in concrete structure strengthening using CFRP and also presents an effective FE modeling methodology that can be utilized for studies performed in continuation of the subject area.

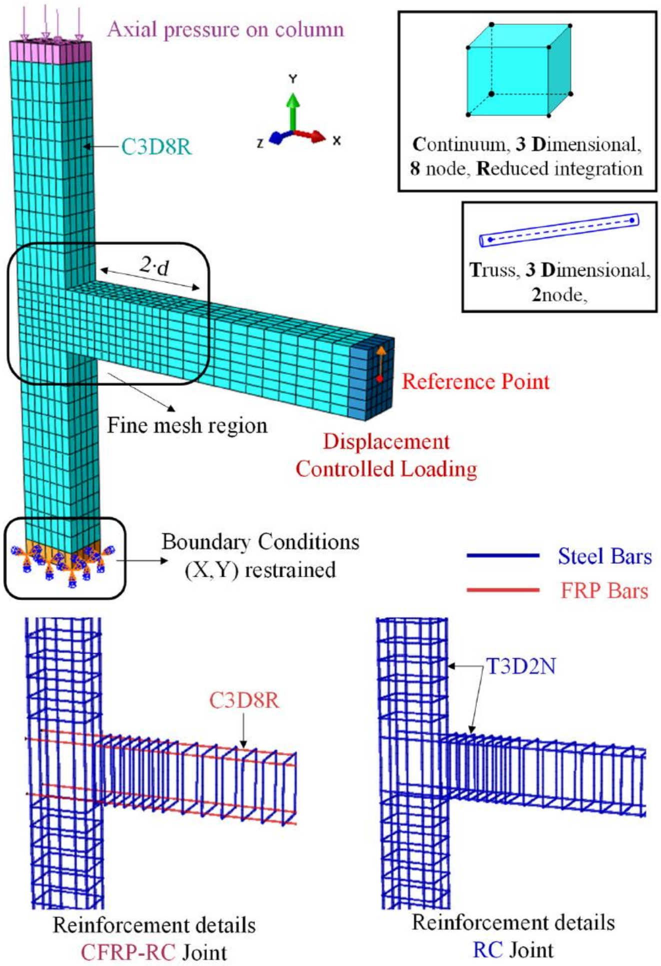


Figure 42 Details of the 3D FE simulation used to simulate the CFRP-RC and RC beam-column joints. (image and caption are from Kytinou et al. 2022)

Tree-View Summary

Objective: To investigate the cyclic lateral response of reinforced concrete (RC) beam-column joints with carbon fiber-reinforced polymer (CFRP) bars as longitudinal reinforcement in the beam using finite element (FE) modeling.

Methodology:

Experimental Testing:

- Two full-scale T-shaped beam-column RC joints
- Cyclic reversal loading with increasing imposed displacement
- Pull-out tests for CFRP bars

FE Model Development:

- 3D nonlinear FE model using Abaqus software
- 8-node linear brick elements for concrete and CFRP bars
- 2-node linear 3D truss elements for steel reinforcement

Material Properties:

- Concrete: Concrete Damaged Plasticity model
- Steel: Elastic-plastic with strain hardening
- CFRP: Linear elastic up to brittle failure

Bond-Slip Behavior:

- Surface-based cohesive behavior
- Traction-separation model calibrated with pull-out test results

Analysis:

- Cyclic loading applied to match experimental procedure
- Comparison of FE results with experimental data

Key Findings:

- FE model accurately predicted load-carrying capacity and load-deflection response
- Model successfully captured failure mechanisms, bond slip, and energy dissipation
- CFRP-RC joints exhibited residual strength >35% of flexural capacity after bar slippage
- CFRP-RC joints dissipated more energy than conventional steel-reinforced joints

Conclusions:

- FE model effectively predicts behavior of CFRP-RC joints under cyclic loading
- CFRP bars show potential for replacing conventional steel reinforcement in RC structures
- Post-failure behavior and hysteretic performance not significantly affected by CFRP bar slippage

Limitations and Future Work:

- Further investigation needed on post-failure mode and overall response of CFRP-RC joints
- Development of regulations and design specifications for wider application of CFRP bars

Significance: This study demonstrates the potential of CFRP bars as a replacement for conventional steel reinforcement in RC structures, particularly in seismic applications. The developed FE model provides a valuable tool for further research and design optimization of CFRP-RC joints.

3.5.4.6 Concluding Remarks

During the last couple of years, structural engineering has made significant advancements in terms of retrofit modeling and the development of new materials to further enhance the performance of concrete. The developments to be discussed within this report represent categories including Textile-Reinforced Mortar (TRM), Seismic Joints and Infill Strengthening, Fiber-Reinforced Polymer (FRP), and Green Concrete and Other Composites. These are representative of the most recent cutting-edge solutions focused on enhancing the durability, sustainability, and performance of new and existing constructions.

With infrastructural systems continuing their degradation and being faced with ever-growing challenges due to seismic activities and a host of other extreme loading conditions, the need for the development of effective strengthening methodologies became important. Besides, the current trend toward sustainable construction precipitated an investigation into different materials and techniques. This report integrates recent findings along these lines of research, focusing on finite element modeling strategies that will enable the accurate prediction and improvement of structural performance.

TRM is a rather sophisticated method for strengthening masonry and concrete using advanced composites. Several research papers by Gulinelli et al. (2020) and Cao et al. (2024) have shown evidence of effectiveness that TRM enhances flexural capacity and ductility. Accurate finite element models, specifically those with a focus on Concrete Damaged Plasticity, may enable better predictions of improved structural performance using TRM for different load conditions.

Seismic Joints and Infill Strengthening are two innovative techniques to enhance the performance of reinforced concrete frames against earthquakes. The research work done by Rousakis et al., 2021, and Akyildiz et al., 2021, on polyurethane flexible joints (PUFJ) and fiber-reinforced polyurethane (FRPU) jacketing, respectively, points out a very high ductility gain and energy dissipation enhancement. These studies underline the need for developing new advanced 3D finite element modeling capable of capturing complex structural interactions.

FRP is still in the mainstream of research, considering a number of practical tests were conducted by Karabinis et al. (2008) and Al-Saawani et al. (2022) on FRP strengthening of concrete beams and columns. The ongoing development of advanced models aimed at predicting debonding failures and the overall structural performances furthered the pace, in order to achieve efficiency with reliable structural design using FRP reinforcement.

Among the most innovative materials researched at the forefront of engineering sustainable construction is Green Concrete, among other composites. Works by Guan et al. (2022) and Luo (2022) reveal the consideration of such materials as steel fiber-reinforced recycled aggregate concrete and fine-particulate composite. Advanced materials provide both ecological advantages and some structural features that could be used for the improvement of performance.

The development and refinement of the finite element modeling techniques are under way in all these areas-from the microstructure-free modeling approach to complex 3-D simulations with the inclusion of damage models-allowing research and engineering to do the most valid predictions about the structural behavior and optimization of the designs.

Observations in this report witness major developments in retrofit modeling as well as for the use of new materials related to concrete structures. Techniques such as TRM, seismic joints, and infill strengthening, along with FRP and green concrete mixes, are practical options for the improvement of structural behavior under extreme loads. This is a general description and classification of retrofit models, given in Table 5.

Table 5 Classification of Recent Research in Retrofit Modeling and Innovative Materials for Concrete Structures

Element	Element Dimension	Material	Analysis
Textile-Reinforced Mortar (TRM)	Masonry Strengthening	Multiscale FEM, Cohesive Elements	Gulinelli et al. (2020)
	Concrete Beam Strengthening	3D Nonlinear FEM, CDP Model	Cao et al. (2024)
	Masonry Bond Behavior	Double Shear Tests, Bond-Slip Relation	D'Ambrisi et al. (2013)
	Seismic and Energy Retrofitting	Macro-modeling, Shell Elements	Karlos et al. (2020)
Seismic Joints and Infill Strengthening	Flexible Joints	PUFJ, FRPU, 3D Explicit Dynamics	Rousakis et al. (2021)
	Infill Wall Protection	PUFJ, Mooney-Rivlin Model	Akyildiz et al. (2021)
	Dynamic Modeling of RC Frames	RHT Damage Model, PUFJ, FRPU	Vanian et al. (2024)
	Damage Reduction System	INODIS, Micromodeling	Butenweg & Marinković (2018)
	Cellular Material Isolation	Single-Strut Elements, Nonlinear Springs	Tsantilis & Triantafillou (2018)
Fiber-Reinforced Polymer (FRP)	Column Strengthening	3D FEM, Drucker-Prager Model	Karabinis et al. (2008)
	Beam Strengthening	Cohesive Zone Model, CDP Model	Al-Saawani et al. (2022)
	FRP-Confined Concrete	Strain-Hardening Drucker-Prager Model	Rousakis et al. (2008)
	Pseudodynamic Analysis	RHT Model	Fanaradelli & Rousakis (2020)
	Thin RC Slab Strengthening	3D Nonlinear FEM, Cohesive Elements	Assad et al. (2022)
	FRP Modeling Strategies Review	Various FEM Techniques	Naser et al. (2021)
Green Concrete and Other Composites	Recycled Aggregate Concrete	Steel Fiber Reinforcement, CDP Model	Guan et al. (2022)
	Fine-Particulate Composites	Microstructure-Free FEM	Luo (2022)
	Geopolymer Concrete	Johnson-Cook Damage Model	Mortar et al. (2022)
	Ultra High-Performance Concrete	CDP Model, Explicit Dynamic Analysis	Al-Osta (2019)
	CFRP Bar Reinforcement	CDP Model, Surface-Based Cohesive Approach	Kytinou et al. (2022)

On the other hand, the development of finite element modeling methodologies has allowed much more realistic prediction of complex structural response and interaction. Such models become indispensable tools for the improvement of design and investigation of effectiveness for various strengthening procedures. While most of the challenges remain, especially regarding long-term performance and standardization of new materials and processes, the tendency of research here is encouraging. Future studies should aim more at bridging the gap between laboratory studies and practice, developing all-rounded design guidelines, and pushing the modeling effort toward a wider coverage of load conditions and material behaviors. Advanced materials and modeling methodologies will be significant in setting the future directions of structural engineering as the construction industry continues to move toward being more resilient and sustainable.

3.6 ENERGY RENOVATION (ER) MODELS FOR VF BUILDINGS

3.6.1 Literature Review

3.6.1.1 "A review of the pricing mechanisms for district heating systems" (Li et al., 2015)

The present paper tries to give the general analysis of pricing approaches applicable to district heating (DH) systems. The authors review different pricing methods and models, including their merits and deficiencies, so as to provide perspectives of improvements of pricing mechanisms for DH systems. The paper underlines the role and importance of district heating at the very beginning of reducing CO2 emission and energy consumption in the heat industry. It further elaborates on the monopolistic features of the DH systems along with the respective price elasticity as critical bases for price determination. To this effect, the authors categorize the price components of district heating into three broad groups, namely, connection fee, standing cost, and unit cost. There is an explanation of how these components feed into the overall price mechanisms associated with the DH systems. The research explores pricing strategies in regulated and deregulated markets, focusing on the different methods and the multifarious influences in the different cases on the pricing approach. For regulated markets, attention is focused on cost-plus pricing techniques, while for the deregulated markets, the use of marginal cost pricing methods is more foreseeable. A significant segment of the paper is dedicated to discussing influences of the marginal-cost pricing method. These include, among others, fuel cost impact, allocation of joint costs from the combined heat and power (CHP) plant, and difference between the short-run and long-run marginal cost. The paper describes a number of techniques for cost allocation to the CHP products: first, any technique which may be employed to determine a basic value for electricity; second, a proportional allocation based on quantities produced of heat and electricity; third, the efficiency-based allocation; and fourth, exergetic allocation. It also addresses other cost concepts and DH pricing-related problems: the incremental cost method, the integrated models of competitive and regulated methods, external costs, shadow price method, smart metering-based real-time pricing, and finally the risks associated with DH pricing. Generally, this review underlines throughout its course that the need for fair and competitive pricing mechanisms is justified by the requirements for reaching the sustainable development of DH systems. They also point out difficulties in elaborating such mechanisms, as DH systems are too complicated and costs and prices depend on so many factors. This study concludes with an overview of some of the existing mechanisms of pricing for district heating systems and thus helps present valuable insights for researchers, policymakers, and professionals who are jointly striving to develop efficient and sustainable DH pricing strategies.

3.6.1.2 "The case for repeatable analysis with energy economy optimization models (DeCarolis et al., 2012)

This research study investigates the need for transparency and reproducibility within energy economy optimization (EEO) modeling, which has recently become an essential tool for analyzing prospective energy systems and will continue to help guide policy-making. The authors discuss how, with growing complexity and influence, this model class still does not get sufficient attention as far as ways to ensure transparent development and usage processes are concerned. The manuscript underlines the following important issues: It involves a number of simplifications and subjective judgments which are usually not very well reflected in results or documentation being published. The intrinsic longevity of such models renders any kind of validation against real-world outcomes practically impossible. Those source codes and data of most EEO models are not publicly available, hence limiting the independent verification of published results by any third party. The complexity of these models suggests that hidden presumptions, coding mistakes, or sensitive parameters could greatly affect the results, and perhaps not be picked up by outside observers.

They conducted a literature review for twelve EEO models and found out that for most of them, reproduction of the model results is impossible today. The authors say that this is a problem because such models form an integral part of energy and environmental policy decisions.

A software framework is, therefore, proposed in this manuscript to allow consistent model analysis of these. Suggestions that were included in the analysis are:

- Be findable by publishing the code and data openly
- Allow third-party running of certain model instances to reproduce published results

The authors insist that transparency in the modeling process is imperative; such is the avenue where, in fact, insights emanating from models could be trusted, thereby raising the quality of energy system analyses.

3.6.1.3 "Modelling energy systems for developing countries" (Urban et al., 2007)

This article, therefore, assesses how well contemporary energy models represent the main characteristics of the energy systems and economies of developing countries. The authors argue that most energy models are biased towards the industrialized nations and, as such, fail to represent the essential features indicative of developing countries. According to them, some key characteristics peculiar to developing nations that should be captured in the energy model include:

- Poor performance of the power sector and shortage of supply
- Low electrification rates along with high uses of traditional biomasses.
- Urban-rural disparities in energy access and utilization Large informal economies and non-monetary transactions ·
- Rapidly changing economic structure
- Insufficient investment choices and improper utilization of subsidies

In this context, the key characteristics identified here have been compared for 12 widely used energy models through a comparative analysis. Review of the models is done by documentation, model runs, and a questionnaire to the model developers. The results are that features such as electrification and traditional biomass use are built into most models, while other features that make developing countries different, such as supply shortages, informal economies, and structural changes in economies, are seldom captured. Bottom-up and hybrid models captured more developing country characteristics than top-down models. According to the authors, no model so far captures all the key features of the energy systems of developing countries. This, according to them, may bring about unrealistic or distorted results from modeling future energy scenarios for developing countries. They suggest that to enhance energy modeling in developing countries:

- Developing new models or reworking existing ones to better incorporate the identified characteristics.
- Employing bottom-up or hybrid approaches instead of top-down models.
- Stress attributes for which accurate data exists: for instance, electrification rates and efficiency in the power sector.

The paper emphasizes that energy models relevant to the particular conditions of developing countries are required, offering more accurate predictions of their future energy scenarios and related environmental impacts. In fact, such models would help in better energy planning and policy formulation for such countries.

3.6.1.4 "Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050" (Fragkos et al., 2017)

This paper aims at investigating the consequences of the European Union's (EU) Intended Nationally Determined Contribution (INDC) in concert with the long-run decarbonization targets for 2050 on the energy system and related policy implications. The present analysis is based on a dual modeling approach that combines the energy system model PRIMES with the computable general equilibrium model GEM-E3 in order to develop simulations for a Reference Scenario as well as a DECARB scenario compatible with the EU's INDC and the broader climate policy objectives. Analysis from various studies consistently indicates that the EU's INDC target of at least a 40% reduction of its greenhouse gas (GHG) emissions below the 1990 level in 2030, and up to 80% by 2050, is achievable with relatively limited macro-economic impacts. The result would be a 0.4% GDP loss in 2030 and 1% in 2050, relative to the Reference scenario, with small, positive effects on employment due to revenue recycling from carbon pricing. The present study reveals the main elements of how the EU climate targets could be reached, including energy efficiency improvement, an increased renewable energy presence, fuel switching to natural gas, and technical progress in abatement. Coupled with decarbonised supply of electricity, electrification of end-use energy demand, particularly in transport, appears to be a vital element of the low carbon economy in 2050. The paper identifies critical structural shifts that will happen within the energy system in the EU: energy efficiency investments, electrification of transport, and large-scale deployment of renewable sources of energy in power, residential, and industrial sectors. These changes will contribute positively to the balance of the EU's fossil fuel trade and its energy import bill. The paper subsequently discusses some of the policy challenges for the implementation of the EU INDC and long-term decarbonization goals: the appropriate policy framework shall be designed and implemented to overcome market and non-market barriers to energy efficiency and saving; coordination challenges linked to technology development, infrastructure, and changes in consumer behavior, such as in transport. This study, in brief, provides an in-depth review of the technical feasibility, economic impacts, and the policy implications of the EU's climate goals and therefore offers useful insights to policy-makers on potential pathways and challenges facing the transition towards a low-carbon economy.

3.6.1.5 "The importance of open data and software: Is energy research lagging behind?" (Pfenninger et al., 2017)

This opinion paper reflects on the current state of open data and software in energy research, which-in contrast to other scientific disciplines-lacks openness and transparency. The authors make the case that energy models and their data-often forming the basis for major policy decisions-must be openly available to increase scientific quality and productivity and to develop a better science-policy interface. The study identifies a number of key arguments for why energy models and data should be open, including: improved scientific quality through transparency and peer review; more effective collaboration across the science-policy boundary; productivity gains through collaborative burden sharing; and the ethical argument that publicly funded research should be publicly available. However, the authors consider valid reasons-ethical and security concerns, risks of undesirable exposures, additional burdens, and institutional inertia-in practice preventing data and code from being open by default. Today's degree of openness in energy research is put into context with respect to other fields, suggesting that compared to efforts under way to improve transparency, energy research appears to be behind even other applied sciences like climate science and public health. The authors further note that there are many examples of progress in energy research, ranging from governmental openness initiatives down to opensource academic frameworks; nevertheless, the lion's share of peer-reviewed energy research is still not issuing code or data publicly. Following such challenges, recommendations are given at both the level of the individual researcher and for the wider energy research community. The authors encourage individual consideration of the relevant audience while defining the scope and type of information that is shared freely, choosing appropriate licenses and distribution channels. For the community as a whole, they challenge that there be a reduced duplication of effort and overlap of labour, while successful integration of efforts from top-down and grassroots approaches promotes and incentivizes open research methods at the level of academia and institutions. The study concludes by underlining the fact that energy research-which is heavily influential in determining policies related to global climate mitigation strategies and their economic outcomes-must achieve better levels of transparency. The authors claim that open code and data should be seen as initial steps in the radical rethinking of how research is carried out and how policymakers are engaged with models and their underpinning assumptions.

3.6.1.6 "A review of computer tools for analysing the integration of renewable energy into various energy systems" (Connolly et al., 2010)

The following article offers a critical review of the publicly available computational tools applied for the assessment of integrated renewable energy resources into various energy systems. Out of 68 instruments reviewed, 37 were selected for the study. It was performed in collaboration with tool developers or recommended contacts to ensure the accuracy and relevance of the data. The review primarily seeks to give policymakers an overview for choosing appropriate energy tools that will be helpful in evaluating the integration of renewable energy into various objectives and scenarios. As observed by the authors, there is no single "ideal" energy tool generally appropriate for all issues that may be relevant in general to renewable energy integration. Instead, one selects the best-suited tool as a function of the objectives specified at the analysis design stage.

The study examines various factors that influence the selection of an energy tool, including:

- Applications: from single building systems to national energy systems
- Energy sectors considered
- Technologies accounted for
- Time parameters used
- Tools' availability
- Previous studies carried out using the tool

The review includes detailed discussions on the functionalities, limits, and common usages for all 37 reviewed tools. This extensive review enables the readers to understand how different tools match up with their own specific needs. The authors have presented the findings by dividing the work, section-wise, dedicating each section to one tool and explaining the features, applications, and other related information about the respective tool. This makes referencing and comparing the different tools fairly effortless. This paper serves as a valuable resource that would guide researchers, policy analysts, and energy experts in integrating renewable energy into the various energy systems. By giving a broad overview of available tools and their respective functionalities, the study helps make informed decisions on the choice of an appropriate tool for any given analysis with regard to the integration of renewable energy.

3.6.1.7 "Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security" (Pfenninger & Keirstead, 2015)

This research explores future scenarios for Britain's power sector in order to compare various mixes of renewables, nuclear, and fossil fuels - with and without carbon capture and storage. In particular, it tries to assess those scenarios by looking at what they would mean in terms of three key metrics: cost, emissions reduction, and energy security.

In this paper, the researchers address two key questions using a high-resolution modeling framework:

- How do different combinations of technologies compare in terms of cost, emissions reductions, and energy security?
- How is the overall system cost affected by cost and availability of grid-scale storage, and what technology combinations does that favor or penalize?

These results show that, out of this very large set of combinations, all costs are relatively close in value, which means that almost all these combinations are technically and economically feasible. However, economically optimal alternatives may not be the best regarding emissions reductions and energy security.

The study finds that when dispatchable generation is in short supply, grid-scale storage dramatically affects the economics-where storage capacity is at low cost, total levelized electricity cost can be as much as 50% lower with the availability of storage.

The research done for Great Britain indicates that domestic wind and solar PV generation can be reliably included at low to medium renewable shares, since the levelized cost increases by more than 10% above the mean of 0.084 GBP/kWh only for the shares ranging between 50% and 70%, and the latter stands at about 35% higher. On the other hand, achieving over 80% renewable generation shares would be economically viable only with large-scale storage, much more power imports, or domestically dispatchable renewables such as tidal range.

This research contributes to the ongoing discussion about decarbonization of the power sector, all within the context of global warming. This does provide significant insight into some of the important trade-offs considered under various technology combinations and energy storage in future power systems. Results will also help policymakers and stakeholders decide about the future of Great Britain's power system owing to the complex interlinkages amongst costs, emission reduction, and energy security.

3.6.1.8 "A review of energy systems models in the UK: Prevalent usage and categorisation" (Hall and Buckley, 2016)

This article systematically reviews relevant academic journals and policy-related documents from 2008 onward to identify dominant energy system modeling approaches and tools used within the United Kingdom (UK). With a view to enhancing the accessibility and understandability of the model landscape, the paper outlines a proposed classification schema toward assessment of the existing models. A preliminary broad literature screening is made based on the sectors covered, technologies included, and mathematical structures applied in the models. The authors have made an inventory of all models mentioned, and a total of roughly 100 models are identified in the scientific literature. In order to relate the full richness and variety inherent in energy system models, the paper suggests a new classification schema. The latter includes three main categories:

- Model purpose and structure
- Technological detail ·
- Mathematical approach

According to the authors, the presented schema, though far from complete, still reflects a wide categorical framework that is informative enough to effectively discriminate between various models. The suggested schema is supposed to contribute to model diversity by making models more accessible to scholars and policy analysts. As a practical application of the suggested categorization, the model universe in the UK is discussed. The indicative selection by the researchers involves 22 models, which they have classified, using the proposed schema, and presented through three tables corresponding to the respective schema sections. Energy system modeling is also emphasized in this review research as highly relevant to the challenge of supplying and demanding energy in a sustainable manner regarding climate change and growing global energy demand. The authors underline that such models are fundamental for describing complex decision-making processes and for testing possible future pathways of energy systems. This work considerably enriches the discipline since it provides a structured framework for classifying and comparing the models of energy systems, thereby offering improvements in the comprehension and usability of these tools. Hence, the proposed classification schema should provide a common basis upon which researchers and policy analysts can evaluate and select appropriate models meeting their respective needs, hopefully leading to better energy policy design and implementation both in the UK and beyond.

3.6.1.9 "Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050" (Lund & Mathiesen, 2009)

The following paper carries out a comprehensive energy system analysis concerning the transition of Denmark toward a 100% renewable energy system. The underlying basis for this paper is the outcome of a project of the Danish Association of Engineers, where 1600 participants took part in more than 40 seminars discussing and designing a model for the future energy system of Denmark.

A multi-disciplinary energy system analysis methodology has been used, wherein comprehensive hour-by-hour computer simulations have been employed to design flexible energy systems that meet electricity supply and demand. The target years are set at two levels, where the first year is 2050 at 100% renewable energy from biomass and combinations of wind, wave, and solar power, and the second year is 2030 at 50% renewable energy.

In the 2050-scenario framework, the paper provides a thorough system design and energy balance of a completely renewable energy supply based on domestic resources. According to the authors, this sort of system is feasible, in principle. The 2030-scenario, however, describes the first prerequisites toward the 2050 goal, that may become feasible within the Danish social context.

The study emphasizes two primary avenues through which Denmark can realize its objectives related to renewable energy:

- The approach is heavily dependent on biomass resources; its large-scale use requires changes to existing agricultural land use.
- Primarily focusing on wind energy, which would be obliged to use a significant percentage of hydrogen or similar energy vectors, bringing about related inefficiencies in the system architecture.

The paper highlights the three major technological shifts linked with moving to 100 percent renewable energy:

- Saving energy on the demand side
- Efficiency gain on energy production
- Substitution of fossil fuels by various sources of renewable energy

They also emphasize that these renewables must be integrated within holistic energy systems, which are impacted by energy efficiency and conservation measures. The present study contributes to the fast-growing literature on renewable energy deployment and provides very important lessons for one and all, be they policymakers or energy strategists. Showing the feasibility of a 100% renewable energy system in Denmark thus points to a probable way forward for other countries that may want to reduce dependence on fossil fuel resources and, consequently, engage in the fight against climate change.

3.6.1.10 "Comparing recent views of public attitude on wind energy, photovoltaic and small hydro applications" (Kaldellis et al., 2013)

This paper assesses the public acceptability of existing and new renewable energy projects in one region of Southern Greece. The authors state that the particular research was conducted in the area with exceptionally poor air quality because of the long-operating lignite-based thermal power station. The data collection was performed by a postal, three-part survey based on a representative sample of residents. The results showed the high level of acceptability of the existing and new projects of all three technologies under survey: for photovoltaic (PV) applications, the highest rate of acceptance was found with about 85% of the subjects surveyed in favor of new projects, while in ranking, wind and hydro energy applications came in high at about 80% or so. Results showed that residents of the host community aware of the existing renewable energy installations in their locality accepted most of the major environmental impacts of these technologies, which are visual disturbance, noise, and land use. It implies that prior experience with renewable energy systems could heighten the level of tolerance towards their possible negative impacts. On the other hand, however, the survey had also profiled a minority of those who opposed the renewable energy installations. These subjects either did not recognize the environmental, social, and financial benefits of renewable energy or valued their reasons for being against renewable energy more than any benefits. The study is invaluable since it gives insights into how the general public in a region already impacted by conventional energy production perceives renewable energy. It also shows the potential for large-scale public support for renewable energy projects to exist even in regions that had prior experience with energy generation. The results of the study would help policy planners and energy developers to plan further installations of renewable energy and develop strategies to combat public concern.

3.6.1.11 "Modeling of end-use energy consumption in the residential sector: A review of modeling techniques" (Swan & Ugursal, 2009)

This paper presents a critical review of different modeling methodologies applied to the projection of energy consumption in the residential sector. The authors realize that with increasing interest in the reduction of energy consumption and the related greenhouse gas emission in all sectors of the economy, there is a strong rationale for studies to target the residential sector due to its high consumption of energy. The study identifies two key approaches to modeling residential energy consumption: top-down and bottom-up. The top-down methodology represents the residential sector as an energy sink, using historical comprehensive energy data to study energy use as a function of driving variables such as macroeconomic indicators, energy price, and weather conditions in general. In the bottom-up approach, projected energy use calculated for a representative sample of individual dwellings is scaled up to regional and national levels. It is further divided into two different methods: statistical methods and engineering methods. The authors have provided a wide-ranging review of each modeling technique concerning strengths, weaknesses, and purpose to be achieved. Furthermore, they consider available input data amount, the required computation or simulation methods, and the value of output obtained from each of the methods. The paper includes a review of most of the models reported in literature, hence offering readers a wide overview of state of the art in residential energy consumption modeling are reviewed. Accordingly, this paper tries to contribute to the debate by providing a state-of-the-art review to help researchers, policy analysts, and energy analysts understand the different instruments available to assess the techno-economic impact of the adoption of energy efficiency and renewable energy technologies in the residential sectors. Such understanding is of primary importance if effective action plans aimed at reducing energy uses and lowering associated greenhouse gas emissions from this sector-a significant component of the overall energy curtailment activities in many countries-are to be developed. The structure of the paper is logical: from the introductory and stated objectives, it goes to a deep overview of the methodologies, and then discusses in detail the two major models, namely top-down and bottom-up. This structure allows the reader to capture the big picture first and zooms in on each of the modeling approaches in such a way as to make this complex subject more graspable for a wide range of scholars and professionals working in energy modeling and policy.

3.6.1.12 "Energy models for demand forecasting—A review" (Suganthi & Samuel, 2012)

Energy Demand Management: This research manuscript reviews some of the different models applied in energy demand management to forecast energy demand. The authors have identified the role of energy in actualizing sustainable development at the social, economic, and ecological levels. They indicate the rapid increase in energy consumption at a global level during the last ten years and identify that adequate energy management is required to ensure economic prosperity and environmental security in the future. The paper reviews a wide range of methodologies applied in electric load forecasting, starting from classical techniques up to the application of more modern soft computing techniques. It includes conventional methods: time series analysis, regression, econometric, decomposition, unit root test, co-integration, and ARIMA (Autoregressive Integrated Moving Average) models. Conventionally, these have been the traditional approaches that have been used in the forecasting of electricity demand from historical data and economic indicators. The authors then go ahead to review some current soft computing methods that are gaining wide acceptance in current energy demand forecasting studies. These include ANN (Artificial Neural Networks), fuzzy logic, genetic algorithms, and expert systems. This paper has emphasized the potentiality of all the mentioned methods in handling the complex and nonlinear relationship in energy demand data. Newer models reviewed include support vector regression, ant colony optimization, and particle swarm optimization. The above methods are being adopted gradually because they may raise forecast accuracy as well as handle large data sets efficiently. This research further considers the bottom-up models comprising MARKAL (Market Allocation), TIMES (The Integrated MARKAL-EFOM System), and LEAP (Long-range Energy Alternatives Planning) that are applicable at a national and regional level and are thus useful for integrated energy demand management. In presenting the materials, the authors comment on the strengths and actual applications of each of the forecast methods. The authors have highlighted that accurate energy demand forecasting is crucially related to the proper allocation of resources and efficient management on the demand side. In summary, this study provides an overview of the different energy demand forecasting models available to the researcher, policymaker, and energy planner. This represents the combination of both classic and new approaches toward an in-depth reference regarding state-of-the-art energy demand forecasting and its essential role within sustainable energy governance.

3.6.1.13 "Energy systems modeling for twenty-first century energy challenges" (Pfenninger et al., 2014)

The manuscript discusses the status and future challenges of energy systems modelling research with regard to models that are relevant for national and international energy policy decision-making processes. Based on these criteria, the authors categorize energy systems models into four main classes: energy systems optimization models, energy systems simulation models, power systems and electricity market models, and qualitative and mixed-methods scenario analysis.

- The research investigates four primary challenges encountered by these models and examines initiatives aimed at addressing these issues:

- The manuscript places great emphasis on how models must increasingly reflect both temporal and spatial dimensions, with increasing complexity in energy systems and the addition of intermittent renewable energy sources.

- It calls for a proper balance between the uncertainties of model inputs and assumptions on one hand, and the requirements of transparency in the modelling process on the other.

- It tends to explore the challenges associated with modeling energy systems that face a continuous rise in their complexity, in a sort of integral variety of energy sources, technologies, and market structures.

- Integration of human behavior in addition to social risks and opportunities: This paper shows how the integration of human behavior and social consideration aspects in energy system models may lead to higher accuracy and better applicability.

The authors have consequently reviewed recent new approaches aiming at surmounting these challenges: high-resolution modeling methodologies, improved techniques for handling uncertainty and reproducibility, sophisticated optimization algorithms, and incorporation of behavioral and social dimensions in models. They also apply a case study of state-of-the-art energy systems modeling in the United Kingdom (UK) to illustrate these concepts. The paper concludes with a discussion on the future directions of energy systems modeling and recommendations that are to be made with regard to ensuring it serves its relevance for policymaking. They emphasize the importance of interdisciplinarity, opensource modeling, and elaboration of more flexible and adaptable modeling frameworks to meet the challenges of the twenty-first-century energy system. The current work decisively contributes to energy system modeling research with its wide review of paradigms, identification of key challenges, and ways these might be met for more effective and relevant model applications in energy policy planning.

3.6.1.14 "Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union" (Connolly et al., 2016)

The paper tries to put forward and discuss one such scenario for European Union (EU) transition towards a 100% renewable energy system by 2050. The study here, for that purpose, constructs a step-by-step transition from a Business As Usual (BAU) Scenario toward a Fully Renewable Energy System Scenario by altering main technology steps. According to the SMART ENERGY SYSTEM approach, the research will evaluate the technical feasibility and economic consequence of this transition. They also model the impacts at each step on primary energy supply, carbon dioxide emission, and total annual socio-economic expenditure. Beyond this, the study investigates the potential job creation in light of shifting to alternative renewable sources of energy. The sequence of transition steps is ordered based on their different levels of scientific and policy certainty, from nuclear energy phase-out, via heat savings, electrification of private transport, and substitution of natural gas by methane to the most relevant linkage at the end-use sector level: electricity, heating, cooling, and transportation. It also emphasizes that linking the sectors of electricity, heating, cooling, and transportation opens up possibilities for added overall flexibility at energy system level. Results from this study show that, from a technical point of view, it is feasible to have 100% renewable energy in Europe, with no evidence of using bioenergy in unsustainable amounts. This it does through sector coupling, which allows for more than 80% intermittent renewable penetration in the power sector. The economic analysis shows that the Smart Energy Europe scenario will require costs of about 10-15% higher in comparison to the business-as-usual scenario. However, the researchers point out that this type of investment in regional renewable energy infrastructure would actually create some 10 million more direct employment positions inside the European Union itself, as these would depend on local investment and not imported fuels. The report provides an in-depth review of the technical and economic issues connected with a shift to an altogether renewable energy structure in Europe. It also critically reflects on the challenges and opportunities of such a transition and further enhances the current debate on sustainable energy futures and climate change mitigation strategies.

3.6.1.15 "Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems" (Heard et al., 2017)

This study conducts a comprehensive review of research proposing 100% renewable electricity systems to evaluate their technical feasibility. The authors examined 24 published studies that forecast regional, national or global energy requirements in sufficient detail to be considered potentially credible. They assessed these studies against four novel feasibility criteria deemed necessary for reliable electricity systems:

- Consistency with mainstream energy-demand forecasts

- Simulating supply to meet demand reliably at hourly, half-hourly, and five-minute timescales, with resilience to extreme climate events
- Identifying necessary transmission and distribution requirements
- Maintaining the provision of essential ancillary services

The review found that none of the 24 studies provided convincing evidence that these basic feasibility criteria can be met. The highest score achieved by any single study was 4 out of a possible 7 points. Key issues identified included unrealistic assumptions about energy demand reductions, inadequate simulation of supply-demand matching, lack of transmission network analysis, and failure to address how critical ancillary services would be maintained. The authors argue that many proposed 100% renewable systems rely heavily on unsustainable levels of biomass and hydroelectric power. They express concern that pursuing such systems could negatively impact land use, biodiversity, and social justice for indigenous peoples. The paper concludes that efforts to date have substantially underestimated the challenge of transitioning to 100% renewable electricity systems. It suggests that excluding other low-carbon technologies like nuclear power from consideration is premature and potentially counterproductive for effective climate change mitigation. The study recommends that policymakers and researchers should seek optimized blends of all available low-carbon technologies to pursue clean electricity systems that are scalable to meet growing global energy demands while rapidly reducing greenhouse gas emissions. The authors argue this approach offers the highest certainty and lowest risk for addressing climate change urgently while safeguarding human development outcomes.

3.6.1.16 "A review of modelling tools for energy and electricity systems with large shares of variable renewables" (Ringkjøb et al., 2018)

This paper presents a comprehensive review of 75 energy and electricity system modeling tools, with a focus on their capabilities for analyzing systems with high shares of variable renewable energy sources (VRES). The authors aim to provide an updated overview of currently available modeling tools and their features to assist modelers in selecting appropriate models for their needs.

The review categorizes the models based on their general logic (purpose, approach, methodology), spatiotemporal resolution, and technological and economic parameters. The authors compiled detailed information on each model's capabilities, including conventional and renewable generation modeling, energy storage, grid representation, demand sectors, market modeling, and emissions. This information was validated by model developers or affiliated contact persons to ensure accuracy.

The study found that while no single model can address all challenges of today's energy system, the reviewed models collectively cover a wide range of capabilities. Many models have been recently developed or updated to better represent the integration of VRES. The authors identify some key challenges and future modeling needs, including:

- Improved representation of short-term variability in long-term studies
- Incorporation of climate change effects on renewable resource potential
- Better modeling of consumer participation and sector coupling
- Consideration of impacts beyond the energy system (e.g., environmental and health impacts)
- Increased transparency and openness in energy modeling

The paper concludes that while current modeling tools offer extensive capabilities for analyzing energy systems with high VRES shares, there are still areas for improvement in addressing variability, demand-side dynamics, and broader system impacts. The authors suggest that future model development should focus on these challenges to better support the transition to renewable energy systems.

3.6.1.17 "A Review of Energy System Models" (Bhattacharyya and Timilsina, 2010)

This paper represents the comparison of model types relevant to developing countries concerning the current energy system. Therefore, the present study considered different categories of models, including bottom-up optimization frameworks, bottom-up accounting frameworks, top-down econometric frameworks, hybrid frameworks, and electricity system frameworks. The models are assessed according to various criteria, including the modeling approach, coverage in terms of geography and sectors, data prerequisites, adaptability to integrate emerging technologies, and capability to accurately depict essential attributes of energy systems in developing countries. The analysis reveals that a majority of current energy system models fail to adequately reflect the distinct characteristics pertinent to developing nations. This inadequacy is particularly evident in econometric and optimization models in contrast to accounting models. The authors comment that features such as informal economic activities, traditional fuels dependence, rural-urban divides, and technological diversity in developing countries are difficult for most models to catch easily. Bottom-up accounting models like LEAP (Long-range Energy Alternatives Planning), because of their flexible requirements and relatively lower order of skills, have more applicability to developing countries. The paper shows how model misrepresentation of energy systems in developing countries can lead to incorrect policy recommendations and infrastructure development strategies. In this regard, it emphasizes the need to embed components in models such as the gap between rural and urban divide, informal economic activities, and transition between traditional and modern sources of energy. The authors have thrown light on how progress in energy system modeling in developing countries is urgently needed to understand better the dynamics of economic growth, energy-environmental linkages, and impacts of climate change in specific contexts. The review sums up the insights related to the strengths and weaknesses of different methodologies of energy modeling while applying them in developing countries. It proposes a guided evaluation that would identify suitable modeling tools; it also points out critical areas that should be improved in the study on energy systems in developing countries.

3.6.1.18 "Modeling Approaches for Residential Energy Consumption: A Literature Review" (Nacht et al., 2023)

It is an extended literature review about different approaches and/or techniques concerning modeling residential energy use. This paper surveys the following methodologies: causal modeling, energy system modeling, mobility modeling, energy efficiency modeling, appliance modeling, energy management systems, energy storage modeling, and generation technology modeling. At the outset of this work, causal models are overviewed and together their realizations in different libraries. It then proceeds with the energy system models across the scales from the individual structures up to large systems. The study further talks about the relationship between mobility and residential energy consumption, underpinning that traffic simulation models are of high relevance for the understanding of energy consumption. Much of the review covers energy efficiency modeling within the realm of buildings, from building envelopes and HVAC to appliances. It explains various methodologies for modeling those components and their eventual impact on the total energy consumption. The study also researches energy management systems (EMS) and identifies them in three categories: open source, research-based, and commercial type. This paper goes deep on the modeling of energy storage, presenting different methodologies that concern different storage technologies, including electrochemical, chemical, mechanical, electrical, and thermal storage systems. Further, it gives methodologies of modeling applicable to the generation technologies relevant in residential settings, including the photovoltaic system, small-scale wind turbines, and combined heat and power (CHP) systems. Finally, some emergent business models discussed in the review in regard to the household electricity demand involve energy as a service, peer-to-peer trading of electricity, and community ownership schemes. The authors further go to discuss urban energy modeling and microclimates, emphasizing the integration of the same in residential energy consumption models. This literature review has, therefore, been able to provide an extensive review of the most current approaches applied in residential energy consumption modeling. It brings the required knowledge to researchers, policy analysts, and industry players with an interest in enhancing energy efficiency and sustainability within the residential sector.

3.6.1.19 "Greek long-term energy consumption prediction using artificial neural networks" (Ekonomou, 2010)

This scholarly article represents the approach and methodology of long-term energy consumption forecasting in Greece using ANNs (Artificial Neural Networks). For the purpose of Greek energy consumption predictions for the years 2005-2008, 2010, 2012, and 2015, the researcher developed an ANN model using the MLP (Multilayer Perceptron). In the present investigation, four major input variables influencing long-term energy consumption were applied: annual ambient temperature, installed power capacity in a year, yearly electricity consumption per resident, and gross domestic product. The final energy consumption was the output variable. Actual recorded data ranging from 1992 to 2004 were used for training and validation of the ANN models. Thousands of MLP ANN models had been designed, tested, and compared by the researcher for every possible combination of backpropagation learning algorithms, transfer functions, and structures of the network. The best generalizing ability model was chosen after an extensive running of simulations. This optimum model was found by utilizing 2 hidden layers, having 20 and 17 neurons, respectively, along with the Levenberg-Marquardt backpropagation learning algorithm with a logarithmic sigmoid transfer function. The optimum ANN model was, finally, utilized to predict Greek energy consumption for the considered years. The corresponding results concerning the years 2005-2008 were compared with the ones derived from the existing recorded data and two other models, a linear regression model, and a support vector machine model. The results demonstrated very high accuracy of the ANN model, with just about 2% percentage error between the forecasted and actual energy consumption values. According to the author, this proposed ANN approach may be useful for effective energy policy implementation since a correct anticipation of energy consumption has an effect on capital investment, environmental quality, revenue analysis, and market research management. The derived model could also be further developed into a user-friendly software tool and become an important resource for electric utilities and the regulation authorities of Greece that could offer them the capability to conduct an accurate long-term energy consumption forecast. In general, this research contributes to the field of energy consumption prediction by showing the effectiveness of the ANNs in forecasting the long-term energy demand, especially in the case of Greece. The methodology and outcomes received may serve for similar forecasting efforts in different countries or regions.

3.6.1.20 "Modeling and Simulation of Energy Systems: A Review" (Subramanian et al., 2018)

This review paper provides a comprehensive overview of modeling and simulation approaches for energy systems from both the Process Systems Engineering (PSE) and Energy Economics (EE) fields. The authors present two key ways to categorize the diverse contributions in this area:

- By modeling approach: computational, mathematical, and physical models. The paper highlights novel hybrid approaches that combine aspects of these different categories.
- By field: Process Systems Engineering (PSE) and Energy Economics (EE). The authors compare these fields based on criteria like the nature of variables, theoretical underpinnings, level of technological aggregation, spatial and temporal scales, and model purposes.

The paper provides a detailed treatment of PSE approaches, which typically model technological characteristics endogenously at the plant or supply chain level. It discusses emerging PSE trends like multi-scale systems engineering and modeling of sustainability criteria. For EE approaches, which model economic characteristics endogenously at higher levels of aggregation, the paper provides a basic overview. The authors make the case for combining PSE and EE approaches to get a more holistic picture of energy systems in a broader economic and policy context. They highlight three valuable application areas for integrated approaches:

- Using demand/price forecasts from EE models to optimize design and operation of flexible processes in PSE models
- Employing hybrid life cycle assessment methods that combine process-level detail with economy-wide scope
- Analyzing feedback effects of breakthrough technologies across scales

The review synthesizes a vast body of literature, referencing over 300 sources. It aims to build bridges between the PSE and EE communities to enable more comprehensive modeling of energy systems. The authors suggest further research is warranted on approaches linking PSE and EE to capture complex interdependencies across technological, economic and policy domains.

3.6.1.21 "Simulation and Optimization of Energy Systems" (Kaddoura, 2022)

The present article is an extensive review related to simulation and optimization approaches relevant to energy systems. This work has illustrated three major steps necessary to achieve the best design of energy systems: modeling, optimization, and control. First of all, while conducting a review analysis, it is relevant to refer to two main ways of modeling: Physics-Based Models and Data-Driven Models. Physics-based models rely on basic physical laws, giving quite detailed results, though computationally expensive. While the physics-based model is more accurate and reliable, yet computationally expensive, the data-driven models rely on large datasets and are computationally efficient, though they offer less rich information about the system. In this work, the authors managed to find that the true bridge between both approaches, by means of Physics-Informed Machine Learning (PIML), leads to an improved predictive model. Then, optimization techniques define the basic components of an optimization problem: objective function, decision variables, and constraints. This document covers a wide range of optimization techniques, ranging from those of linear and nonlinear programming to evolutionary algorithms like genetic algorithms and particle swarm optimization. The cost-minimization strategies have been elaborated, and equations have been given to work out annualized capital costs, Levelized Cost of Energy (LCOE), and payback period. Pretty significant parts of the manuscript have been devoted to the optimum integration of energy systems. The author has emphasized that most of the challenges with renewable sources are due to their intermittent nature and has thrown light on possible remedies in the form of adding storage devices or combining complementary renewable sources, a typical example of which is a solar-wind hybrid. Finally, the paper presents control approaches that seek an optimum performance of energy systems in real time. Two major widely spread control methodologies in industries are discussed: Model Predictive Control (MPC) and Fuzzy Logic Control (FLC). MPC controls represent a class of optimization-based techniques; therefore, their control problems are directly translated into optimization problems, whereas Fuzzy Logic Control acts by emulating the human-like reasoning process based on "if-then" rules. The author has provided examples of developed open-source simulation models alongside the developed paper and referred to works in which the mentioned techniques have been applied for different systems such as solar, wind, and hybrid. This review essentially contributes to researchers and engineers in the design, optimization, and management of energy systems, with a view to renewable energy integration and clean power generation.

3.6.1.22 "Energy Modelling: Methods and Applications" (Rebelatto and Frandoloso, 2020)

This article is a critical review of methodologies and applications of energy modeling, with a special focus on energy systems related to buildings and urban areas. The authors first introduce the concept of energy modeling, which they define as a methodology that develops or utilizes models to represent energy as an economic commodity under real system characteristics. Energy modeling, according to them, can play an important role in the fulfillment of the United Nations' SDG (Sustainable Development Goal) 7, Affordable and Clean Energy. It has talked about different categories of energy models, especially BEM (Building Energy Models) and UBEM (Urban Building Energy Models). Further explanation on BEM, using physically based simulation methodologies to predict energy use in buildings, while UBEM models extend these into building clusters within an urban context, was also addressed. The authors explained the different methodologies of modeling, which include engineering, statistical, and artificial intelligence models and their specific advantages and applicability. A significant portion of the paper is devoted to analyzing the impact of occupants' behavior on energy consumption and its modeling. The authors review several behavioral constructs, such as the Theory of Planned Behavior, the Norm Activation Model, and the Stimulus-Organism Response model, which help explain and predict energy-saving behaviors. This paper further reviews the applications of energy models to policy analysis and outlines that the long-run energy-economic models are integral to the analysis of energy and environmental policy. The paper discusses the challenges concerning model quality assessment and stresses the importance of transparency in energy system modelling software. The paper provides an overview of a few simulation tools used in energy modelling, including EnergyPlus, TRNSYS, and DesignBuilder. It points to the importance of calibration for model accuracy and focuses on methodologies such as Bayesian calibration. Finally, the authors discuss the future challenges in building performance simulations, namely, the need for improved design support and optimally managed building operations. They underline the crucial integration of energy efficiency strategies with occupant behavioral considerations in the delivery of more accurate and effective results of energy modeling. Generally speaking, the work conducted a review of methodologies, tools, and applications related to energy modeling and provided main insights for researchers, policy analysts, and practitioners who participate in the sustainable energy and architectural design area.

3.6.1.23 "Energy related system dynamic models: a literature review" (Leopold, 2016)

The paper provides a critical literature review of system dynamics (SD) models applied to energy-related topics between the year 2000 and 2015. The author has categorized the reviewed materials under four main headings, namely: fossil fuels, renewable energy, electricity, and other energy resources. The review commences with a brief overview of system dynamics modeling and its beginning in the late 1950s and its applications in a wide range of fields. It then gives the methodology of the literature review, taking into account only the studies from the year 2000 onwards. Relevant SD models on each of the main topics are introduced, including purpose, time horizon, and regional context, summarized from key findings and conclusions. It thus provides insight into how SD has been applied to a variety of energy-related challenges. The review covers the models on oil production, natural gas markets, and coal investments within the category of fossil fuel. Most of them are on the forecast of reserves, analysis of market dynamics, and assessment of policy impacts. Renewable energy considerations are covered by SD applications in wind power, solar energy, biofuels, and geothermal resources. Such models often discuss the adoption of technology, policy effectiveness, and issues regarding the integration of renewable sources into the market. The section of electricity goes over the SD models dealing with power generation capacity, market dynamics, and long-term planning. The majority of these analyses are used to assess policy options, market reforms, and transition to low-carbon electricity systems. The final section on other energy resources deals essentially with models related to nuclear energy but also includes hydrogen and fusion power. The author identifies the different uses of SD in energy modeling throughout the review, which range from forecasting, policy analysis, and understanding the behavior of complex systems to supporting decision-making processes. The recommendations towards the identification of potential further research areas are made at the end of the paper on energy system transformation processes, transition to renewable energy sources, consumer-centric modeling, and assessment of alternative energy technology potentials. The review is presented in tabular form, where summary tables outline for each study the authors, year of publication, title, objectives, duration, and geographic focus. This wide review is a valuable resource for researchers and practitioners for enhancing a better understanding of the status of the latest developments in energy system dynamics modeling and identification of paths for potential research.

3.6.1.24 "Review of models for integrating renewable energy in the generation expansion planning" (Dagoumas & Koltsaklis, 2019)

This review article elaborates on the models adopted in integrating Renewable Energy Sources (RES) into Generation Expansion Planning (GEP). The authors recognize GEP as one of the most important topics in the energy sector, at least in regard to attaining crucial goals related to emissions reduction and the decarbonization of economies. Various models adopted in GEP have been assessed in this paper in order to classify the relative strengths and weaknesses associated with each model theory, characteristics, advantages, and disadvantages. This research categorizes all GEP models into three major groups: optimization models, general or partial equilibrium models, and alternative models that do not realize optimal RES integration within the GEP framework. In analyzing different methodological approaches, the authors try to provide insight into their appropriateness for capturing the various dimensions of the GEP problem. The research underlines the complexity of GEP, which needs to balance technological, economic, financial, spatial, and environmental aspects. It does this by stressing the importance of understanding the underlying theory behind each model, since this may inherently bias the output produced. As the authors mention, debate continuously rages over which methods are appropriate since forecasted outcomes often differ so substantially from reality. Consequently, one of the major contributions of this article is an attempt to provide insight into what the expected outcome of each methodology will be. The confrontation and comparison of these models helps the reader to deepen their comprehension of the relative strengths and weaknesses of the approaches in modeling RES integration in GEP. Interesting both for academic scholars and energy world decision-makers, this paper offers a general overview of state-of-the-art GEP models, focusing on recent developments and major RES penetration rates in power capacity mixes. Furthermore, the models' classification and analyses in this paper provide a more orderly basis on which the preferred approaches to this complex planning problem may be reviewed. In general, this review gives a comprehensive guide to the state of modeling of RES integration in GEP, with insights to ensure appropriate future research directions and pragmatic decision-making in sustainable energy planning.

3.6.2 Discussion

There are a number of key themes and challenges arising from this overall review of energy system modeling approaches. One of the more obvious general trends is a move towards more complex and multi-sector modeling, partly driven by the need to analyze systems with high penetrations of variable renewable energy sources. Models are becoming more sophisticated in providing the required temporal and spatial resolution for the representation of variability of renewables, energy storage, and grid constraints. However, Pfenninger et al. 2014 observe that this increased sophistication from several perspectives results in greater challenges, such as computational burden, input data, and model transparency. Literature available stresses a dichotomy that exists between top-down economic models versus bottom-up engineering approaches, but recent interest seems to shift towards hybrid models capturing elements of each. Top-down approaches are certainly capable of capturing macro-economic effects, but it is the bottom-up approaches that provide the necessary technological detail to assess specific transitions. Indeed, Bhattacharyya and Timilsina (2010) argue that many contemporary models cannot capture crucial features of the energy systems of developing countries and therefore require tailored analyses. A common thread running through these papers is model transparency and reproducibility. DeCarolis et al. (2012) make a strong case for repeatable analysis in energy-economy optimization models, while Pfenninger et al. (2017) strongly advocate open data and software in energy research. All these different efforts towards openness contribute to trusting model results and the collaborative improvement of modeling tools. The high renewable energy scenarios are controversial regarding their feasibility. While studies like Connolly et al. (2016) project the technical feasibility of 100% renewable energy systems in Europe, others like Heard et al. (2017) argue that proposed 100% renewable electricity systems fail to meet key feasibility criteria. This disagreement underlines the relevance of transparency in assumptions and methodologies during energy system modeling. Analysis reveals an increasing interest in embedding human behavior and social influences within energy modeling frameworks. The traditional techno-economic approaches are thus supplemented with insights from behavioral science that better represent consumer decisions and societal transformations. This is also underpinned by increased application of agent-based modeling approaches, including the inclusions of behavioral variables within system models. Recent advances in artificial intelligence (AI) and machine learning have reached a point where they influence energy system modeling. For example, the work of Ekonomou (2010) uses the capacity of artificial neural networks in order to forecast long-term energy consumption. Further works investigate the use of AI for demand forecasting and system optimization. Those techniques open ways toward handling larger datasets and extracting complicated nonlinear dependences within energy systems. Literature highlights that energy storage will play a critical role in the development of high-renewable energy (REN) scenarios. New modeling advances the representation of different storage technologies and their operating characteristics. However, longer-duration and seasonal balancing remains one of the challenging factors in effective modeling. There is increasingly a recognition that broader sustainability indicators beyond the simple cost and emissions profile are required. Newer models indeed consider land use, water consumption, and social impact, among other factors. In this, it is a holistic approach that aligns with the UN's Sustainable Development Goals and is representative of the complex trade-offs that come with energy transitions.

3.6.3 Conclusion

This thus evidences the rapid development that has taken place in methodologies of energy system modeling due to the challenges associated with the transition towards low-carbon energy systems. With the increasing sophistication in representational power, there are a number of significant challenges that persist. These are a function of the findings related to the model-complexity-versus-transparency debate, improved representation of human behavior and social interactions, and the need for methods tailored to the specific developing-country context.

Another encouraging trend is that of open data and reproducible analysis, likely to result in more credible, collaboratively enhanced energy models. But the field must learn to live with the unavoidable uncertainty of long-term energy projections and find ways to communicate these helpfully to policymakers.

Ambitious climate goals can be achieved only by deploying energy system models to support policy making and investment decisions. Future work should place a stronger focus on integrating more effectively insights from the behavioral sciences, on better representation of energy storage and sector coupling, and on the development of more integrated approaches, considering wider sustainability criteria.

Energy system models are powerful tools for analyzing future scenarios but need to be used with great caution. Limitations and assumptions of such models need to be stated in tandem with their results. Continuous improvement and accurate evaluation of modeling approaches will become increasingly necessary during the transition towards a sustainable energy system so that models can remain relevant and valid in supporting a pathway toward a Forestry renovation (FR) models for VF buildings

3.6.4 Introduction

Green Infrastructure options related to forestry-related elements of Reinforced Concrete (RC) structures meeting present project parameters include green roofs, elevated forests, green terraces, vertical forests, green walls, and green facades. Such novel urban greening methods are new paradigm shifts in architectural design and in environmental engineering study, with substantial benefits accruing to the built form and to the inhabitants. A short overview of each of these concepts is presented in the paper which follows with a view to defining their fundamental characteristics.

Green roofs, also known as living roofs or eco-roofs, are roofs with vegetation cover and are considered an environmental alternative to traditional roofs. Elevated forests add an element of verticality to this concept, incorporating tree-like features at various levels into the building structure. Green terraces differ from these in offering a lateral integration of vegetation, creating biophilic spaces that enhance not only the view but also functionality.

Vertical forests are a more aspirational use of green infrastructure, where the entire surface of a tall structure is turned into a verdant environment. This can also add important aesthetic value to the structure and contribute to both urban biodiversity and microclimate regulation. Green walls and facades share a common concept but vary in approach and level of sophistication. More precisely, green walls represent very complex systems for the growth of plants directly on a vertical surface, while green facades usually use climbing plants or modular systems attached to the façade of a building.

Each one of these forestry objects has its different challenges and opportunities in its design, construction, and maintenance concerning reinforced concrete structures. Their integration has to be made with great care regarding load-carrying capacity, moisture, and durability for long-term service. For an in-depth and detailed discussion of those concepts, inclusive of technical specifications, environmental impact, and relevant case studies, see the document below from Greenergy, D1.4 (2024), where such a topic is dealt with in full.

3.6.5 Literature Review for Finite Element Modeling

Since the literature review was focused on spotting those models apt for Finite Element Modeling (FEM) analysis, it was relevant to perform an appropriate standardization and to provide a quick overview of the results. Therefore, two different kinds of summaries of the source papers were produced.

3. **Text Summary**: The text summary is the reasoned, written summary of each paper considered within the literature. It shows an overview yet highly representative expression of the content of each paper, whereby the reader can appreciate the central ideas in quick time.

4. **Tree-View Summary**: A tree view summary represents the key information from each paper in an orderly, hierarchical fashion. It provides an instantaneous and clear visual picture of the essence of what it is that the paper contributes. In this format, material can be directly compared from various papers, increasing productivity by presenting complex information in a more palatable format. Here's a detailed explanation of each component: ·

- **Objective**: The main goal or purpose of the study (1-2 sentences).
- **Methodology**: A brief explanation of how the research was carried out.
- **Key Findings**: Major findings or identification of the revelations obtained through this research.
- **Conclusions**: Major ideas or interpretations of findings.
- **Limitations and Future Work**: This involves limitations in this survey and suggestions for the future. ·
- **Significance**: The importance of the study, or relevance, to the discipline.

These summaries, both in textual and tree view format, are intended to quick understanding and efficiency, not to replace the original research papers. Readers are encouraged to view these summaries as starting resources or quick references, referring back to the original documents for further detail in conceptual explanations and methodologies applied.

3.6.5.1 "Analysis of the Static Behavior of a Single Tree on a Finite Element Model" (Moravčík et al. 2021)

Text Summary

This study introduces an innovative approach to tree risk assessment, combining advanced 3D scanning technology with finite element analysis (FEM) to predict potential breakage points in urban trees. The researchers used terrestrial laser scanning to capture the precise geometry of a Tilia cordata Mill. tree and acoustic tomography to detect internal decay. They then created a detailed 3D model of the tree, representing it as a beam structure with variable cross-sections. Abstract modeling information is depicted in Figure 43.

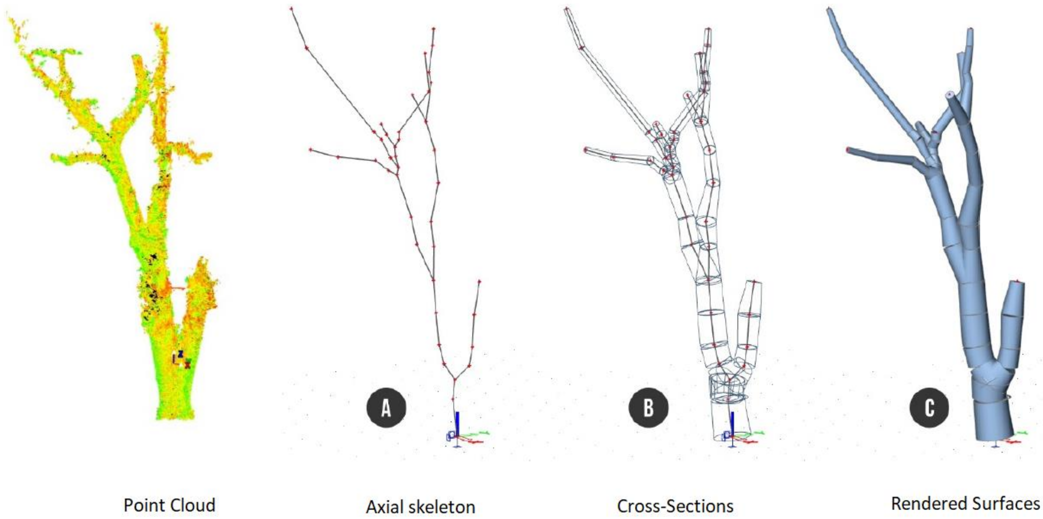


Figure 43 Tree modeling process (images from Moravčík et al. 2021)

The model incorporated green wood properties and considered loads from the tree's self-weight, foliage, and wind. Using SCIA Engineer software, the researchers performed static structural analysis to evaluate displacements and stresses under different load combinations.

Key findings included a maximum horizontal displacement of 280.4 mm under wind load, and maximum tensile and compressive stresses of +8.8 MPa and -8.9 MPa respectively, after filtering out abnormal cross-sections. These stress levels, when compared to literature values, did not indicate a high risk of breakage for the studied tree.

While the method provides a comprehensive analysis of tree structure and potential weak points, the researchers acknowledge several areas for improvement. These include the need for experimental validation, more accurate green wood property data, automation of the modeling process, and consideration of root structure and soil characteristics in future models.

This approach represents a significant advancement in tree risk assessment, offering a more detailed and potentially more accurate method for evaluating tree stability. It's particularly valuable for urban tree management and the preservation of monumental trees, allowing for precise, long-term monitoring of tree health and structural integrity.

Tree-View Summary

Objective: The study aimed to develop a comprehensive method for tree risk assessment, focusing on predicting potential breakage points in urban trees using advanced technology and finite element analysis (FEM).

Methodology:

Data Acquisition:

- Used terrestrial laser scanning (TLS) to capture precise 3D geometry of a Tilia cordata Mill. tree
- Employed acoustic tomography to detect internal decay

Model Creation:

- Converted point cloud data to a 3D CAD model
- Created a beam structure model with 13 beams and 42 nodes
- Defined 44 different cross-sections along the trunk and branches

Material Properties:

- Used green wood properties (50% moisture content)
- Defined modulus of elasticity, rigidity, and wood density

Load Cases:

- Self-weight of wood and foliage
- Wind load (calculated according to Eurocode standards)

Analysis:

- Performed static structural analysis using SCIA Engineer software
- Evaluated displacements and stresses under different load combinations

Key Findings:

- Maximum horizontal displacement: 280.4 mm under wind load
- Maximum tensile stress: +8.8 MPa (after filtering abnormal cross-sections)
- Maximum compressive stress: -8.9 MPa

Conclusions:

- The method provides a detailed analysis of tree structure and potential weak points
- Based on literature values, the observed stress levels do not indicate a high risk of breakage
- The approach is particularly suitable for assessing monumental trees over time

Limitations and Future Work:

- Need for experimental validation through tree pulling tests
- Requirement for more accurate green wood property data
- Potential for automating the point cloud to CAD conversion process
- Consideration of root structure and soil characteristics in future models

Significance: This study presents a novel, integrated approach to tree risk assessment, combining precise 3D geometry acquisition with advanced structural analysis. It offers a more comprehensive and accurate method for evaluating tree stability and predicting potential failure points, particularly valuable for urban tree management and preservation of monumental trees.

3.6.5.2 "Finite element analysis of trees in the wind based on terrestrial laser scanning data" (Jackson et al. 2019)

Text Summary

This paper presents a new way of representing the dynamic behavior of trees through the use of finite element method (FEM) based on terrestrial laser scanning (TLS) due to wind loading. A group of authors led by T. Jackson attempted to develop and verify a method that could simulate the response of trees to wind loads accurately without the need for a labor-intensive mapping of tree geometry. Figure 44: Typical processing chain used in this work. Project combined TLS measurement of tree objects in Wytham Woods, UK with field measurement of strain on the stem and ambient wind speed. Authors have created Quantitative Structure Models (QSMs) from TLS data cleaned and then after converted it into finite element model by Abaqus software. Material properties were assumed from literature values and the wind forces were applied via a power law profile.The model demonstrated strong predictive capabilities, accurately simulating 5-minute time-series strain responses and maximum strains at given wind speeds. It also showed moderate success in predicting critical wind speeds and fundamental sway frequencies, though with some systematic underprediction in the latter.

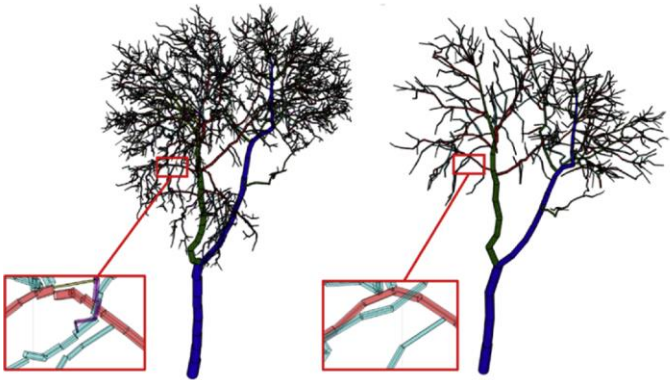


Figure 44 Left – QSM directly from the fitting process. Right – simplified QSM with longer cylinders and fewer small branches (images and caption are from Jackson et al. 2019)

This approach offers several advantages over previous methods, including the ability to model complex broadleaf tree geometries and the potential for application to a wide range of tree types and environments. However, the researchers noted limitations, such as the need for integration with wind flow models for landscape-scale applications and potential improvements in material property assignments and QSM simplification methods.

The significance of this study lies in its potential to enhance our understanding of tree-wind interactions and improve risk assessment and management strategies for both natural forests and urban trees. By providing a framework for detailed mechanical analysis of trees based on readily obtainable TLS data, this method opens up new avenues for research in forest ecology, urban forestry, and climate change impact studies.

Tree-View Summary

Objective: To develop and validate a method for modeling the dynamic behavior of trees in wind using finite element analysis based on terrestrial laser scanning (TLS) data.

Methodology:

Data Acquisition:

- TLS data collection of trees in Wytham Woods, UK
- Field measurements of strain in tree stems
- Wind speed measurements using anemometers and sonic anemometers

Model Creation:

- Generation of Quantitative Structure Models (QSMs) from TLS data
- Simplification of QSMs by removing small branches and averaging cylinders
- Conversion of simplified QSMs to finite element models in Abaqus software

Material Properties:

- Wood density, elasticity, and modulus of rupture from literature values
- Species-specific properties used where available

Load Case:

- Wind forces applied using power law wind profile
- Drag forces calculated for each cylinder in the model

Analysis:

- Non-linear dynamic simulations for time-series strain response
- Static analysis for maximum strain at given wind speeds
- Modal analysis for fundamental sway frequencies

Key Findings:

- The model predicted 5-minute time-series strain with a mean cross-correlation coefficient of 0.71.
- Strain predictions at 5 ms^{-1} and 15 ms^{-1} wind speeds showed strong correlations with field data (R^2 = 0.81 and 0.79, respectively).
- Critical wind speed predictions showed moderate agreement with field-based estimates (R^2 = 0.40).
- Fundamental frequency predictions followed the correct trend but were systematically underpredicted (R^2 = 0.38).

Conclusions:

- The combination of TLS data and finite element analysis can effectively model complex broadleaf tree dynamics.
- The approach accurately predicts strain responses to wind forcing and maximum strains for given wind speeds.
- The method provides a framework for studying tree mechanics without manual mapping of tree architecture.

Limitations and Future Work:

- The model relies on local wind data and needs integration with wind flow models for landscape-scale application.
- Accuracy of material property assignments and QSM simplification methods could be improved.
- Incorporation of leaves, twigs, and more detailed crown architecture could enhance summer condition modeling.
- The approach could be extended to model effects of pruning or support systems on urban or veteran trees.

Significance: This study demonstrates a novel approach to modeling tree-wind interactions using highly detailed 3D tree models derived from TLS data. The method opens up new possibilities for studying the relationship between tree architecture and dynamics in a wide range of environments, from natural forests to urban settings, potentially improving our understanding of wind damage risks and tree management strategies.

3.6.5.3 "Large deformation of trees in a strong wind" (P. Zhang 2024)

Text Summary

This paper presents a novel physics-based model for analyzing large deformations of trees in strong winds. The study, authored by Peng Zhang, addresses limitations of previous models that relied on small-deformation assumptions. The model integrates a branched tree architecture with nonlinear structural mechanics and dynamic aerodynamic loading.

The methodology employs a sympodial branching pattern and allometric scaling laws to construct realistic tree geometries. Nonlinear partial differential equations govern the large deformations, incorporating axial, bending, and shear components. Aerodynamic loading is modeled based on instantaneous relative velocity between wind and tree structures. The model uses material properties typical of oak trees and simulates hurricane-force winds of 45 m/s.

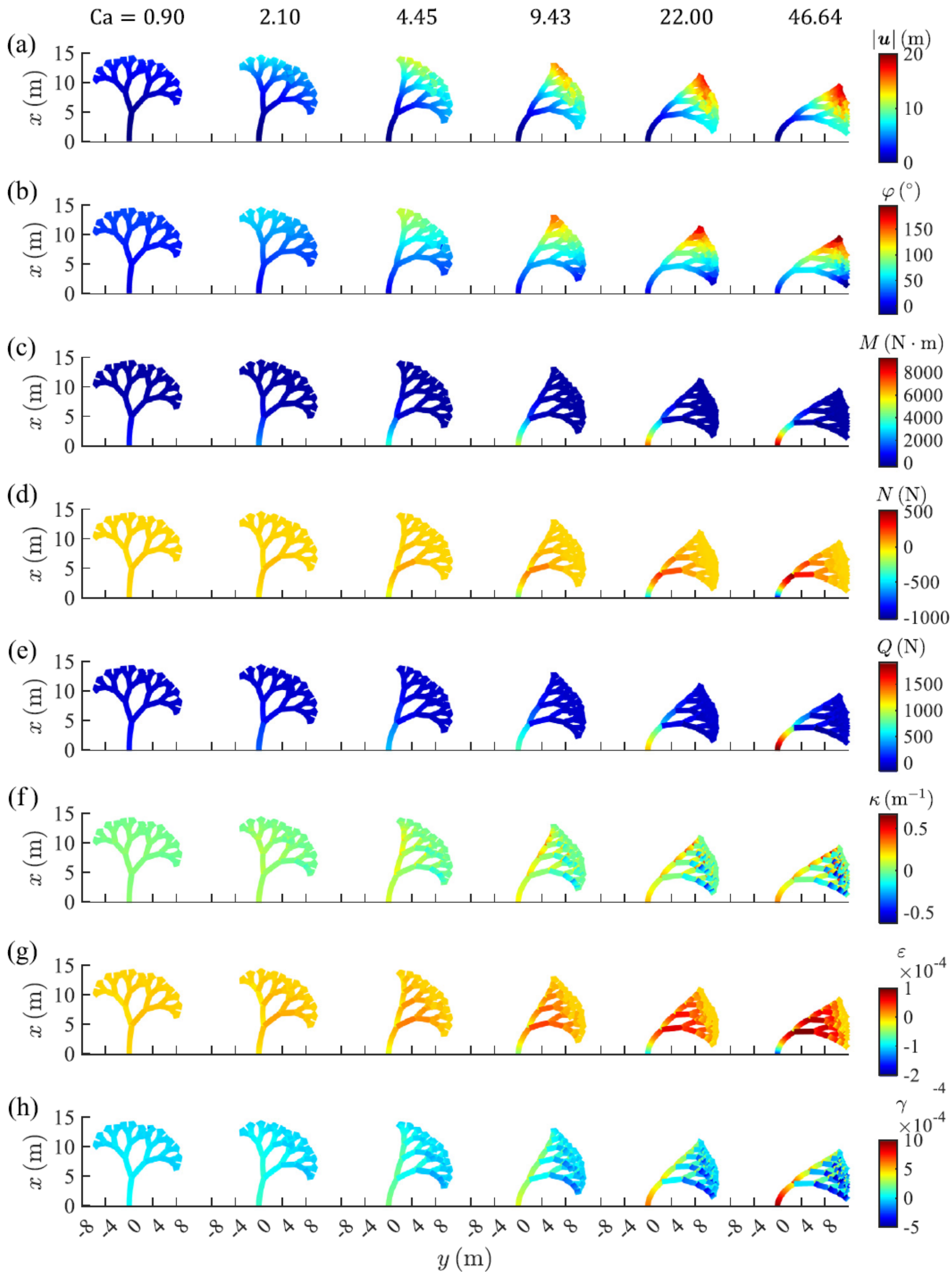


Figure 45 Steady-state deformation of the branched tree at a few selected Ca, illustrating (a) the displacement magnitude, (b) rotation angle, (c) bending moment, (d)axial force, (e) shear

force, (f) bending curvature, (g) axial strain, and (h) shear strain (images and caption are from P. Zhang 2024).

Numerical solutions are obtained using the finite difference method and Newton-Raphson iterations, validated against finite element simulations in Ansys Mechanical APDL. The model successfully captures large deformations, stress distributions, and reveals self-similarity in bending curvature among branches of different orders. It quantifies aerodynamic damping without empirical assumptions and demonstrates exponential drag reduction due to shape reconfiguration at high wind speeds. Steady-state deformation of the branched tree are depicted in Figure 45 for selected Cauchy number.

Key findings include the identification of trunk and first-order branches as locations of peak stress, providing insights into potential failure points. The model's ability to naturally capture aerodynamic damping and reconfiguration effects represents a significant advancement over previous approaches.

Limitations include the restriction to two-dimensional deformations, neglect of leaf influences, and assumptions of rigid branch connections and isotropic material properties. Future work could address these limitations and extend the model to forest-scale interactions.

The study does contribute to valuable insights into forest management and damage mitigation strategies, providing the computationally efficient framework that could be easily adapted to most any tree architecture. Its holistic modeling of wind-tree interactions advances the understanding of tree behavior under extreme weather conditions.

Tree-View Summary

Objective: A geometrically exact, physics-based model will be developed which is capable of quantifying the large, dynamic deformation of trees in strong winds and considers various shortcomings of previous models assuming small deformation.

Methodology:

Tree Architecture:

- Implemented branched tree model with iterative bifurcation process
- Used allometric scaling laws for branch sizes
- Focused on sympodial branching pattern

Mathematical Model:

- Derived nonlinear partial differential equations for large deformations
- Incorporated axial, bending, and shear deformations
- Modeled aerodynamic loading based on instantaneous relative velocity

Material Properties:

- Young's modulus: 13.0 GPa (longitudinal)
- Poisson's ratio: 0.3
- Density: 550 kg/m^3

Load Case:

- Wind speed: 45 m/s (comparable to hurricane conditions)
- Direction: Cross-wind (perpendicular to trunk)

Analysis:

- Made use of FDM for a numerical solution

- Nonlinear equations with the Newton-Raphson method
- Validated against FEM solutions in the commercial software Ansys Mechanical APDL

Key Findings:

- Accurately captured large deformations and stress distributions in tree structures
- Unfolded self-similarity in the bending curvature within branches of different orders
- Quantified aerodynamic damping without relying on empirical assumptions
- Demonstrated exponential drag reduction due to shape reconfiguration at high wind speeds
- Identified trunk and first-order branches as locations of peak stress

Conclusions:

- The model effectively couples complex tree architecture with nonlinear structural mechanics.
- There is natural aerodynamic damping from wind-tree interactions without empirical coefficients.
- Shape reconfiguration significantly reduces drag forces at high wind speeds
- The model provides insights into stress distribution, helping predict potential failure points

Limitations and Future Work:

- Limited to two-dimensional deformations
- Neglects the influence of leaves on aerodynamic loading
- Assumes rigid connections between branches
- Uses isotropic material properties instead of anisotropic wood properties
- Does not account for tree-induced modifications of airflows in forests

Significance: This study represents a significant advancement in modeling tree behavior under strong winds. By accurately capturing large deformations and complex wind-tree interactions, the model provides valuable insights for forest management and damage mitigation strategies. The framework's adaptability to various tree architectures and its computational efficiency make it a powerful tool for future research in urban forestry, wind damage prediction, and sustainable forest management practices.

3.6.5.4 “Wind loading on trees integrated with a building envelope“ (Mousaad et al. 2013)

Text Summary

This study by Aly et al. investigates wind loading on trees integrated with building envelopes, employing a multi-scale experimental approach. The research combines small-scale wind tunnel tests and full-scale open-jet facility experiments to comprehensively assess both global interference effects and local wind-tree interactions. Small scale models are depicted in Figure 46.

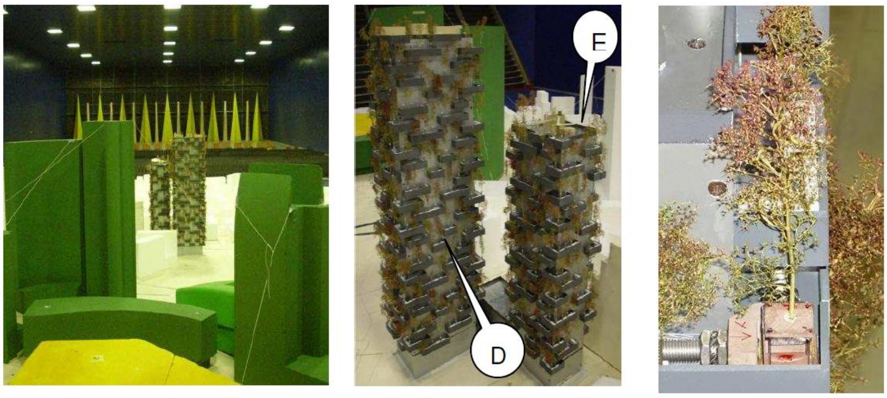


Figure 46 Small-scale trees mounted on two tall buildings (towers D and E) tested in the boundary-layer windtunnel of the Politecnico di Milano (images and caption are from Mousaad et al. 2013)

The methodology involved 1:100 scale building models with miniature trees tested in a boundary-layer wind tunnel, and full-scale tests of 3-4 m tall trees in a Wall of Wind facility. Wind forces were measured using dynamometers and load cells, respectively. The study examined wind speeds ranging from 6.3 m/s in small-scale tests to 53 m/s in full-scale tests, with corresponding Reynolds numbers from 1.43 x 10^4 to 4.89 x 10^6. Images from Phase 2 are depicted in Figure 47.

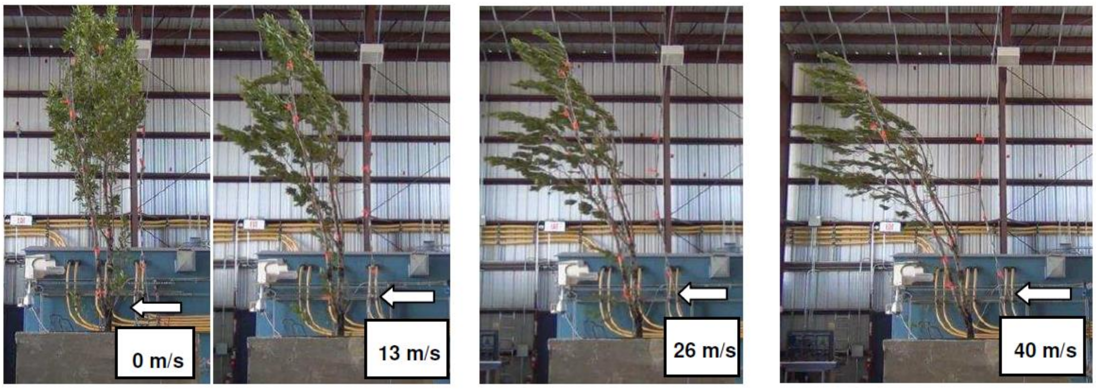


Figure 47 Lateral photographs of actual trees at 0, 13, 26, and 40 m/s: (b) Phase 2 (images and caption are from Mousaad et al. 2013)

Key findings reveal that small-scale tests may overestimate wind loads compared to full-scale results. Importantly, at higher wind speeds, tree shape changes due to bending reduces effective wind loads. The research observed no resonance or vortex shedding in full-scale tests, attributing this to the trees' natural flexibility and damping characteristics from branches and leaves.

The study also evaluated proposed mitigation techniques, including a steel cage and vertical safety strands, finding them unnecessary for the tested design. However, the authors acknowledge limitations, such as the lack of turbulence simulation in full-scale testing and the need for scaling laws to extrapolate results to larger trees or different species.

This research contributes valuable insights to the design of vegetated building envelopes, potentially improving guidelines for integrating trees into sustainable urban architecture. The authors suggest future work should focus on dynamic structural analysis for various tree species, combining CFD with structural modeling, and conducting long-term monitoring of trees on actual buildings for model validation.

Tree-View Summary

Objective: To assess wind loads on trees integrated into building envelopes, considering both global interference effects and local wind-tree interactions.

Methodology:

Small-scale Wind Tunnel Testing:

- 1:100 scale models of buildings with trees
- Boundary-layer wind tunnel simulation
- Force measurements using dynamometers
- Reynolds number: 1.43 x 10^4

Full-scale Testing:

- Wall of Wind (WoW) facility testing
- Four tree species, 3-4 m tall
- Load measurements using multi-axis load cells
- Reynolds number: 1.18 x 10^6 to 4.89 x 10^6

Test Configurations:

- Phase 1: Trees on steel frame with/without mitigation cable
- Phase 2: Trees in concrete planter box with various mitigation techniques

Load Cases:

- Wind speeds: 12.8 m/s, 26.2 m/s, 40 m/s, and up to 53 m/s
- Wind directions: 0° and 90°

Analysis:

- Calculation of total force coefficients and moment coefficients
- Assessment of shape change effects
- Evaluation of mitigation techniques' effectiveness

Key Findings:

- Small-scale tests may overestimate wind loads on trees compared to full-scale tests.
- At higher wind speeds, tree shape change (bending) reduces effective wind loads.
- No resonance or vortex shedding was observed in full-scale tests.
- Tree flexibility and leaf/branch damping mitigate potential instabilities.
- Proposed mitigation techniques (steel cage, vertical cable) were found to be unnecessary for the tested design.

Conclusions:

- Full-scale testing has given more precise measures of the wind forces acting upon trees.
- Both tree flexibility and shape significantly impact wind load coefficient changes
- Trees' natural damping mechanisms help mitigate wind-induced instabilities.

Limitations and Future Work:

- Lack of turbulence simulation in full-scale testing

- Need for scaling laws to extrapolate results to larger trees
- Further research on dynamic structural analysis for different tree species and ages
- Investigation of long-term performance of trees on building envelopes

Significance: This paper provides critical insight into the complex wind-tree interaction for vegetated building envelopes, pointing out that full-scale testing, considering tree flexibility in wind load assessment, can result in far more realistic, possibly less conservative design guidance on green buildings.

3.6.5.5 "FEA Simulation of the Biomechanical Structure Overload in the University Campus Planting" (Dounar et al. 2020)

Text Summary

This is a paper authored by Dounar et al. presenting the FEA simulation of a failure of a chestnut tree branch which happened on campus. It included several key elements: 3D modeling, advanced material representation, nonlinear analysis techniques applied to a biomechanical study of tree structure, and failure mechanism. The detailed 3D model of the tree is developed that includes variations in crown shape and size, as shown in Figure 48 and Figure 49. The isotropic and orthotropic material models were adopted for the wood, reflecting only the directional dependence of wood strength. Prescribed wind pressures and masses of crowns were modeled for different conditions, applying both linear and geometrically nonlinear FEA techniques.

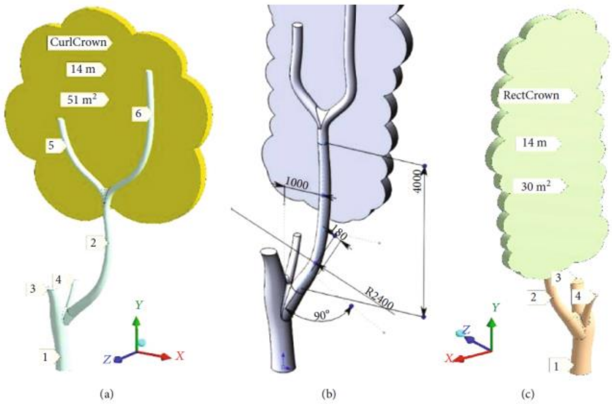


Figure 48 Tree geometry: (a) model with curled crown (CurlCrown) on the downwind side; (b) the internal dimensions of the branch; (c)elongated crown (RectCrown) from upwind (images and caption are from Dounar et al. 2020).

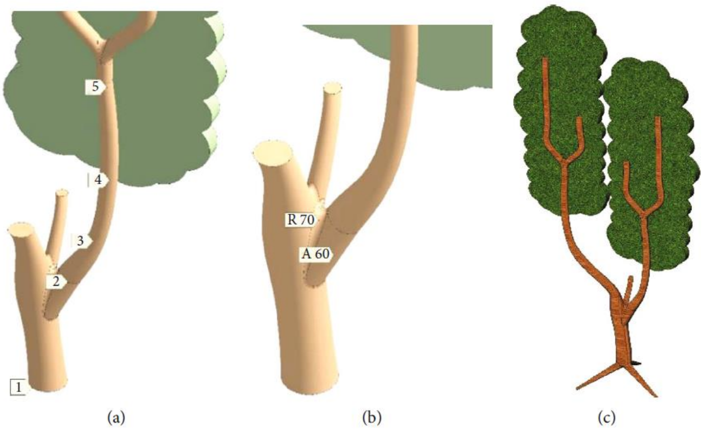


Figure 49 Models of the branch: (a) the trunk-branch junction; (b) the tree with two branches; (c) two crowns and stylized roots (DoubleTree) (images and caption are from Dounar et al. 2020).

Key findings reveal that the branch behaves like an "equal-strength console," with stresses distributed uniformly along its length due to its varying cross-section. The trunk-branch junction was found to be well-reinforced, contrary to common assumptions about weak points in trees. The highest stresses occurred in specific tension and compression zones along the branch, rather than at the junction.

The study highlighted the importance of nonlinear analysis, which predicted 33% higher displacements, and 35% higher stresses compared to linear analysis. Orthotropic material models, while predicting larger deformations, yielded similar stress levels to isotropic models.

This research demonstrates the potential of advanced FEA techniques in analyzing complex biomechanical structures. The insights gained can be applied to urban forestry for assessing potential hazards and to engineering for improving bionic design principles. The study was limited to static analysis and used simplified crown modeling, suggesting areas for future research including dynamic analysis and more detailed material failure models.

Tree-View Summary

Objective: To investigate the breakage of a chestnut tree branch on a university campus using finite element analysis (FEA) simulation, focusing on the biomechanical aspects and stress distribution.

Methodology:

Data Acquisition:

- Laser scanning of the tree
- Sketches by gardeners
- Weather data from nearby station

Model Creation:

- 3D modeling of trunk, main branch, and crown
- Multiple crown shapes: CurlCrown and RectCrown
- DoubleTree model with two main branches

Material Properties:

- Isotropic model (ChestISO): $E = 8000$ MPa, $\mu = 0.42$, $\rho = 600$ kg/m³
- Orthotropic models (ChestTKP and ChestWH) with direction-dependent properties
- Crown modeled with low rigidity ($E = 2$ MPa)

Load Case:

- Wind pressure: 380 Pa (normal) and 600 Pa (peak)
- Gravity force
- Various crown masses: 750 kg, 1225 kg, and 1550 kg

Analysis:

- Static FEA simulation
- Linear and geometrically nonlinear analyses
- Mesh variations: R-mesh (rare) and D-mesh (dense)
- ANSYS software (inferred from figures)

Key Findings:

- The branch behaves like an "equal-strength console" with uniform stress distribution along its length.
- Trunk-branch junction is well-reinforced, with stresses twice lower than in the branch itself.
- Highest stresses occur in the Strip of Strong Tension (SSTe) and Strip of Strong Compression (SSCo) along the branch.
- Nonlinear analysis shows 33% higher displacement and 35% higher stress compared to linear analysis.
- Orthotropic models predict 58% higher displacements but similar stress levels compared to isotropic models.
- Stress distribution is relatively insensitive to wind direction changes.

Conclusions:

- Branch failure likely occurred due to overall overloading rather than a specific stress concentrator.
- The tree's structure demonstrates effective bionic stress stabilization (BiSS) through self-organized wood growth.
- Geometrically nonlinear analysis is crucial for accurate prediction of large deformations and stresses.
- The trunk-branch junction is not the weak point in the tree's structure.

Limitations and Future Work:

- Limited to static analysis; dynamic effects not considered
- Simplified crown modeling: more detailed representation could improve accuracy
- No consideration of wood defects or previous damage
- Future work could include dynamic analysis and more detailed material failure models

Significance: This study demonstrates the application of advanced FEA techniques to analyze complex biomechanical structures like trees. The findings provide insights into tree failure mechanisms and structural adaptations, which can be applied to assess potential hazards in urban forestry and improve bionic design principles in engineering.

3.6.5.6 “Study on windbreak performance of tree canopy by numerical simulation method“ (Jian et al. 2018)

Text Summary

The study "Study on windbreak performance of tree canopy by numerical simulation method" by Zhang Jian, Li Bo, and Wang Mingyue investigates the windbreak effectiveness of tree canopies using computational fluid dynamics (CFD) simulations. The researchers employed a porous media approach to model tree canopies, incorporating additional source terms in the momentum equations and utilizing a modified Realizable k-ε turbulence model.

The study examined the effects of canopy porosity (20-100%), shape (cylindrical, conical, quadrilateral pyramid), and tree spacing (0.1-2.0m) on windbreak performance. The model was validated against wind tunnel measurements and previous numerical studies, showing good agreement especially at canopy height. Shapes of tree canopy depicted in Figure 50.

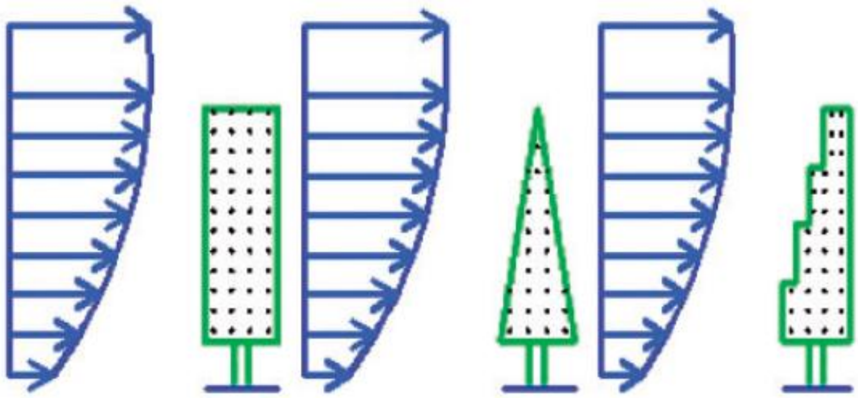


Figure 50 Shapes of tree canopy (images and caption are from Jian et al. 2018).

Key findings reveal that canopy porosity significantly influences windbreak performance, with lower porosity not always resulting in better windbreak, particularly near the ground. Canopy shape primarily affects upper flow regions, while tree spacing effects are most noticeable near the canopies. Far downstream, spacing effects can be approximated by equivalent porosity changes.

The researchers conclude that the porous media approach effectively simulates tree canopy windbreak performance, with porosity being the most influential parameter. They suggest that simplifying complex canopies to cylindrical shapes is acceptable for most applications.

Future work could include more detailed canopy structure representation, consideration of seasonal variations, coupling with thermal effects for urban microclimate studies, and integration of large eddy simulation for improved turbulence modeling.

This study provides valuable insights for optimizing windbreak designs in urban planning, agriculture, and environmental protection, offering a foundation for mitigating wind-related issues in various environments.

Tree-View Summary

Objective: To analyze the windbreak performance of tree canopies using computational fluid dynamics (CFD) simulations, investigating the effects of canopy porosity, shape, and tree spacing.

Methodology:

Model Development:

- Tree canopy modeled as porous media
- Additional source terms added to momentum equations
- Realizable k-ε turbulence model used with modifications for canopy effects

Numerical Setup:

- SIMPLE algorithm for pressure-velocity coupling
- Second-order upwind scheme for spatial discretization
- Power law velocity profile at inlet
- No-slip condition at ground, slip condition at top, outflow condition at outlet

Model Validation:

- Compared CFD results with wind tunnel measurements and previous numerical studies
- Focused on velocity profiles at various downstream locations

Parameter Studies:

- Canopy porosity: 20% to 100% (8 cases)
- Canopy shapes: cylindrical, conical, quadrilateral pyramid
- Tree spacing: 0.1m to 2.0m (5 cases)

Analysis:

- Examined velocity profiles at different downstream locations
- Compared effects of various parameters on windbreak performance

Key Findings:

- Canopy porosity significantly impacts windbreak performance
- Lower porosity doesn't always result in better windbreak, especially near the ground
- Canopy shape mainly affects upper regions of the flow
- Tree spacing effects are most pronounced near the canopies
- Far downstream, spacing effects can be approximated by equivalent porosity changes

Conclusions:

- Porous media approach effectively simulates tree canopy windbreak performance
- Porosity is the most influential parameter on downstream wind field characteristics
- Simplifying complex canopies to cylindrical shapes is acceptable for most applications
- Tree spacing primarily affects near-canopy regions; far-field effects are similar to porosity changes

Limitations and Future Work:

- More detailed representation of canopy structure needed
- Inclusion of seasonal variations in leaf density
- Coupling with thermal effects for urban microclimate studies
- Integration of large eddy simulation (LES) for more accurate turbulence modeling
- Consideration of flexible canopy deformation under strong winds

Significance: This study provides valuable insights into the complex interactions between wind and tree canopies, offering a foundation for optimizing windbreak designs in various applications such as urban planning, agriculture, and environmental protection. The numerical approach developed here can be extended to more complex scenarios, potentially improving our ability to mitigate wind-related issues in built and natural environments.

3.6.5.7 “Simulation of direct shear tests on rooted and non-rooted soil using finite element analysis“ (Mickovski et al. 2011)

Text Summary

This study by Mickovski et al. investigates root-soil reinforcement mechanisms using finite element analysis (FEA) to simulate direct shear tests. The researchers developed 2D and 3D models using Plaxis and Diana software, respectively, to compare rooted and non-rooted soil behavior under shear stress. 2D model is depicted in Figure 51.

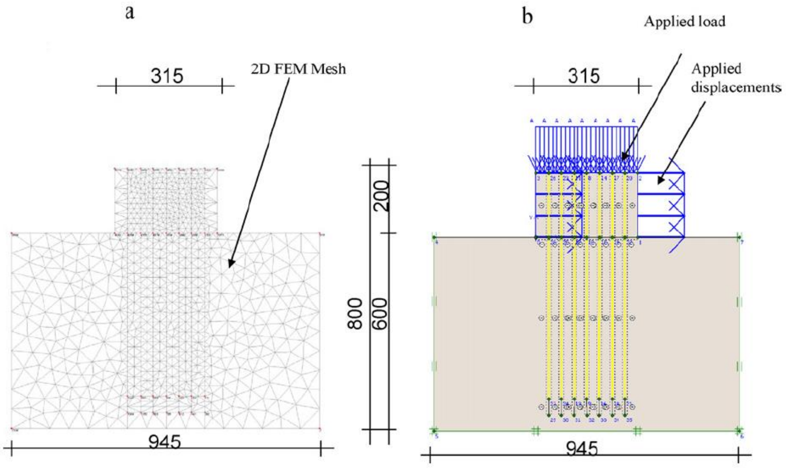


Figure 51 Finite element mesh (a) and loading (b) for a 2D multi-rooted simulation. Dimensions in mm (images and caption are from Mickovski et al. 2011).

The models incorporated Mohr-Coulomb elastic-plastic soil properties and represented roots as linear elastic structural elements. Single-rooted and multi-rooted distributions were simulated based on real plant species. The analysis included gravity loading, vertical normal load, and prescribed horizontal displacement to mimic shear conditions.

Key findings revealed that root presence increased overall soil shear strength, with multi-rooted models showing significantly higher resistance than single-rooted or non-rooted ones. 3D models predicted higher peak shear stress compared to 2D models, suggesting more realistic representation of root-soil interactions. The study also examined the effects of tension cut-off in soil modeling, finding that models allowing tension showed a stiffer response but lower ultimate shear capacity.

To validate the FEA results, the researchers conducted laboratory direct shear tests using soil samples with analogue roots and compared findings with in-situ test data from literature. The physical tests corroborated the model predictions, showing increased ductility and shear strength in rooted samples.

While the study demonstrates the potential of FEA in understanding root-soil reinforcement, the authors acknowledge limitations such as the need for more accurate root property data and further investigation of root orientation and branching effects. Future work should focus on refining 3D modeling techniques, exploring soil moisture effects, and validating models against field data for various plant species.

This research contributes valuable insights to eco-engineering practices for slope stability and erosion control, potentially improving the design and management of vegetation-based soil stabilization systems

Tree-View Summary

Objective: To simulate direct shear tests on rooted and non-rooted soil using finite element analysis to better understand the fundamental mechanisms of root-soil reinforcement.

Methodology:

Model Creation:

- 2D models developed in Plaxis
- 3D models developed in Diana

- Models simulated direct shear tests on soil blocks

Material Properties:

- Soil: Mohr-Coulomb elastic-plastic model
- Roots: Linear elastic structural elements (geogrids in 2D, embedded reinforcements in 3D)
- Interface: Elastic-plastic model based on Mohr-Coulomb equation

Root Distribution:

- Single-rooted and multi-rooted models
- Root sizes and distribution based on two perennial herbaceous species

Load Case:

- Gravity load
- Vertical normal load (150 N/m2)
- Prescribed horizontal displacement for shear

Analysis:

- 2D plane strain analysis in Plaxis
- 2D and 3D analysis in Diana
- Comparison of rooted and non-rooted soil behavior
- Investigation of tension cut-off effects

Validation:

- Laboratory direct shear tests on soil with analogue roots
- Comparison with in-situ direct shear tests from literature

Key Findings:

- Presence of roots increased overall soil shear strength
- Multi-rooted models showed significantly higher shear resistance than single-rooted or non-rooted models
- 3D models predicted higher peak shear stress than 2D models
- Models with tension cut-off showed less stiff response but higher ultimate shear load capacity
- Root inclusion increased ductility of soil samples in physical tests

Conclusions:

- Finite element analysis can effectively simulate root-soil reinforcement mechanisms
- Root distribution and concentration significantly affect soil shear strength
- 3D models provide more realistic representation of root-soil interactions
- Model results qualitatively align with physical test observations

Limitations and Future Work:

- Need for more accurate root material and strength properties data
- Further investigation of root orientation and branching effects required
- Refinement of 3D modeling techniques and interface elements needed
- Investigation of soil moisture and hydrological condition effects
- Validation against refined numerical models and field data for various plant species

Significance: This study demonstrates the potential of finite element analysis in understanding and quantifying root-soil reinforcement mechanisms. The findings can guide the design and management of vegetation-based soil stabilization systems, contributing to more effective eco-engineering practices for slope stability and erosion control.

3.6.5.8 "Tree stability under wind: simulating uprooting with root breakage using a finite element method" (Yang et al. 2014)

Text Summary

This study by Yang et al. presents a novel finite element model for simulating tree uprooting, with a focus on incorporating progressive root breakage. The researchers developed a 3D model using ABAQUS software, integrating a soil domain, root system, and rigid stem (see Figure 52). A key innovation is the implementation of a constitutive law for root failure based on continuum damage mechanics, allowing for the simulation of individual root breakages during the uprooting process.

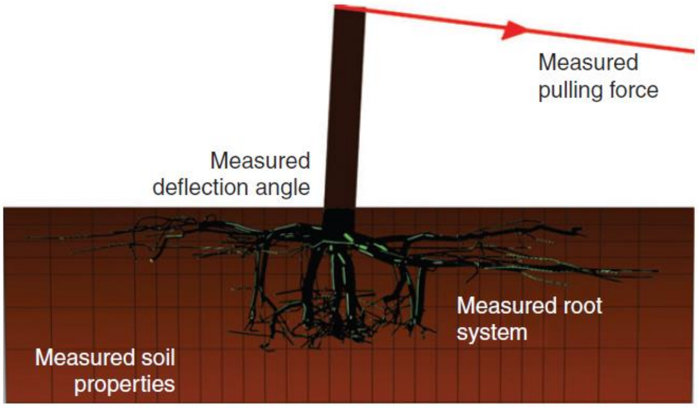


Figure 52 FEM model (image is from Yang et al. 2014).

The model was validated using data from a tree-pulling experiment on a 13-year-old Pinus pinaster. The researchers digitized the tree's 3D root architecture and measured soil properties through laboratory tests. Root mechanical properties were varied with root diameter, while soil was modeled as an elastic-plastic material using the Mohr-Coulomb failure criterion.

Simulations showed good agreement with experimental results in terms of force-displacement response and energy estimations. The model successfully captured the progressive nature of root breakage during uprooting, a feature does not present in previous models. Results highlighted the significant influence of root mechanical properties on anchorage strength, with thick counter-winchward lateral roots contributing more to stability than fine roots.

While the model overestimated initial root-soil system stiffness, it represents a significant advancement in understanding tree anchorage mechanisms. Limitations include the need for better root material property data and improvement in modeling initial root-soil stiffness.

This study provides valuable insights into tree stability and has potential applications in forestry management, wind risk assessment, and understanding tree adaptation to environmental stresses. Future work could extend the model to more complex root architectures of adult trees and incorporate heterogeneous soil conditions.

Tree-View Summary

Objective: To develop a new finite element model for simulating tree uprooting that incorporates progressive root breakage, using realistic root architecture and soil properties.

Methodology:

Model Development:

- Created 3D finite element model in ABAQUS
- Incorporated soil domain, root system, and rigid stem
- Developed constitutive law for root failure based on continuum damage mechanics

Data Acquisition:

- Conducted tree-pulling experiment on 13-year-old Pinus pinaster
- Digitized 3D root architecture using Polhemus Fastrak low magnetic field digitizer
- Measured soil properties through laboratory tests

Material Properties:

- Root: Varied mechanical properties with root diameter
- Soil: Used elastic-plastic model with Mohr-Coulomb failure criterion

Root-Soil Interaction:

- Employed embedded element method
- Compared with frictional behavior approach in preliminary study

Load Case:

- Applied gravity in first step
- Imposed horizontal displacement at stem top in second step

Analysis:

- Performed simulations using ABAQUS software
- Analyzed turning moment vs. deflection angle and energy induced by pulling force

Key Findings:

- Model successfully simulated progressive root breakage during uprooting
- Simulated response curves showed good agreement with experimental results
- Root mechanical properties significantly influenced anchorage strength
- Thick counter-winchward lateral roots contributed more to anchorage than fine roots
- Model overestimated initial root-soil system stiffness

Conclusions:

- First model to simulate root breakages during tree uprooting
- Provided realistic force-displacement response and energy estimations
- Highlighted importance of root mechanical properties in tree stability
- Demonstrated potential for analyzing root system optimization and soil management impacts

Limitations and Future Work:

- Need for better data on root material properties
- Improve modeling of initial root-soil stiffness

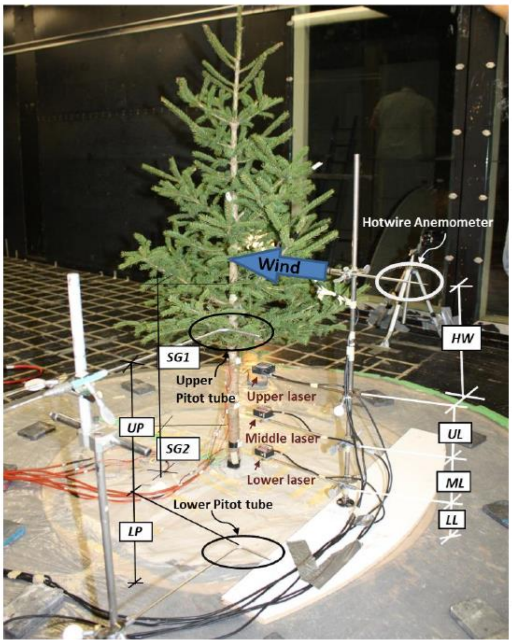
- Extend model to more complex root architectures of adult trees
- Incorporate heterogeneous soil conditions and water table effects
- Validate root failure behavior through individual root mechanical tests

Significance: This study represents a significant advancement in understanding tree anchorage mechanisms. The developed model provides a powerful tool for investigating the uprooting process as a function of tree characteristics and soil properties. It has potential applications in forestry management, wind risk assessment, and understanding tree adaptation to environmental stresses.

3.6.5.9 “Foundation Effects of Trees Under Wind Loads“ (Sagi 2016)

Text Summary

This thesis by Padmavathi Venkata Sagi investigates the response of trees to wind loading, focusing on root-soil interaction and the effects of trenching on tree stability. The research combines field testing of a mature Norway spruce tree with wind tunnel experiments (see Figure 53) on tree saplings, employing a novel approach to study trenching effects.



Dimension Description		Setup		
Description	Symbol	T1 in Sand	T2 in Sand	T2 in Clay
Height of hot wire anemometer above wind tunnel floor	HW	68.0	68.0	68.0
Height of upper pitot tube above lower pitot tube	UP	37.0	37.4	37.4
Height of lower pitot tube above tunnel floor	LP	30.8	31.3	31.25
Height of upper laser above middle laser	UL	11.25	12.1	10.0
Height of middle laser above lower laser	ML	12.5	12.8	10.0
Height of lower laser above wind tunnel floor	LL	11	16.5	27.25
Height of strain gauge attachment above lower strain gauge attachment	SG1	49.25	56.5	56.5
Height of lower strain gauge attachment above soil level	SG2	13.25	3.0	3.0

Note: All dimensions in cm

Figure 53 Tree sapling in the wind tunnel and instrument positions of the experimental setup (images and caption are from Sagi 2016).

The methodology involved winching tests on a mature tree instrumented with strain gauges and tilt sensors, as well as wind tunnel tests on saplings with intact root systems in sand and clay soils. The author developed a Winkler foundation model to represent root-soil interaction and used cantilever beam analysis for stem response. Dynamic properties were analyzed through natural frequencies, damping ratios, and admittance functions.

Key findings include the observation that tree stem response approximates a cantilever beam, and that root-soil interaction significantly affects tree dynamic response. The study revealed that aerodynamic damping varies with wind speed, reaching up to 3-4 times the structural damping. Importantly, load redistribution was observed in root systems in cohesive soils but not in frictional soils, indicating that soil type plays a crucial role in tree stability during wind loading.

The research also demonstrated that trenching impacts tree stability differently depending on soil type. The Winkler foundation model proved effective in representing root-soil interaction, offering a new approach to incorporate soil parameters in tree stability analysis.

While the study provides valuable insights, limitations include the need for more validation data and potential impacts of tree sapling desiccation during wind tunnel testing. Future work should focus on higher sampling rates in field tests and investigation of damping variations with wind speed.

This research contributes significantly to the understanding of tree-wind interactions, particularly regarding root-soil dynamics. The novel experimental techniques and analysis methods presented offer valuable tools for improving numerical models of tree stability, with potential applications in urban forestry management and tree risk assessment.

Tree-View Summary

Objective: To investigate the response of trees to wind loading, focusing on root-soil interaction and the effects of trenching on tree stability.

Methodology:

Field Testing:

- Winching test on a mature Norway spruce tree
- Instrumentation with strain gauges and tilt sensors
- Measurement of tree properties (stem taper, crown shape, root architecture)

Wind Tunnel Testing:

- Tests on Norway spruce saplings with intact structural root systems
- Custom soil box for testing in sand and clay media
- Instrumentation of stems and roots with strain gauges
- Application of incremental wind loads

Trenching Experiments:

- Novel wind tunnel tests with incremental trenching around tree roots
- Examination of trenching effects in sand and clay soils

Data Analysis:

- Winkler foundation model for root-soil interaction
- Cantilever beam analysis for stem response
- Dynamic analysis (natural frequencies, damping ratios, admittance functions)
- Rainflow counting for cyclic loading analysis
- Statistical analysis of sway patterns and failure probabilities

Key Findings:

- Tree stem response approximates a cantilever beam
- Root bending moment and shear force responses align with previous research
- Winkler foundation model effectively represents root-soil interaction
- Dynamic tree sway is significantly influenced by root-soil support system
- Aerodynamic damping varies with wind speed, up to 3-4 times structural damping
- Load redistribution occurs in root systems in cohesive soils, but not in frictional soils
- Trenching effects on stability differ between cohesive and frictional soils

Conclusions:

- Simple engineering principles can be applied to analyze tree stability
- Root-soil interaction significantly affects tree dynamic response
- Soil type influences load redistribution in root systems during wind loading
- Trenching impacts tree stability differently depending on soil type

Limitations and Future Work:

- Limited data for result validation
- Potential desiccation of tree saplings during wind tunnel testing
- Pruning of fine roots may have altered root system response
- Need for higher sampling rates in field tests
- Further investigation of damping variations with wind speed required
- Testing of tree groups in wind tunnel to understand tree interaction effects

Significance: This study provides novel experimental data and analysis techniques for understanding tree-wind interactions, particularly regarding root-soil dynamics. The findings and methodologies presented offer valuable insights for improving numerical models of tree stability and can inform urban forestry management practices, especially concerning trenching near trees.

3.6.5.10 "A Generic 3D Finite Element Model of Tree Anchorage Integrating Soil Mechanics and Real Root System Architecture " (Dupuy et al. 2007)

Text Summary

This study by Dupuy et al. presents a novel 3D finite element model (FEM) for simulating tree anchorage and uprooting, integrating real root system architectures with soil mechanics. The researchers developed the model using ABAQUS software and validated it against field data from two poplar cultivars.

The methodology involved measuring root system architectures and conducting static bending tests on trees in the field. The FEM was created with automatic mesh generation from root architecture data, modeling soil as an elastic-perfectly plastic material with Mohr-Coulomb criteria and roots as elastic-plastic material with von Mises yield criterion. Root-soil interaction was simulated using kinematic coupling between nodes. Plastic strain results are depicted in Figure 54.

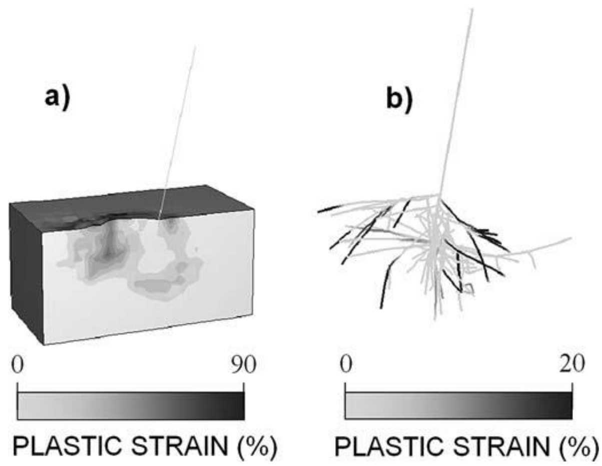


Figure 54 Simulated fields of plastic strain generated in the frictional soil(a) and in the root system (b) during the uprooting of the Raspalje cultivar.In (a), permanent deformations were

greater on the windward side of the tree. In (b), failure of root elements appeared in the region of soil plasticfailure. (images and caption are from Dupuy et al. 2007).

Key findings revealed that root architecture strongly influences anchorage strength, and soil type affects failure patterns. Soil cohesion emerged as the most influential parameter for uprooting resistance. The model consistently overestimated anchorage strength compared to field tests, highlighting areas for improvement.

The study concluded that the developed FEM provides valuable insights into root-soil interactions during uprooting and allows for virtual experiments to isolate effects of individual roots or soil properties. However, limitations such as the need for more realistic root-soil interface modeling and incorporation of anisotropic root wood properties were identified.

This research might be seen as a quantum leap into predicting tree uprooting during storms. The generality of the model allows its application to a wide range of tree species and soil conditions, thus making it valuable in perspectives for forest management and storm damage prediction. The model reduces the need to conduct destructive field tests that provide only limited insight into the mechanics of tree anchorage by allowing virtual experiments.

Tree-View Summary

Objective: The development and testing of a generic 3D-FE model simulating anchorage and uprooting of trees in soil should involve realistic root system architecture and soil mechanics.

Methodology:

Data Acquisition:

- Measurement of root system architecture for two poplar cultivars
- Static bending tests on trees in the field

Model Creation:

- Development of FEM using ABAQUS software
- Automatic mesh generation from root architecture data

Material Properties:

- Soil: Elastic-perfectly plastic material with Mohr-Coulomb criteria
- Roots: Elastic-plastic material with von Mises yield criterion
- Root-soil interaction: Kinematic coupling between nodes

Load Case:

- Lateral displacement applied to tree trunk to simulate uprooting

Analysis:

- Comparison of simulated vs. measured uprooting forces
- Analysis of plastic strain fields in soil
- Sensitivity analysis of soil and root parameters

Key Findings:

- Root architecture strongly influences anchorage strength
- Soil type (frictional vs. cohesive) affects failure patterns
- Soil cohesion was the most influential parameter for uprooting resistance
- Model overestimated anchorage strength compared to field tests

- Raspalje cultivar showed higher uprooting resistance than Beaupré in both simulations and experiments

Conclusions:

- The developed FEM can provide insights into root-soil interactions during uprooting
- Root system structure and soil properties both play crucial roles in tree anchorage
- The model allows for virtual experiments to isolate effects of individual roots or soil properties

Limitations and Future Work:

- Need for more realistic root-soil interface modeling
- Incorporation of anisotropic properties of root wood
- Development of more advanced soil models (e.g., poro-viscoplastic)
- Reduction of computation time and improvement of convergence
- Validation with more experimental data

Significance: This represents the important step to develop a powerful tool predicting the uprooting of trees during storm events. Because the model is somewhat generic, it can now be applied to many tree species and soil types-a fact that might well lead to better forest management and, perhaps more important, better storm damage prediction. The model can further reduce reliance on expensive and destructive field testing by enabling the running of virtual experiments, while offering detailed information about the process of anchorage failure.

3.6.5.11 "Tree Biomechanics Literature Review: Dynamics" (James et al. 2014)

Text Summary

This review by James et al. revisits biomechanical investigations into trees using dynamic analytical methodologies, with a particular emphasis on open-grown specimens in an urban setting. The authors review various methodologies for such research approaches, including forestry investigations, open-grown tree analyses, wind tunnel experiments, and computational simulations. It is emphasized how development in this regard has moved from simple tree models to sophisticated multi-modal and finite element method (FEM) strategies as far as branch dynamics are concerned.

The review shows that material properties are of limited importance in the tree dynamics, while the form and morphology of the trees and branches are an essential factor in the dynamic response of trees to wind. All such simplified models not including branch dynamics are considered inadequate for the open-grown trees, and multi-modal analysis would better represent the interaction between the branch and trunk.

Key results include the application of dynamic amplification factor (DAF) and dynamic response factor (DRF) on trees in the recent literature, along with complex, nonlinear damping of trees. They mentioned that the effect of branch oscillation on the tree dynamic behavior appears to be much larger than it would be expected with regard to mass, and hence, branch dynamic consideration is particularly important for stability assessment.

The evaluation delineates multiple domains for prospective inquiry, notably the necessity for additional empirical data concerning real wind loads and the failure of trees in storm circumstances, along with an examination of the torsional forces affecting trunks and branches. Furthermore, it underscores the paucity of recommendations pertaining to the pruning of open-grown trees aimed at mitigating wind-related damage.

This review, therefore, underpins that more sophisticated modeling approaches are required for realistic analysis of open-grown trees, which may provide major impacts on current urban forest management and risk assessment methodologies. Results bring into focus the complexity of tree biomechanics and the pressing need for further research in this area.

Tree-View Summary

Objective: To review biomechanical studies of trees using dynamic analysis methods, focusing on open-grown trees typically found in urban areas.

Methodology:

Literature Review:

- Focused on studies published in the last 20 years
- Included seminal older studies where appropriate
- Emphasized open-grown trees rather than forest or plantation trees

Dynamic Analysis Methods:

- Lumped-mass procedure
- Generalized displacements for uniformly distributed mass
- Finite element method (FEM)

Research Strategies:

- Forestry (trees in groups)
- Open-grown trees (individual trees with branches)
- Wind tunnels (small trees to measure drag coefficients)
- Modeling (dynamic models of trees)

Model Types:

- Simple tree models
- Complex multimodal models
- Finite element analysis models

Key Findings:

- Material properties play a limited role in tree dynamics.
- Form and morphology of trees and branches significantly influence tree dynamics.
- Simple models ignore branch dynamics, while complex models and FEM analyses develop a multimodal approach to represent branch dynamics.
- Branch oscillations influence tree dynamic behavior more than can be explained by their additional mass alone.
- Dynamic amplification factor (DAF) and dynamic response factor (DRF) have been applied to trees in only a few studies.
- Damping in trees is complex and may have a non-linear response.

Conclusions:

- Open-grown trees require more complex, multimodal analysis due to the dynamic coupling of branches.
- The dynamic response of open-grown trees in winds is greatly influenced by the size and form of the tree.
- Multimodal analysis is needed to represent the dynamics of branches on trees accurately.

- Recent studies indicate that tree form has a greater influence than material properties on dynamic response.

Limitations and Future Work:

- Limited recommendations for pruning open-grown trees to reduce wind damage.
- Need for further research on the dynamic contribution and damping effects of branches.
- Lack of measurements of tree failure under actual wind conditions.
- Limited published data on actual wind loads on trees.
- Torsional forces and loads on trunks and branches have not yet been investigated.

Significance: This review highlights the importance of considering branch dynamics in tree stability assessments and wind load predictions. It emphasizes the need for more complex modeling approaches to accurately represent open-grown trees, which could lead to improved urban forest management practices and risk assessment methodologies.

3.6.5.12 "Tree biomechanics" (James et al. 2017)

Text Summary

This review article by James, Moore, Slater, and Dahle examines recent developments in tree biomechanics, focusing on how trees respond to mechanical loads, particularly wind. The authors conducted a comprehensive literature review using major scientific databases and personal communications with colleagues.

Key findings highlight the importance of tree form and architecture in determining dynamic response to wind, surpassing the influence of material properties. The review emphasizes the role of branches as coupled oscillators that modify trunk sway and provide damping. Recent evidence suggests that strain, rather than stress, may be the primary trigger for adaptive growth responses in trees, challenging traditional concepts like uniform stress distribution.

The manuscript deals with the key innovative measurement methodologies of optical strain measurement, enabling one to closely observe the strain distribution within intricate arboreal structures in ways that were hitherto not possible. These are the things producing new insights into mechanical behavior and growth responses.

Also included are new views on branch attachment mechanisms, with more complicated structures than formerly believed, in which interlocking grain patterns are integral to determining branch strength.

The biomechanics of trees is moving toward more dynamic, strain-based models of tree response to loading, the authors conclude. Integration across the investigations conducted both within forest-grown and urban trees, as well as more complex modeling-a model that incorporates tree architecture, branch dynamics, and active growth-will be required.

The review is important given its implication for forest management, urban tree care, and our general view of plant adaptation strategies. A shift toward more dynamic and strain-based models may indicate pathways to improved risk assessment and management strategies for both forest and urban trees.

Tree-View Summary

Objective: To review recent research in tree biomechanics, focusing on how trees respond to mechanical loads, especially in winds, and to discuss new insights into tree structure, growth response, and failure mechanisms.

Methodology:

Literature Review:

- Searched databases including CAB Abstracts, Google Scholar, Agricola, and Web of Science
- Used keyword search terms including biomechanics, trees, wind, morphology, stress, strain, mechanosensing, thigmomorphogenesis, and branches
- Checked references from obtained articles for additional relevant material
- Communicated with colleagues for upcoming unpublished studies

Analysis of Recent Developments:

- Examined studies on tree dynamic response to wind loading
- Reviewed research on stress and strain measurements in trees
- Analyzed studies on growth response to mechanical loads
- Evaluated new concepts in branch attachment and tree structure

Key Findings:

- Tree form and architecture significantly influence dynamic response to wind more than material properties.
- Branches act as coupled oscillators, modifying trunk sway behavior and providing damping.
- Recent evidence suggests strain, rather than stress, may be the primary trigger for adaptive growth response in trees.
- New optical strain measurement techniques allow for more detailed analysis of strain distribution in complex tree structures.
- Traditional concepts like uniform stress distribution in trees are being challenged by new research.
- Branch attachment mechanisms are more complex than previously thought, with interlocking grain patterns playing a crucial role.

Conclusions:

- Tree biomechanics is moving towards more dynamic, strain-based models of tree response to loading.
- Tree architecture and morphology are key factors in understanding wind-tree interactions.
- New measurement techniques are providing more detailed insights into tree mechanical behavior.
- Traditional concepts in tree biomechanics are being reevaluated in light of new evidence.

Limitations and Future Work:

- Need for more integration between forest-grown and urban tree biomechanics research.
- Further investigation required to fully understand the role of strain in triggering growth responses.
- Development of more sophisticated models incorporating tree architecture, branch dynamics, and adaptive growth.
- More research needed on the biomechanics of different tree species and growth forms.

Significance: This review discusses the significant advances that have been achieved in tree biomechanics, with particular attention to understanding the dynamic properties of trees under wind loading. The results give important implications for the management of forests, care of urban trees, and greater insight into plant adaptive strategies. Moving on towards more dynamic, strain-based ways of modeling trees' responses may provide better methods for both risk assessment and management within the forest and urban environments.

3.6.5.13 "Using FEM to predict tree motion in a wind field" (Hu et al. 2008)

Text Summary

This study by Hu et al. presents a finite element method (FEM) approach to predict tree motion in wind fields. The researchers developed two FE tree models: a realistic nature-looking model and a geometrically symmetric model (see Figure 55, Figure 56). They modeled trunks and branches as tapered cantilever beams with circular cross-sections using beam elements in FE software.

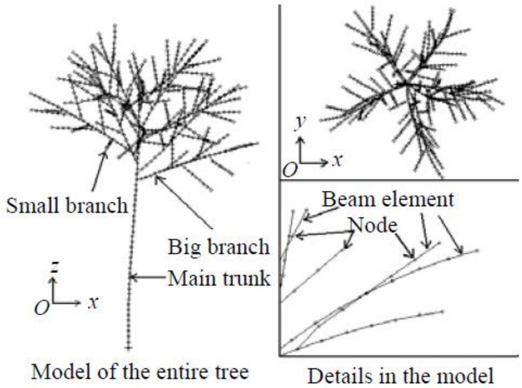


Figure 55 FE tree model-I (asymmetric model) (images and caption are from Hu et al. 2008).

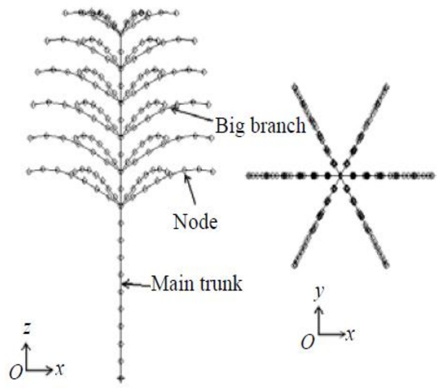


Figure 56 FE tree model-II (symmetric model) (images and caption are from Hu et al. 2008).

The study considered two scenarios: trees without leaves and trees full of leaves. For leafless trees, they applied vortex-induced vibration (VIV) theory to calculate wind forces. For trees with leaves, they used fluid-structure interaction (FSI) analysis with a virtual shell as a coupling surface on the canopy.

The researchers employed MSC.PATRAN for preprocessing and MSC.Dytran for dynamic FE analysis. They also conducted Fourier power spectrum analysis of oscillating signals to investigate tree motion characteristics.

Key findings include the impact of asymmetric material properties on tree motion, resulting in complex looping movements. Leaves were found to significantly increase wind force and swaying amplitude along the wind direction, while crosswind swaying was mainly attributed to branch interaction. The study also revealed that trees with leaves exhibit a lower frequency peak (about 0.27 Hz) due to leaf influence, while higher frequency peaks (0.38-0.50 Hz) are primarily caused by the main trunk and big branches.

Importantly, the research demonstrated that branch interactions play a crucial role in preventing dangerous resonant swaying motions from developing. This finding has significant implications for understanding tree stability in wind conditions.

Some of the limitations of the study are the need for further leaf modeling, including the dynamics of the soil-root system, and simulating more complex wind field models. Further research could address these limitations and thus dig deeper into the relationship of asymmetric material properties and adaptation to wind forces in trees.

Results obtained in this research contribute to a better understanding of tree biomechanics and may have possible applications in forestry management, urban development, and engineering of wind-resistant constructions, glimpsing at the mechanics of trees.

Tree-View Summary

Objective: The work is aimed at developing the finite element method approach to simulate tree motion under wind loading, considering complex interactions at the branch level and material properties asymmetry.

Methodology:

Model Creation:

- Two FE tree models: Model-I (realistic nature-looking) and Model-II (geometrically symmetric)
- Trunks and branches modeled as tapered cantilever beams with circular cross-sections
- Used circular cross-section beam elements in FE software
- For trees with leaves, enclosed a virtual shell (coupling surface) on the canopy

Material Properties:

- Wood density: 850 kg/m³
- Structure modulus of elasticity (SME):
- Main trunk: 10.0 GPa
- Big branches: 2.0-5.0 GPa
- Small branches: 0.50 GPa
- Material damping factor: 0.05

Wind Profile:

- Logarithmic wind profile used
- Wind speed as a function of height above ground

Load Case:

- Considered two scenarios: trees without leaves and trees full of leaves
- For leafless trees: Used vortex-induced vibration (VIV) theory
- For trees with leaves: Used fluid-structure interaction (FSI) analysis

Analysis:

- Preprocessing: MSC.PATRAN
- Dynamic FE code: MSC.Dytran
- Fourier power spectrum analysis of oscillating signals

Key Findings:

- Asymmetric material properties result in complex looping movements of trees under wind loading
- Leaves significantly increase wind force and swaying amplitude along the wind direction
- Crosswind swaying is mainly due to branch interaction, less affected by leaves
- Trees with leaves exhibit a lower frequency peak (about 0.27 Hz) due to leaf influence
- Higher frequency peaks (0.38-0.50 Hz) are mainly due to the main trunk and big branches
- Branch interaction prevents dangerous resonant swaying motions from developing

Conclusions:

- FEM models incorporating branches and asymmetric properties provide more accurate predictions of tree motion in wind fields
- Leaf presence significantly affects along-wind motion but has little impact on crosswind motion
- Branch interactions play a crucial role in preventing dangerous swaying motions

Limitations and Future Work:

- Leaf modeling could have more detail implemented.
- Incorporating soil-root interaction may probably provide a complete insight into the mode
- Turbulence can be simulated using advanced models of the wind field
- Further investigation of the relationship between asymmetric material properties and tree adaptation to wind loads

Significance: The present work introduces a comprehensive FEM approach to tree motion under wind loading, taking into consideration some critical aspects, such as branch interaction and asymmetrical properties. Results are important for the understanding of tree biomechanics and will find applications in forestry management, urban planning, and biomimetic design of wind-resistant civil structures.

3.6.5.14 “An Experimental Investigation of the Wind Forces on Trees“ (Crespi et al. 2014)

Text Summary

This study, titled "An Experimental Investigation of the Wind Forces on Trees" by Crespi, Franchi, Longarini, and Aly, explores the effects of wind on trees planted on high-rise building balconies. The research, motivated by design challenges in Milano, aims to evaluate tree safety systems under wind loads.

The methodology combines full-scale wind tunnel testing at Florida International University's Wall of Wind facility with numerical modeling. Experiments were conducted in two phases: individual tree tests and tests on a complete system including a concrete box and steel cage. Various wind speeds and directions were tested, with forces measured using load cells.

Numerical analysis employed Finite Element Modeling (FEM), representing the tree trunk as beam elements and the crown force as a concentrated load (see Figure 57). The researchers developed drag coefficient curves for different tree species and performed a construction stage analysis to simulate soil behavior.

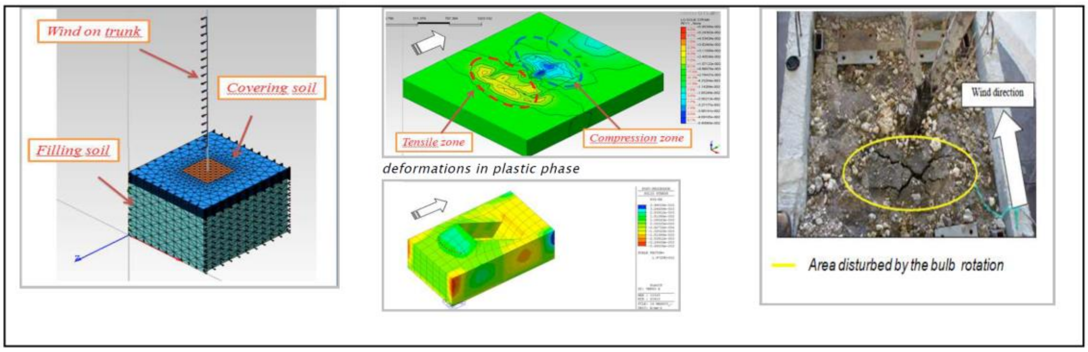


Figure 57 Construction stage Analysis and results comparison to the WoW test. (images and caption are from Crespi et al. 2014).

Key findings reveal that experimental forces were lower than assumed design values, and no failures occurred during testing. The numerical models showed good agreement with experimental results in predicting maximum tree displacements. The study highlights the importance of accurately estimating drag coefficients, which vary significantly with wind speed and crown permeability.

It concludes that extensive wind tunnel tests provide substantial data about the trees' reactions to wind forces, computational models can predict the movement of trees with sufficient accuracy, and the testing done in the preparatory phase provides highly useful insights into soil reactions to wind stresses.

This study contributes to improving building codes and design criteria for hurricane-prone regions, particularly for integrating trees into high-rise building designs. Future work could expand to testing more tree species and investigating long-term wind effects on trees and soil.

Tree-View Summary

Objective: To examine the aerodynamic forces acting on trees situated on the balconies of high-rise buildings and to assess the efficacy of tree bracing frameworks and safety mechanisms.

Methodology:

Experimental Setup:

- Used Wall of Wind (WoW) facility at Florida International University
- Tested full-scale trees under various wind speeds
- Employed load cells to measure forces at tree base

Test Phases:

- Phase 1: Individual tree tests
- Phase 2: Tests on complete system (tree + concrete box + steel cage)

Numerical Modeling:

- Created Finite Element Model (FEM) of trees
- Modeled trunk as beam elements
- Represented crown force as concentrated load

Load Cases:

- Wind speeds: v1=13.4 m/s, v2=26.8 m/s, v3=40.2 m/s, v4=54.9 m/s
- Wind directions: 0° and 90°

Analysis:

- Computed drag forces on the trunk and crown
- Construction stage analysis was performed using FEM.
- Contrasted quantitative findings with experimental data

Key Findings:

- Experimental forces were lower than assumed design values
- No collapse or failure occurred during tests
- FEM results have shown good agreement with experimental displacements.
- Drag coefficient is considerably dependent on the wind speed and crown permeabili

Conclusions:

- Full-scale wind tunnel testing provides valuable data for tree behavior under wind loads
- Numerical models can accurately predict maximum tree displacements
- Construction stage analysis helps understand soil behavior under wind loads
- Proper estimation of drag coefficient is crucial for accurate force predictions

Limitations and Future Work:

- Limited tree species tested; expand to more varieties
- Further investigation needed on long-term effects of wind on trees and soil
- Develop more sophisticated models for crown aerodynamics

Significance: This study provides crucial insights for designing safe and effective tree installations on high-rise building balconies. The combination of full-scale experiments and numerical modeling offers a comprehensive approach to understanding wind forces on trees, which can be applied to improve building codes and design criteria for hurricane-prone regions.

3.6.5.15 “Biomechanics of Buttressed Trees: Bending Strains and Stresses” (Clair et al. 2003)

Text Summary

This study, "Biomechanics of Buttressed Trees: Bending Strains and Stresses" by Clair et al. 2003, investigates the mechanical behavior of buttressed trees under bending loads. The researchers examined two Sloanea species trees in French Guiana, applying controlled bending forces and measuring strains at various points on the buttresses and trunk (see Figure 58).

The methodology combined field experiments with theoretical modeling. Strain gauge sensors measured longitudinal, tangential, and shear strains, while a simple beam model based on strength of materials theory was developed for comparison. Wood properties and cross-sectional geometries were also analyzed.

Key findings revealed that buttresses exhibit linear and elastic behavior under small strains. Longitudinal strains remained nearly constant along buttress ridges, while shear strains were minimal near ridges and maximal on sides near the trunk. The beam model accurately predicted strain variations around cross-sections but struggled with variations along height.

Importantly, the study found that the highest failure risks occurred on buttress sides due to shear and tangential stresses, not on ridges where longitudinal stresses were highest.

Different strain patterns were observed between flat and curved buttresses, highlighting the importance of buttress shape in mechanical behavior.

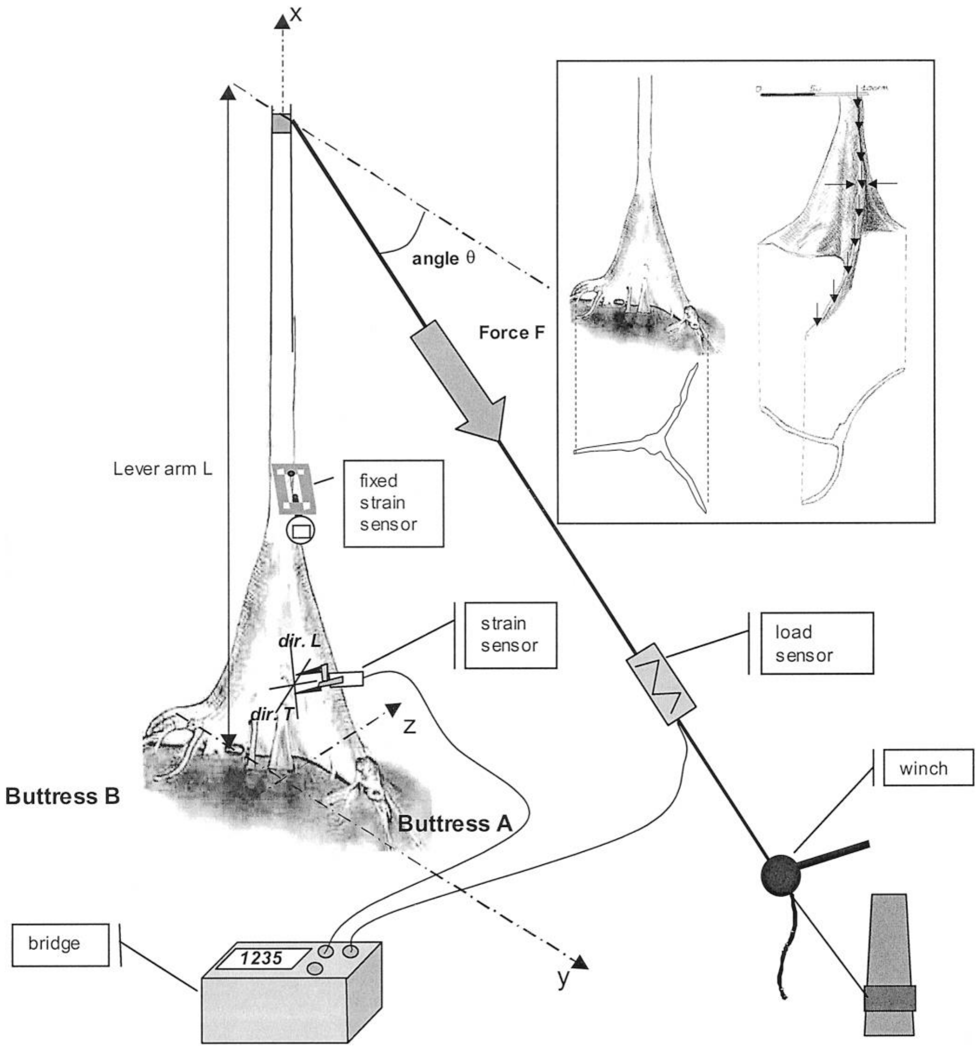


Figure 58 Design of the bending tests and buttress forms of trees of Sloanea spp. Inset: left, first tree, with flat buttresses; right, second tree, with curvedbuttresses. On the first tree, measurements were made in every part of the buttressed zone. On the second tree, the locations of the measurements are indicatedby arrows (images and caption are from Clair et al. 2003).

The research challenges the universal applicability of the constant stress hypothesis for buttress formation and emphasizes the crucial role of shear and tangential stresses in buttress failure risks. However, limitations include a small sample size and lack of chronological data on buttress development.

This study advances our understanding of tropical tree biomechanics, suggesting the need for more sophisticated 3D modeling approaches and further investigation into wood property variations within buttresses. The findings have significant implications for comprehending tree stability and adaptation in tropical forests.

Tree-View Summary

Objective: To investigate the biomechanics of buttressed trees by measuring and analyzing bending strains and stresses, and to evaluate the constant stress hypothesis for buttress formation.

Methodology:

Sample Selection:

- Two trees of Sloanea species with typical thin buttresses
- Located in French Guiana rainforest

Field Experiments:

- Applied bending forces to trees using manual winch and cable
- Measured strains at different locations on buttresses using strain gauge sensors
- Recorded applied forces with load cell

Data Collection:

- Measured longitudinal, tangential, and shear strains
- Collected cross-sectional geometry data
- Determined wood basic density and Young's modulus

Modeling:

- Developed simple beam model based on strength of materials theory
- Used cross-sectional geometry and wood properties as inputs
- Computed theoretical strains for comparison with experimental data

Analysis:

- Compared experimental and modeled strain patterns
- Analyzed spatial variations of strains
- Evaluated stress distributions and failure risks

Key Findings:

- Linear and elastic behavior observed for small applied strains
- Longitudinal strains nearly constant along buttress ridges
- Shear strains minimal near ridges, maximal on sides near trunk
- Model predicted strain variations around cross-sections well, but not along height
- Highest failure risks on buttress sides due to shear and tangential stresses
- Different strain patterns observed in flat vs. curved buttresses
- Breakage initiated by cracking on the concave side of compressed buttress

Conclusions:

- Simple beam theory model has limitations in predicting strain variations with height
- Constant stress hypothesis not universally applicable to buttress formation
- Shear and tangential stresses play crucial roles in buttress failure risks
- Buttress shape (flat vs. curved) influences strain patterns significantly

Limitations and Future Work:

- Limited sample size (two trees)
- Lack of chronological data on buttress development
- Need for more sophisticated 3D modeling approaches
- Further investigation of wood property variations within buttresses

· Exploration of time-dependent growth and adaptation processes

Significance: This study provides valuable insights into the biomechanics of buttressed trees, challenging existing theories on buttress formation and function. The findings highlight the importance of considering multiple stress components in understanding tree stability and adaptation, paving the way for more comprehensive models of tree biomechanics in tropical forests.

3.6.5.16 "A finite element model for investigating effects of aerial architecture on tree oscillations" (Sellier et al. 2006)

Text Summary

This study by Sellier, Fourcaud, and Lac develops a finite element model to investigate how tree aerial architecture influences structural dynamics, particularly oscillations and damping. The researchers used three 4-year-old Pinus pinaster Ait. saplings for their analysis, creating detailed 3D models using Timoshenko beam elements for the tree structure and a U-joint connector for the root system.

The model accurately predicted fundamental sway frequencies, with errors below 4.5% across different pruning stages. It revealed that simplifying crown structure by aggregating branch masses leads to significant overestimation of frequencies. The study found that needles contribute about 80% of overall damping in the saplings, while flexible branch modeling is crucial for accurate damping predictions.

Key findings include the importance of detailed crown topology modeling for understanding damping mechanisms and the negative influence of third-order axes on stem damping. The model successfully captured these complex interactions, demonstrating the effectiveness of finite element methods in predicting tree dynamic characteristics using measured structural properties.

While the model shows promise, the authors identify areas for improvement, including better representation of needle aerodynamics, more detailed soil-root interaction modeling, and integration with wind and growth models. These enhancements could lead to more comprehensive understanding of tree responses to wind loads and improve predictions of wind damage in forests.

This research significantly contributes to our understanding of tree biomechanics by highlighting the critical role of detailed architectural modeling in predicting tree dynamic behavior. It provides a foundation for future studies integrating various aspects of tree-wind interactions and growth responses to mechanical stresses.

Tree-View Summary

Objective: To develop and validate a finite element model for studying the influence of aerial architecture on the structural dynamics of trees, focusing on oscillation frequencies and damping characteristics.

Methodology:

Data Acquisition:

- Morphological measurements on three 4-year-old Pinus pinaster Ait. saplings
- Free sway tests to measure dynamic characteristics
- Static tests to determine stem and root anchorage stiffness

Model Creation:

- Used 3D Timoshenko beam elements for vegetative axes

- Modeled connections between axes as rigid
- Represented needles by modifying mass and dissipative properties of supporting elements
- Modeled root system as a U-joint connector element

Material Properties:

- Wood density: 1100-1350 kg/m³
- Longitudinal modulus of elasticity (E): Fitted based on static tests
- Poisson's ratio (ν): 0.38
- Rayleigh damping coefficients: αW for wood, αN for needles

Load Case:

- Simulated free oscillations by applying and releasing a constant load at one-third of tree height

Analysis:

- Used modal analysis to extract vibration modes and frequencies
- Employed direct time integration techniques (Newmark algorithm) for oscillation calculations
- Utilized ABAQUS software for FE modeling and analyses

Key Findings:

- The model predicted fundamental sway frequencies with errors less than 4.5% for different pruning stages.
- Simplifying crown structure by aggregating branch masses led to frequency overestimation by about 20%.
- Needles were responsible for about 80% of overall damping in the studied saplings.
- Damping of stem movement decreased by approximately 50% when branches were modeled as rigid bodies.
- The model successfully captured the negative influence of third-order axes on stem damping.

Conclusions:

- Accurate modeling of branch geometry and flexibility is crucial for predicting tree dynamics.
- Crown topology directly affects damping characteristics and mechanisms.
- The finite element method can effectively predict dynamic characteristics of trees using measured structural properties.

Limitations and Future Work:

- Improve modeling of aerodynamic friction of needles to capture damping anisotropy.
- Develop more detailed modeling of soil-root interactions.
- Couple the model with wind models to study energy transfer from foliage to stem and roots.
- Integrate with root models to investigate mechanisms of tree breakage and uprooting.
- Incorporate the dynamic model into tree growth models to study morphological adaptation to external loads.

Significance: This study demonstrates the importance of detailed modeling of tree architecture for understanding tree dynamics. The developed model provides a foundation for more complex coupled models integrating wind effects, root systems, and tree growth, potentially improving our ability to predict and mitigate wind damage in forests.

3.6.5.17 “Simulating the dynamic behavior of Douglas-fir trees under applied loads by the finite element method“ (Moore and Maguire 2008)

Text Summary

This study by Moore and Maguire investigates the dynamic behavior of Douglas-fir trees under wind loading using finite element method (FEM) modeling (see Figure 59). The researchers aimed to improve upon previous models by representing branches as individual cantilever beams rather than discrete masses attached to the stem.

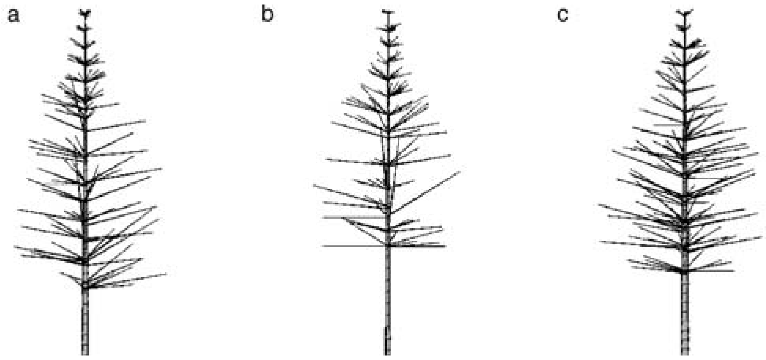


Figure 59 Finite element models showing the crown structure of Trees (a) 7, (b) 9 and (c) 11.(images and caption are from Moore and Maguire 2008)

Three 20-year-old Douglas-fir trees were selected for detailed measurement and modeling. Using ANSYS software, the authors created FEM models with stems and branches represented as 3D tapered beam elements. They tested different values of branch modulus of elasticity (E) to assess its impact on tree behavior.

The models were subjected to various loading scenarios, including modal analysis, ramped loads, and time series of wind forces. Analysis techniques included time-domain analysis, spectral analysis, and calculation of mechanical transfer functions.

Key findings revealed that modeling branches as cantilever beams improved natural frequency predictions compared to discrete mass models, especially for trees with large crowns. Branch oscillations were found to contribute significantly to overall tree damping, particularly with lower branch stiffness. The models showed high sensitivity to branch E values.

The study highlights the importance of accurately representing branch structure in tree dynamic models. It provides valuable insights into structural damping and the role of branch properties in overall tree behavior under wind loading. However, the authors note several areas for future improvement, including better data on branch properties, improved modeling of stem characteristics and root-soil interactions, and incorporation of aerodynamic factors.

It deals with great insight into the stability of trees, risk of windthrow, and response of trees to wind loading within forest ecosystems. This improved modeling approach may also contribute importantly to forest management and within tree breeding for wind resistance.

Tree-View Summary

Objective: In this study, an attempt has been made to model the dynamics of wind-loaded Douglas-fir trees using FEM, considering the branches as a whole segment cantilever beam and not as a discrete mass.

Methodology:

Data Acquisition:

- Selected three 20-year-old Douglas-fir trees
- Measured stem diameter, branch geometry, and mass distribution
- Conducted field sway tests for natural frequency and damping ratios

Model Creation:

- Used ANSYS finite element software
- Represented stems and branches as 3D tapered beam elements
- Created nodal points at measured locations and branch attachment points

Material Properties:

- Stem density: 1000 kg/m³
- Branch density: 1160 kg/m³
- Stem modulus of elasticity (E): 5.1-6.2 GPa (tree-specific)
- Branch E: 4, 5, and 6 GPa (tested separately)
- Viscous damping ratios: 0.0117-0.0380 for stems, up to 0.073 for branches

Load Cases:

- Modal analysis for natural frequency
- Ramped loads for free vibration tests
- 15-minute time series of wind forces

Analysis:

- Modal analysis for natural frequencies
- Time-domain analysis for tree response to applied loads
- Spectral analysis and mechanical transfer functions

Key Findings:

- Modeling branches as cantilever beams improved natural frequency predictions compared to discrete mass models.
- Branch oscillations contributed significantly to overall tree damping, especially with lower branch stiffness.
- Models were highly sensitive to branch modulus of elasticity (E) values.
- Mechanical transfer functions showed decreased tree response at higher frequencies when forces were applied to branches vs. the stem.

Conclusions:

- FEM models with explicit branch representation provide valuable insights into tree biomechanics under wind loading.
- Structural damping from branch oscillations plays a crucial role in energy dissipation.
- Branch stiffness (E) significantly influences overall tree dynamic behavior.

Limitations and Future Work:

- Need for better data on branch modulus of elasticity (E) and its variation within tree crowns

- Improve stem E modeling by incorporating longitudinal variations and root-soil connection stiffness
- Include stem eccentricity to better capture out-of-plane movement
- Incorporate aerodynamic admittance in wind force calculations
- Improve modeling of within-canopy wind speeds and forces
- Consider coupling with root anchorage models
- Investigate using predictive branch models to reduce data requirements

Significance: This study demonstrates the importance of accurately representing branch structure in tree dynamic models. The findings have implications for understanding tree stability, windthrow risk, and potential morphological and physiological responses to wind loading in forest ecosystems. The improved modeling approach can inform forest management practices and tree breeding programs aimed at enhancing wind resistance.

3.6.5.18 "Finite Element Analysis of Wood Materials" (Tankut et al. 2014)

Text Summary

The paper reviewed the state of the art using the Finite Element Method in the design and analysis of wood products, with focus on furniture and structural items. Authors Tankut Nurgul, Ali Naci Tankut, and Mustafa Zor reviewed various kinds of FEM modeling strategies, applications of software, and different methods of analysis that are applied in the domain. This study pronounces the versatility of FEM to analyze complex wood structures, ranging from 3D solid models, beam and spring element models, from linear to nonlinear analyses. Its main software tool is ANSYS, though other software tools are equally mentioned like IDEAS and APDL. Review has emphasized that "Wood-orthotropic properties have to be modelled precisely as well as the behavior of semi-rigid joints, if reliable results are desired." Key findings have demonstrated that FEM successfully simulates static and dynamic loading, stress distributions, and deformations in wood products. It has also been shown that the integration of FEM with experimental testing enhances the validation of models, while parameterized models enable design optimization. Limitations to proper modeling of the wood's complex material properties and high computational costs for detailed 3D models still remain. The paper concludes that FEM is indeed a powerful tool in wood product design, enabling minimal physical prototyping while allowing complex analyses. It points out that the potential of FEM for substantially enhancing furniture design processes exists, with the proviso that material characterization and model validation will have to be carefully considered. Future research is recommended in more realistic modeling of wood properties and semi-rigid joints, overcoming computational drawbacks, and in the introduction of advanced wood failure criteria into FEM analyses. One can realize from this study how FEM may revolutionize the entire wood industry by making the products cheaper, more efficient, and more innovative.

Tree-View Summary

Objective: To provide a comprehensive review of Finite Element Method (FEM) applications in analyzing wood products and furniture structures, focusing on strength analysis and design optimization.

Methodology:

Literature Review:

- Examined studies on FEM applications in wood product design
- Focused on furniture, structural components, and other wood products

FEM Model Types:

- 3D solid models (e.g., 8-node brick elements)
- Beam and spring element models

- 2D plane stress/strain models
- Linear and non-linear models

Software Utilization:

- ANSYS (primarily used)
- IDEAS, APDL (also mentioned)

Material Modeling:

- Orthotropic material properties for wood
- Semi-rigid joint modeling using reduced stiffness elements

Analysis Techniques:

- Static and dynamic loading simulations
- Stress distribution analysis
- Deformation and buckling studies

Key Findings:

- FEM effectively analyzes complex wood structures and furniture designs
- Accurate joint modeling is crucial for reliable results
- Combining FEM with experimental testing improves model validation
- Parameterized models facilitate easy design optimization
- Wood's anisotropic properties present modeling challenges

Conclusions:

- FEM is a valuable tool for wood product design and optimization
- It reduces the need for physical prototyping while allowing complex analysis.
- Careful material characterization and model validation are essential
- FEM can significantly improve furniture design processes

Limitations and Future Work:

- Need for more accurate modeling of wood's complex material properties
- Improving representation of semi-rigid joints in FEM models
- Addressing computational demands for detailed 3D models
- Developing standardized FEM procedures for wood product design
- Integrating advanced wood failure criteria into FEM analyses

Significance: This study underlines the possibility of showing that might completely change the designing and manufacturing of wood products by using FEM. This review study will support further dissemination in the wood industry for its comprehensive review about the current applications and challenges in this area, potentially leading to more efficient, cost-effective, and innovative wood product designs.

3.6.5.19 "Analysis on vibratory harvesting mechanism for trained fruit tree based on finite element method" (Dong et al. 2017)

Text Summary

This paper by Wang et al. discusses the optimization of mechanical fruit harvesters using FEA in modeling dynamic responses of various types of trained fruit trees under different kinds of shaker excitation. The authors generated the 3D models of spindle, open center, and vertical plane trees using Pro/Engineer, which was then imported into ANSYS for FEA. The models used SOLID186 elements with an elastic modulus of 10 GPa and density of 1000 kg/m³, without damping.

The modal analysis was run in the 1-50 Hz range; harmonic response analyses were also conducted for the following types of excitation of the shakers: reciprocal, orbital, and multidirectional. Among others, results showed that tree morphology greatly affects the natural frequencies and mode shapes, the resonance frequency for the three types of trees being between 7 and 20 Hz. The studies had shown that 13.5 Hz of frequency represented the 10th mode corresponding to the multidirectional excitation of spindle-shape trees, the orbital excitation of open center trees at 12.0 Hz was optimum, corresponding to the 11th mode, and both the reciprocal and orbital excitations were suitable for vertical plane trees.The research demonstrates the potential of FEA in optimizing mechanical fruit harvesters for different tree types, allowing for more efficient design processes without extensive physical prototyping. However, the study has limitations, including the simplification of tree structures and material properties. Future work could involve more detailed modeling of tree components, incorporation of damping and soil-root interactions, and more extensive experimental validation across tree types.

This approach could significantly improve harvesting efficiency and reduce fruit damage across various orchard types, potentially enhancing the competitiveness of fruit production industries.

Tree-View Summary

Objective: To optimize mechanical harvester designs for different trained fruit tree types using finite element analysis of tree dynamic responses to various shaker excitations.

Methodology:

Tree Modeling:

- Created 3D models of three trained fruit tree types (spindle, open center, vertical plane) using Pro/Engineer
- Included trunk and secondary limbs, excluded leaves and twigs

Finite Element Model:

- Imported 3D models into ANSYS software
- Used SOLID186 elements (3D 20-node structural solid elements)

Material Properties:

- Elastic modulus: 10 GPa
- Density: 1000 kg/m³
- Damping: Set to 0

Load Cases:

- Modeled three shaker excitation types: reciprocal, orbital, and multidirectional
- Applied harmonic forces at specific nodes

Analysis:

- Performed modal analysis (1-50 Hz range)
- Conducted harmonic response analysis

Key Findings:

- Natural frequencies and mode shapes were influenced by tree morphology
- Resonant frequencies for the three tree types were in the 7-20 Hz range
- Multidirectional excitation was most effective for spindle-shape trees (13.5 Hz, 10th mode)
- Orbital excitation was optimal for open center trees (12.0 Hz, 11th mode)
- Both reciprocal and orbital excitations were suitable for vertical plane trees

Conclusions:

- Different tree shapes require different optimal shaker excitation patterns
- FEM can effectively predict tree dynamic responses to various excitations
- The method can be used to optimize harvester designs for different tree types

Limitations and Future Work:

- Include more detailed tree structures (branches, twigs) in the model
- Incorporate material property variations within the tree
- Add damping to the model for more realistic behavior
- Model fruit attachment and detachment mechanisms
- Consider soil-root interactions
- Validate models with more extensive experimental data across tree types

Significance: This study demonstrates the potential of using finite element analysis to optimize mechanical fruit harvesters for different tree types. By simulating tree responses to various shaker excitations, researchers can design more efficient and less damaging harvesting equipment without extensive physical prototyping and testing. This approach could lead to improved harvesting efficiency and reduced fruit damage across various orchard types.

3.6.5.20 "Analysis of the Effect of Inertial Forces on Car Occupants in Frontal Collision with a Fixed Barrier" (Karapetkov et al. 2023)

Text Summary

This study by Karapetkov et al. investigates the effects of inertial forces on car occupants during frontal collisions with fixed barriers. The researchers developed a comprehensive model incorporating six degrees of freedom, tire and suspension elasticity, and various forces acting on the vehicle. Using Abaqus/Explicit software for finite element analysis, they simulated both the impact and post-impact phases of the collision. Figure 60 depict an impact result between

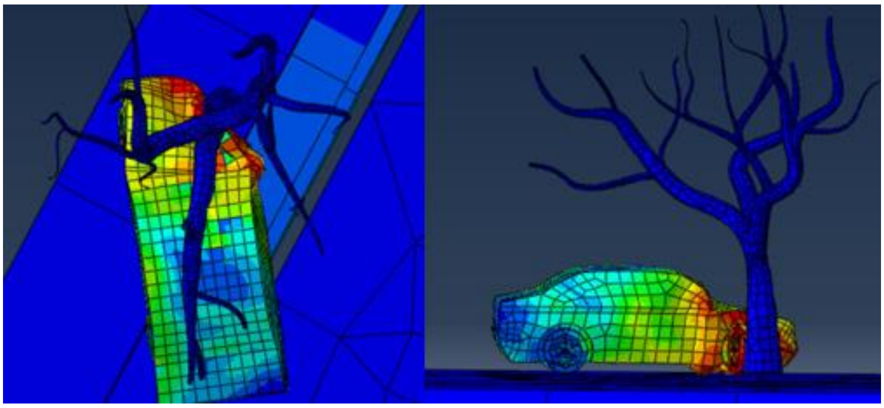


Figure 60 Deformation resulting from an impact between a car and a tree obtained using theAbaqus/Explicit software product (images and caption are from Moore and Maguire 2008).

car and a tree. The study's key findings highlight the dominance of translation inertial force during impact, followed by the significance of centrifugal and Coriolis forces post-impact. The researchers observed that angular velocity around the vertical axis significantly influences the magnitude of inertial forces. They also emphasized the crucial role of seat belts in maintaining occupant stability.

The model successfully predicted the maximum magnitudes of inertial forces and provided insights into occupant motion within the vehicle compartment. By applying the work-energy theorem and impulse-momentum theorem, the researchers were able to calculate relative speeds and analyze the impact process in detail.

The study concludes that finite element analysis can accurately predict translation inertial forces on passengers. It underscores the importance of considering both impact and post-impact phases for a comprehensive understanding of collision dynamics. The investigators emphasize that for the protection of occupants during a frontal collision, passive safety mechanisms would be very contributive. While the dominant part of the research dealt with frontal collisions, a methodological framework in the future could be extended to different collision scenarios and different models of vehicles. The results provide fundamental insights into automotive safety, contributing to the future design of safety systems and procedures for carrying out crash tests. Further validation by real-world crash data, besides the inclusion of active safety systems, might provide even higher relevance and reliability in future studies.

Tree-View Summary

Objective: Understand the effect that the inertia forces exert on the car occupants in a head-on collision against a fixed barrier during impact and after.

Methodology:

Model Development:

- Six-degree-of-freedom model (3 linear displacements, 3 rotations)
- Incorporation of tire and suspension elasticity
- Consideration of various forces (normal reactions, friction, damping, inertial)

Simulation:

- Use of Abaqus/Explicit software for finite element analysis
- Implementation of mixing problem with differential equations

Force Analysis:

- Calculation of translation inertial forces during impact
- Evaluation of centrifugal and Coriolis inertial forces post-impact
- Consideration of angular velocity around the vertical axis

Occupant Motion:

- Analysis of passenger movement within the vehicle compartment
- Assessment of the effect of seat belts on occupant position

Data Processing:

- Application of work-energy theorem for relative speed calculation
- Use of impulse-momentum theorem for impact analysis

Key Findings:

· Translation inertial force is dominant during the impact phase

· Centrifugal and Coriolis forces become significant in the post-impact phase

- Angular velocity around the vertical axis affects the magnitude of inertial forces
- Seat belts play a crucial role in maintaining occupant stability

Conclusions:

- Finite element analysis can accurately predict translation inertial forces on passengers
- Considering both impact and post-impact phases provides a comprehensive understanding of collision dynamics
- The model successfully predicts maximum magnitudes of inertial forces
- Passive safety systems significantly affect occupant safety in frontal collisions

Limitations and Future Work:

- The study focuses primarily on frontal collisions; other collision types could be explored
- Further validation with real-world crash data could enhance the model's reliability
- Integration of active safety systems into the model could provide additional insights

Significance: This study enhances our understanding of vehicle collision dynamics and occupant safety. By accurately modeling inertial forces throughout the collision event, it provides valuable insights for improving vehicle safety systems and potentially reducing injuries in frontal collisions. The methodology developed could be applied to various vehicle types and collision scenarios, contributing to advancements in automotive safety design and crash test protocols.

3.6.6 Literature Review for Additional Information

This literature review involved extensive research to understand the physical implications of various design components for proper Finite Element Method (FEM) modeling, especially in areas where existing literature was lacking. The study examined diverse sources to comprehend the relationships between structural elements and materials. This comprehensive analysis aimed to enhance FEM modeling accuracy in scenarios not well-represented in current literature, bridging the gap between theoretical concepts and practical applications to improve engineering modeling techniques.

3.6.6.1 "Green wall systems: A review of their characteristics" (Manso and Castro-Gomes, 2015)

This paper performs a critical review of green wall systems, their characteristics, and the state of the art in the field. Amongst other main elements and requirements, the authors explore various kinds of green wall systems that are differentiated in relation to their construction methods. The review begins by dividing green walls into two main groups: green facades and living walls. Green facades can be differentiated into two categories: direct and indirect, whereas living walls have been further classified into continuous or modular systems - Figure 61 . The main characteristics, advantages, and disadvantages of each type have been pointed out by the authors.It proceeds to explain in detail a variety of elements making up the green wall system-supporting elements, growing media, vegetation, drainage, and irrigation-and enumerates recent innovations in these aspects, such as lightweight materials, better systems for water retention and drainage, and methods for minimizing water and nutrient consumption. The authors go on to discuss critical aspects of the implementation of green walls regarding installation, maintenance, and replacement processes. It describes a 'prevailing trend' towards modular systems with benefits 'in terms of ease of installation and maintenance efficiency'. This review covers ecological performance and financial considerations associated with different green wall systems. It covers the life cycle assessment, and it points out that the selection of materials with low environmental impact is extremely important and must be accompanied by climate-suitable plant species for sustainable performance.

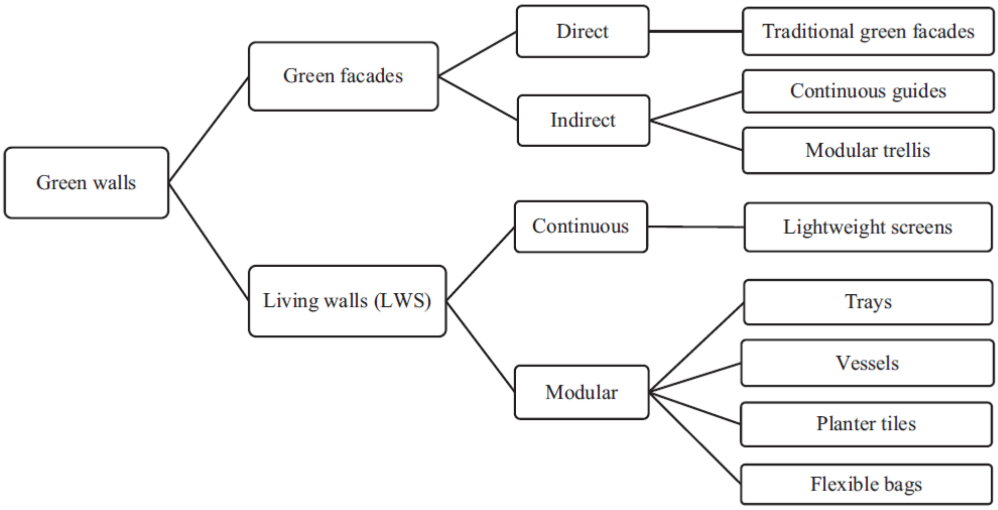


Figure 61 Classification of green walls, according to their construction characteristics (images and caption are from Manso and Castro-Gomes, 2015).

The paper therefore identifies potential pathways for further research in the development of green wall technology that could offer better adaptability to different geometries and angularities of surfaces, enhance sustainability with embedded recycled materials and native vegetation, and continue the evaluation of the overall impact of green walls on building performance.Generally, this review makes a comprehensive analysis of the present status of green wall systems, describing the characteristics and future development of green wall systems. It serves as a necessary reference for researchers, designers, and practitioners who are involved in applying green walls in urban environments and green architectural design. "Seismic and Energy Performance Evaluation of Large-Scale Curtain Walls Subjected to Displacement Control Fasteners" (Lee et al., 2021) It designed and tested a seismic-resistant curtain wall system withdisplacement control fasteners. On one hand, detailed experiments are executed; on the other,Performed 3D finite element modeling (see Figure 62) to assess the

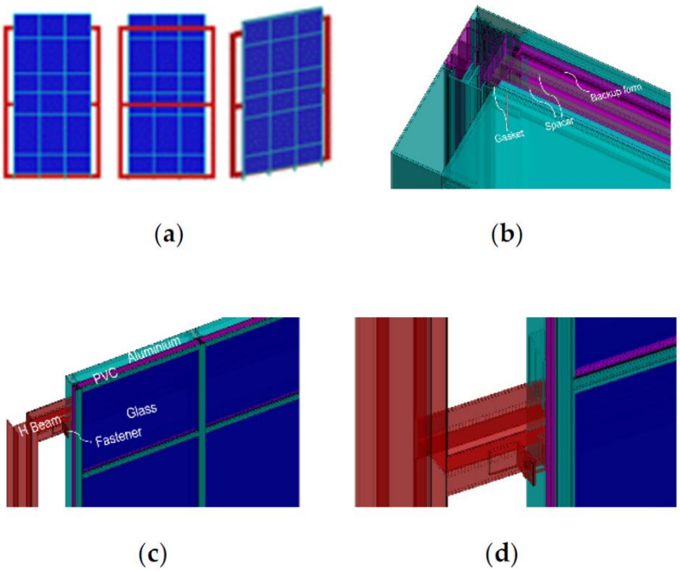


Figure 62 Details of full-frame FE model in solid form: (a) external shape of the FE model; (b) internal member detail; (c)chamber and aluminum frame; (d) anchor connection (images and caption are from Lee et al., 2021)

performance of the system. The investigators developed extensive FEM models of all the components of curtain walls to accurately simulate the actual system performance for different loading conditions. Such detailed models were essential for the analysis of stress distributions and the location of vulnerabilities in conventional curtain walls, as well as the validation of the seismic design proposed in this study. Besides, seismic performance is much better in the new curtain wall system with mobile fasteners and inter-story separated modules than in conventional designs. Using FEM analysis, it can be shown that the stresses transmitted to outside materials in this new system are smaller during earthquakes. In addition, it evaluated the usability of curtain walls, including thermal insulation, airtightness, water resistance, and wind pressure resistance. All the above-mentioned performances fulfilled or exceeded the proposed system's performance criteria. This research provides recommendations that are useful in designing safer and more resilient curtain wall systems in seismic-prone areas, with the detailed 3D FEM modeling being a keystone in the development and validation.

3.6.6.2 "Towards a worldwide wood economics spectrum" (Chave et al., 2009)

This review synthesizes the modern understanding of functional traits linked to wood and introduces the concept of a "wood economics spectrum," a suite of interrelated wood traits that represent trade-offs in plant functioning and resource allocation. The authors synthesize and analyze the global datasets on key wood attributes: density, anatomy, hydraulic conductivity, mechanical properties, and chemical composition. They report results showing relationships and trade-offs among various wood traits. For instance, wood density increases with mechanical strength but decreases with hydraulic conductivity. The authors then go on to relate these wood properties to other plant traits such as leaf traits, plant height, and growth form. More importantly, however, the paper shows that wood traits, particularly wood density, are related to demographic rates of growth and mortality. These authors construct arguments that these concerted wood traits represent a wood economics spectrum, parallel to the leaf economics spectrum, ranging from the fast-growing species with low-density wood to the slow-growing species with strong and dense wood. The authors review the geographic and phylogenetic variation of the wood economics spectrum among plant species. Attention is drawn to the ecological and biogeochemical significance of wood traits. Wood traits strongly control forest structure, biomass, carbon storage, and nutrient cycling. They also mentioned that including data on wood characteristics into Dynamic Global Vegetation Models (DGVMs) would further improve both of these models and the ability to forecast forest response to climate change. The review identifies critical gaps in the knowledge of the Wood Economics Spectrum (WES) and outlines an agenda of research activities toward its full characterization. These are applied to create standardized wood trait databases, to investigate relationships between wood and whole-plant function, and to incorporate wood traits into ecological and biogeochemical models. In general, the synthesis paper presents reasons why wood traits are fundamentally important to plant ecology and also proposes the wood economics spectrum as an organizing framework to understand variation in wood properties across species and environments. The authors argue this concept could significantly advance plant ecology and improve predictions of forest dynamics under global change.

3.6.6.3 "Fast Automatic Precision Tree Models from Terrestrial Laser Scanner Data" (Raumonen et al., 2013)

This paper describes an automated approach for generating detailed 3D models of trees from TLS point cloud data. The method will attempt to generate a richly detailed and highly accurate model of trees and effectively capture the branching structure and size of the various components of trees. In this regard, the proposed approach adopts a cover set method where the point cloud is partitioned into small surface patches. These patches contribute towards the routine re-construction of surface and topology. The tree is subdivided into its branches, which are modeled individually as an assembly of cylindrical forms. The approach allows one to quantify such features of trees as the architecture of branching, the dimensions of the branches among other characters.

Basic ingredients of the approach are:

- Automatic operation without manual intervention

- Fast processing (within minutes to under an hour for 1-5 million points)
- Compact model output compared to raw point cloud
- Ability to derive several tree-related measurements and statistics from the model
- Scale-independence, allowing reconstruction down to the measurement accuracy

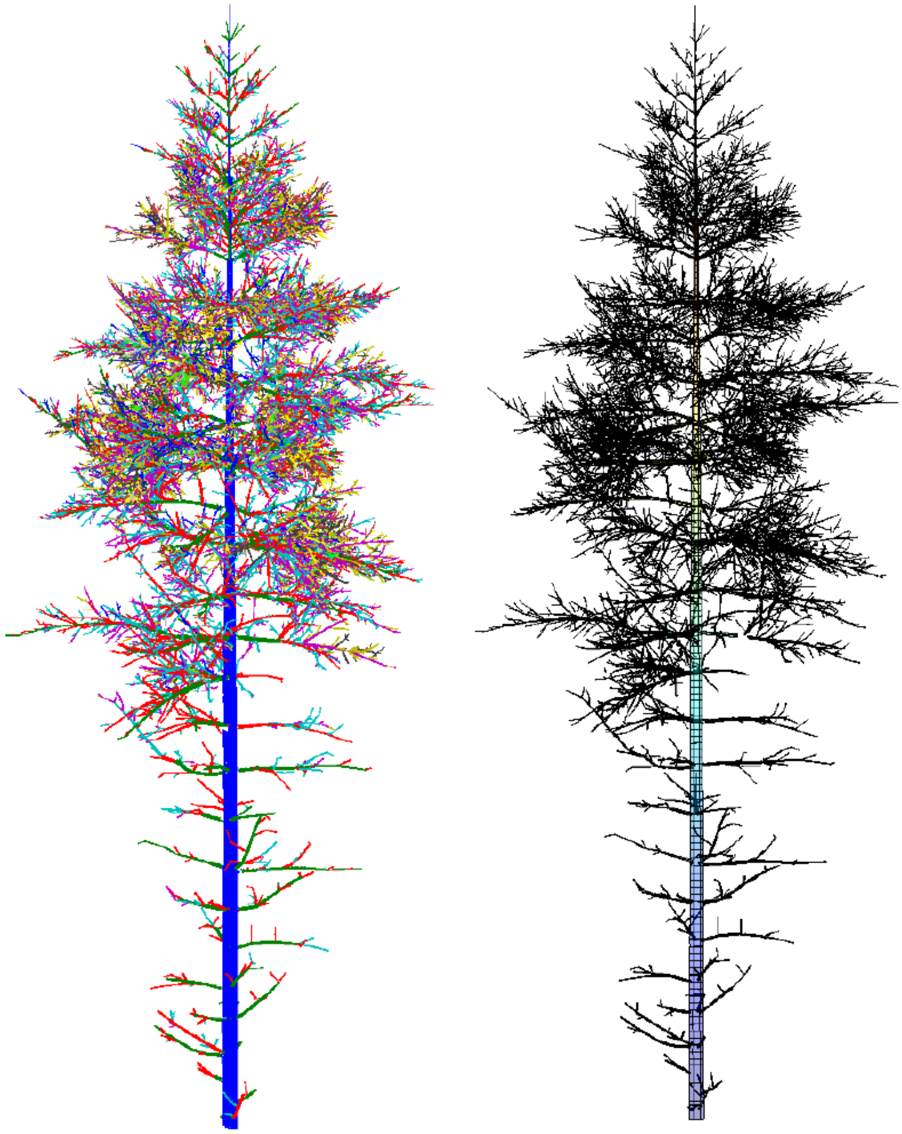


Figure 63 Segmented point cloud (left) and the final cylinder model (right) of the artificial Scots pine.(images and caption are from Raumonen et al., 2013)

The authors validate the approach using simulated and actual TLS data from various tree species. It follows from the results that this approach can reconstruct volume in trunks and larger branches quite well, even with incomplete scanning coverage, up to a few percent. The small branches close to the limit of accuracy while scanning, approximately at 1-3 cm diameter, are also detectable but with far higher uncertainties. The study concludes that the integration of the method with TLS technology offers a proficient avenue of acquiring comprehensive geometric and topological data on trees, thereby substantially increasing the existing quantitative information about tree structure relevant in forestry, biomass assessment, and many more applications. Generally, the authors declare some important limitations with foliage and integrity of input data and propose some directions for future improvements and validation of the methodology.

3.6.6.4 "Street Tree Structure, Function, and Value: A Review of Scholarly Research (1997–2020)" (Coleman et al., 2022)

This review synthesizes natural and social sciences literature on the topic of urban street trees. Reviewers drew upon 429 scientific articles discussing, between January 1997 and mid-2020, the structural features, functional purposes, and values attributed to street trees in urban settings. Collected records were coded for descriptive information, such as publishing journal and geography of study areas, on one hand, and emergent focal research areas, including ecosystem services and economic valuation, inventory methods on the other. They examined the trend of the volume of publication, geographic distribution of studies, and key research themes.

Key findings of the review include:

- A significant growth in street tree literature over time, especially following major developments in urban forestry.
- Most discussed in the literature was the regulating ecosystem functions and services of street trees, including cooling effects.
- Other relevant themes found were the use of means coming from waste due to pruning for building purposes; advantages/disadvantages related to human health and safety; indications on environmental justice.
- The majority of research originated from North America, with increasing contributions from Europe and Asia in recent years.
- Other important themes canvassed included: economic valuation, studies pertaining to social values, and governance of street trees..

The authors identified some future paths of inquiry, including integrated studies of interwoven biophysical and human factors affecting the life span and growth of street trees, and called for further development of the economic and budgetary barriers to managing urban forests. This review represents a remarkable synthesis of current knowledge regarding urban street trees and points out the complexity of the research on street trees within different disciplines. It thus proffers more cogent perspectives to scholars, city planners, and decision-makers concerning the primary foci of attention besides probable lacunas in our knowledge about street trees in an urban environment

3.6.7 Discussion

3.6.7.1 Forestry Models

In the field of structural engineering and biomechanics, the Finite Element Method (FEM) has emerged as a crucial tool for analyzing complex biological structures such as trees. The application of FEM to tree modeling presents a unique set of challenges and opportunities, primarily due to the intricate and variable nature of tree morphology. This discussion focuses on three distinct approaches to FEM modeling of trees (see Figure 64), each representing a different level of abstraction and computational complexity. The most detailed representation, as illustrated in model (a), is a high-fidelity 3D model. This approach typically utilizes data from advanced imaging techniques such as LIDAR (Light Detection and Ranging) to capture the tree's intricate geometry with exceptional accuracy. The resulting model includes a detailed trunk structure, complex branching patterns, a comprehensive root system (rare case primarily in experimental setup when revealing of root system is available), and even individual leaves or leaf clusters. This level of detail allows for precise analysis of stress distribution, wind load effects, and dynamic responses. However, the creation and processing of such models demand significant computational resources (advanced 3D CAD system) and time. Researchers working with these high-fidelity models often rely on specialized tree material databases, such as the Forest Inventory and Analysis Database (Forest Products Laboratory,

2024) or the Global Wood Density Database (Zanne et al., 2009), or handbook like Wood Handbooks (Forest Products Laboratory, 2021), to accurately represent the varying material properties throughout the tree structure.

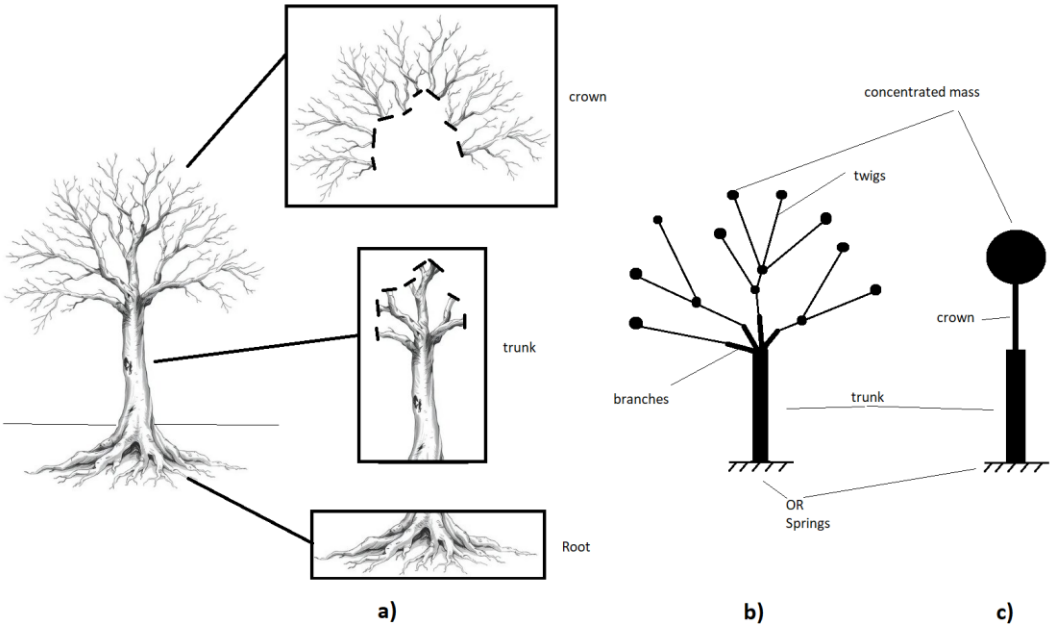


Figure 64 Finite Element Method (FEM) modeling approaches for tree structures, showing increasing levels of abstraction from left to right. (a) High-fidelity 3D model, (b) Simplified branch-mass model, and (c) Equivalent two-element model for efficient large-scale simulations.

Going further to even more simplification, model b may be considered as an intermediate model between information and computational efficiency. A tree in this model may be visualized as a system of connected lines and point masses. In other words, there would be one main vertical line, at times with inclining lines representing the trunk and secondary lines accounting for the major branches and tertiary lines for the smaller ones or even twigs. One crucial feature included is that of the distributed masses, represented by the black circles at the terminus of the branches. These masses have important implications for the obtaining of precise transient analyses, especially when the response of the tree is tested for dynamic forces due to wind or seismic activity. This sort of approach to modeling is based on the work of James et al. 2014, who provided the basic infrastructure necessary for developing such effective but simplified models.

The most abstracted representation, model, reduces the tree to its very basic elements. This highly simplified model consists of a single vertical line but slanted lines can be employed for the trunk, a broken line at the top for the crown, and a large black dot that represents the overall mass of the entire crown system. Although this may be a somewhat over-simplified model, it nonetheless serves a major role in large simulations or situations when speed of analysis is important. Such an equivalent mass on the crown can thus be justified based on several literature referring to the dynamic properties of trees, such as that of Moore and Maguire 2008 that establishes methods for the estimation of natural frequencies.

Each of these approaches embodies a critical trade-off between the goals of the research, the available computational resources, and the scale of the inquiry. High-fidelity models (a) are extremely useful for studies at the level of the individual tree, especially in assessing the vulnerability of a tree to disease or structural defect, or in undertaking detailed wind load analyses on valuable or historic trees. These models can provide highly detailed 3D information about tree structure. Raumonen et al., 2013.

The scheme in the branch-mass model, b, has been very effective in the study of urban forestry and in applications dealing with groups of trees or small stands. Its applications are mostly within the study of tree-wind interactions in urban settings and the valuation of the risk of tree failure during storms. The researcher in this model can obtain information on the Urban Tree Database provided by McPherson et al. 2016 on the development of urban trees, structural aspects, and ecosystem services.

Table 6 Comparative Analysis of FEM Tree Modeling Approaches

Aspect	High-Fidelity 3D Model (a)	Simplified Branch-Mass Model (b)	Equivalent Two-Element Model (c)
Level of Detail	Highest	Intermediate	Lowest
Main Components	- Detailed trunk - Complex branching - Root system - Individual leaves/clusters	- Main trunk line - Branch lines - Twig lines - Distributed masses	- Single trunk line - Crown line - Single crown mass
Geometric Representation	Full 3D geometry	Interconnected lines	Two connected lines
Mass Distribution	Distributed throughout structure	Concentrated at branch ends	Single point at crown top
Computational Complexity	Highest	Moderate	Lowest
Typical Data Source	LIDAR or detailed 3D scans	Field measurements, simplified scans	Basic tree measurements
Best Suited For	- Individual tree analysis - Detailed stress studies - Wind load analysis	- Small forest studies - Urban tree assessment - Wind-tree interaction	- Large-scale forest simulations - Preliminary urban planning - Rapid assessments
Key Advantage	Highest accuracy	Balance of detail and efficiency	Computational efficiency
Main Limitation	High computational demand	Reduced local detail	Limited individual tree information
Transient Analysis Capability	Highly detailed	Good, with distributed masses	Basic, using single crown mass
Scalability	Limited to few trees	Moderate, suitable for small groups	Highly scalable, large forests

The two-element model (c) represents the most abstracted of the representations, but an important simulation element of far-reaching forest simulations and first studies in urban planning. Its simplicity also provides the possibility of rapid assessments of urban wind corridors or preliminary studies of the conditions of forest dynamics over wide areas. This class of model is used quite often with forest inventory databases, such as the Forest Inventory and Analysis National Program database, Forest Products Laboratory 2021 to provide quite broad information about forest structure and dynamics.

As computational systems become more powerful, a clear trend toward adaptive methods of modeling develops that can smoothly vary levels of detail. An example of an adaptive model would be one starting with a coarse version c, performing the extensive preliminary analyses on this, and then refining to b or a as areas of interest come into focus. This would have the tendency of increasing computational resource usage even as it provides relevant fineness where it is most needed. Comparison of different FEM-based techniques on tree modeling is shown in Going further to even more simplification, model b may be considered as an intermediate model between information and computational efficiency. A tree in this model may be visualized as a system of connected lines and point masses. In other words, there would be one main vertical line, at times with inclining lines representing the trunk and secondary lines accounting for the major branches and tertiary lines for the smaller ones or even twigs. One crucial feature included is that of the distributed masses, represented by the black circles at the terminus of the branches. These masses have important implications for the obtaining of precise transient analyses, especially when the response of the tree is tested for dynamic forces due to wind or seismic activity. This sort of approach to modeling is based on the work of James et al. 2014, who provided the basic infrastructure necessary for developing such effective but simplified models.

The most abstracted representation, model, reduces the tree to its very basic elements. This highly simplified model consists of a single vertical line but slanted lines can be employed for the trunk, a broken line at the top for the crown, and a large black dot that represents the overall mass of the entire crown system. Although this may be a somewhat over-simplified model, it nonetheless serves a major role in large simulations or situations when speed of analysis is important. Such an equivalent mass on the crown can thus be justified based on several literature referring to the dynamic properties of trees, such as that of Moore and Maguire 2008 that establishes methods for the estimation of natural frequencies.

Each of these approaches embodies a critical trade-off between the goals of the research, the available computational resources, and the scale of the inquiry. High-fidelity models (a) are extremely useful for studies at the level of the individual tree, especially in assessing the vulnerability of a tree to disease or structural defect, or in undertaking detailed wind load analyses on valuable or historic trees. These models can provide highly detailed 3D information about tree structure. Raumonen et al., 2013.

The scheme in the branch-mass model, b, has been very effective in the study of urban forestry and in applications dealing with groups of trees or small stands. Its applications are mostly within the study of tree-wind interactions in urban settings and the valuation of the risk of tree failure during storms. The researcher in this model can obtain information on the Urban Tree Database provided by McPherson et al. 2016 on the development of urban trees, structural aspects, and ecosystem services.

Table 6.

All the various scales of finite element modeling of the structures of trees highlight not only the flexibility but also the effectiveness of the computational methods for biomechanical and forestry features. Depending on the selected degree of refinement, researchers can weigh their analyses against specific goals, so that the need for accuracy is combined with computation resource limitations. With increased understanding in tree biomechanics and constant evolution in computational methodologies, one can expect the development of advanced and detailed approaches that will continuously improve the capability to study and manage such complex biological systems

3.6.7.1.1 Forestry interactions and fixing

The interaction between trees and the surrounding environment, particularly concerning wind, snow, and seismic actions, is a very complex and important domain within forestry and arboriculture. Understanding these interactions is crucial for being able to predict tree stability, assess risks, and develop effective management strategies. The aim of this chapter is to explore various aspects of the tree-environment interactions and to emphasize the importance of suitable anchoring for the stability of trees.

3.6.7.1.2 Wind Interactions

Wind is the most common and major environmental factor that affects the growth of trees. The interaction of trees and wind loading is one complex topic that has been studied in scholarship through various studies trying to unravel this complex interaction using empirical and computational approaches. A wide-ranging review by James et al. (2014) develops a trend in tree biomechanics research where the recent efforts move over from the simple models of trees into more sophisticated multi-modal and FEM frameworks. They note that the form and morphology of trees and branches are vastly more important in the dynamic response of trees to wind than material properties alone. That particular finding has put special significance on considering tree architecture in studies related to wind-tree interaction. The Finite Element Method has recently become one of the powerful tools able to simulate tree behavior subjected to wind loads. Moore and Maguire 2008 presented an FEM for Douglas-fir trees where the branches were modeled as cantilever beams instead of discrete masses. They found that the branch oscillation provides a high contribution to the total damping of the tree, especially for small values of branch stiffness. It shows the importance of branch dynamics on tree stability when subjected to wind loading. Hu et al. (2008) further developed the use of FEM in tree-wind interactions by providing asymmetric material property considerations. Asymmetry thus obtained resulted in the complex looping movement of trees under wind loading, hence giving a very realistic view of how trees actually interact in natural conditions.

3.6.7.1.3 Snow and Seismic Loads

While wind is most often discussed as the key factor, snow and seismic loads are also major environmental applied loads impacting the biomechanics of trees and forest dynamics. It is obvious that these environmental loadings may well cause considerable damage to trees and forests. As for effective forest management and risk assessment, it basically requires proper understanding of such loading.

3.6.7.1.3.1 Snow Loads

Snow accumulation can significantly affect tree biomechanics, especially in colder climates and at high altitudes. Increased load and unequal distribution of weight due to snow Can lead to branch failure, crown deformation, or whole tree toppling. James et al. (2017) reviewed recent developments in tree biomechanics and considered that strain, rather than stress, may The key for initiating the major adaptive growth responses in woody plants. This is especially relevant within the context of trees adaptation to the action of recurrent snow loading.

Dounar et al. (2020) have developed a very detailed FEM model of a sweet chestnut tree that may serve adapted to model scenarios involving snow load. The authors accentuated the nonlinear The analysis, which predicted 33% higher displacements and 35% higher stresses compared to Linear analysis would suggest that only for the exact representation of the arboreal answers to snow loads, consideration of geometric nonlinearities.

3.6.7.1.3.2 Seismic Loads

Less common than wind or snow load, seismic events nonetheless exert very dramatic impacts on both forests and urban trees. The sudden, multidirectional forces exerted by earthquakes can cause either root system damage, trunk failure, or complete uprooting. Yang et al. (2014) developed a new FEM model for simulation of the uprooting of trees under consideration of progressive root breakage. According to the study by the authors, FEM has great potential in optimizing tree stability assessment on a wide range of environmental stresses, including seismic activities.

Sellier et al. (2006) used FEM to analyze how tree aerial architecture affects structure dynamics. Some of their results on the role of crown topology in damping properties are of particular relevance for studies of tree response to seismic forces. In fact, the research determined that needles accounted for about 80% of the total damping in the studied saplings;

this would confirm that foliage plays a major role in dissipating energy during any form of dynamic loading, such as earthquakes.

Future research efforts should focus on the development of holistic models that simulate tree responses to multiple, co-occurring environmental stresses, perforce giving a better approximation of the complex issues that face trees in both natural and urban settings.

3.6.7.1.4 Soil-Root Interactions

The interaction between the tree roots and soil has been recognized as an important component of overall stability. Mickovski et al. (2011) examined the mechanism of root-soil reinforcement by modeling direct shear tests using FEM. They found that the presence of roots increased the overall soil shear strength and that multi-rooted models displayed significantly increased resistance compared to single-rooted or non-rooted models. Dupuy et al. (2007) developed a 3D FEM model integrating real root system architectures with soil mechanics. They concluded that root architecture significantly influences anchorage strength while soil type influences the pattern of failure. They found among all the parameters taken, cohesion is the most influential parameter for uprooting resistance.

3.6.7.1.5 Fixing Conditions

The fixing conditions of trees, particularly in urban environments or for young trees in plantations, plays a crucial role in their stability and growth. Sagi (2016) investigated the effects of trenching on tree stability, employing both field testing and wind tunnel experiments. The research introduced a Winkler foundation model to represent root-soil interaction, offering a new approach to incorporate soil parameters in tree stability analysis.

For modeling purposes, linear and rotary springs can be used to represent the fixing conditions of trees, especially in simplified models. Linear springs can represent the lateral resistance of the soil, while rotary springs model the rotational resistance at the base of the tree. This approach is particularly useful for models (b) and (c) as described in the current document (see Figure 64).

3.6.7.1.6 Integrated Modeling Approaches

For understanding tree behavior facing different environmental loads, integrated modeling approaches are needed. By developing a finite element model, Sellier et al. (2006) investigated the effect of tree aerial architecture on the main characteristics of structural dynamics, that is, oscillations and damping. Their research underlined the importance of detailed crown topology modeling when dealing with damping mechanisms. Crespi et al. (2014) conducted extensive wind tunnel tests complemented by numerical calculations of the wind forces acting on trees integrated into building facades. In this investigation, the relevance of the large-scale interference phenomena, together with the local wind-tree dynamics in the urban environment, was highlighted.

The research into forestry interactions and conditions of fixing becomes important in understanding tree stability, predicting the possibility of failures, and establishing efficient management strategies. Advanced modeling techniques, especially FEM, have considerably advanced the capability to simulate complicated tree-environment interactions. Challenges persist, however, in the accurate representation of the intricate nature of trees regarding material property variation, soil-root interaction, and dynamic response to several environmental factors. Future research should be directed at developing more sophisticated models accounting for all different aspects of tree biomechanics, such as explicit root structure, variable soil conditions, and complicated wind fields. The development and verification of these models require both longer-term studies and more extensive experiments for a large range of tree species and environmental conditions. By advancing our understanding of forestry interactions and fixing conditions, we can improve urban forest management, enhance wind risk assessment methodologies, and develop more resilient and sustainable forest ecosystems.

3.6.7.1.7 Concrete – Forestry Interface Envelope

The modeling approach for Green Walls presented in Table 7 could potentially extend the work of Manso and Castro-Gomes (2015) by applying FEM modeling to the different types of green wall systems. This extension would represent a significant advancement in the field, moving beyond classification and description to provide a quantitative analysis framework. While Manso and Castro-Gomes provided a comprehensive classification and description of green wall systems, this proposed FEM modeling approach could allow for detailed structural analysis, potentially enabling engineers and designers to assess the structural implications of different green wall systems on buildings. The approach suggests a two-phase modeling process: Phase One would involve creating detailed 3D models (as in Lee et al., 2021) for living walls (both modular and continuous types) and green facades (indirect), while Phase Two would use simplified shell or beam models. For green facades using direct approach only additional gravity loads may applied to the original model. This phased approach could allow

Table 7 : FEM modeling approach for Green Walls

Note: The Original classification of different Green Wall Types was adapted from (Manso & Casto-Gomes, 2015)

Green Walls			
Living Walls		Green Facades	
Modular	Continuous	Direct	Indirect
- Trays - Vessels - Planter tiles - Flexible bags	Lightweight screens	Traditional Green Facades	- Continuous Guides - Modular trellis
FEM Model			
Phase One			
Detailed 3D Model			Additional Gravity Loads
Phase Two			-
Simplified Shell or/and Beam Model			

for appropriate levels of detail depending on the complexity of the system. The proposed FEM modeling could allow for the integration of green wall models with overall building structural models, potentially enabling a holistic analysis of the building-green wall system interaction. While Manso and Castro-Gomes discussed the potential benefits of green walls, this FEM modeling approach could provide a tool for quantitatively predicting and optimizing the performance of these systems under various conditions. The FEM models could be used to optimize the design of green wall systems, potentially leading to more efficient and effective implementations than those based solely on the qualitative descriptions in the original paper.

By providing a quantitative analysis tool, this approach could enable better risk assessment for different green wall systems, extending beyond the general advantages and disadvantages discussed in the original work. A simplified diagram is provided in Figure 65.

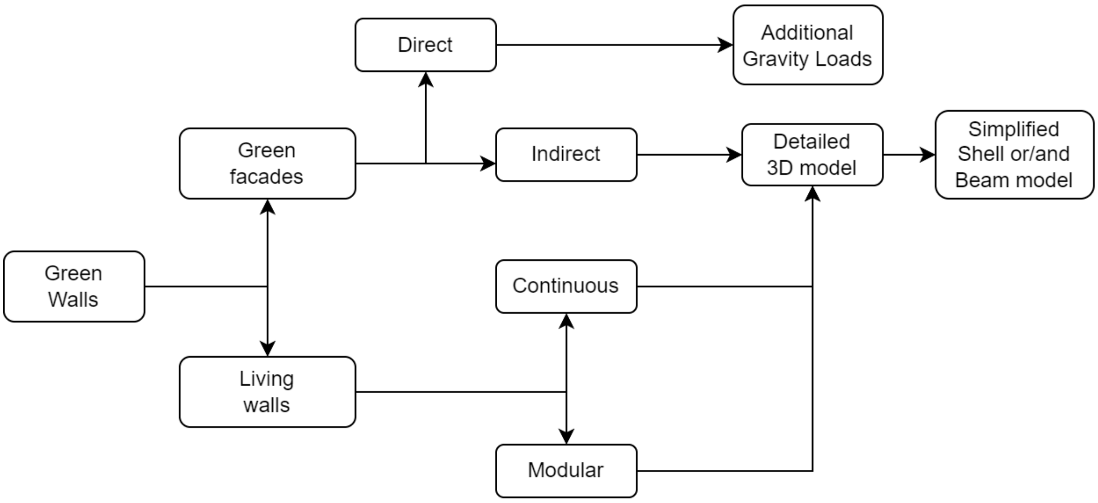


Figure 65 Classification of green walls for FEM modeling

Note: The Original classification of different Green Wall Types was adapted from (Manso & Casto-Gomes, 2015)

For green facades, Manso and Castro-Gomes (2015) describe two main types of supporting structures: direct and indirect systems.

Direct Green Facades:

Traditional Green Facades:

- These typically do not have a dedicated support structure.
- Plants (usually climbing species) attach directly to the building wall.
- The wall itself serves as the support for plant growth.
- While simple, this method can potentially damage the building surface over time.

Indirect Green Facades:

These create an air gap between the building surface and vegetation, functioning like "double-skin facades". They are further divided into continuous and modular systems:

- Continuous Guides:
    - Use cables, wires, or trellis made of galvanized or stainless steel.
    - Provide a framework for climbing plants to grow along.
    - Allow for more controlled and directed plant growth.
- Grids and Wire-nets:
    - Have smaller intervals between supports.
    - Useful for slow-growing plants or those needing denser support.
- Steel Structures and Tensile Cables:
    - Used for climbing plants with denser foliage.
    - Can support heavier plant growth.
- Modular Trellises:
    - Include pots filled with substrate.
    - Have individual support structures for each module.
    - Allow for suspension of elements at various heights along the wall.

    - Some new forms include curved grids to add rhythm and three-dimensionality to the facade.

Key Features of Indirect Green Facade Supports:

- Anchor and hold vegetation weight.
- Increase system resistance to environmental factors (wind, rain, snow).
- Create distance between plants and the building surface, potentially reducing moisture issues.
- Allow for easier maintenance and replacement of plants.

Researchers note that indirect green facades, especially modular trellises, offer advantages over direct systems in terms of installation and maintenance. They decrease the impact of dispersed growth of climbing plants along the surface and enable easier substitution of unsuccessful plants.

The researchers also discuss supporting structures for living walls in detail, particularly for continuous and modular living wall systems (LWS)

Continuous Living Wall Systems:

- Frame structure: These systems typically start with a frame fixed to the building wall, creating a void space between the system and the surface.
- Base panel: The frame supports a base panel, which serves as the foundation for the subsequent layers.
- Permeable layers: The base panel is covered with multiple layers of permeable, flexible, and root-proof screens. These screens are typically stapled to the base panel.
- Planting pockets: The external layer of the screen is cut to form pockets, allowing for the individual insertion of plants.

Modular Living Wall Systems:

- Trays:
    - Usually made of lightweight materials such as plastic (polypropylene or polyethylene) or metal sheets (aluminum, galvanized steel, or stainless steel).
    - Often include interlocking systems on the sides to connect modules.
    - May have a front cover forming a grid to prevent plants from falling.
    - The back surface might include hooks or mounting brackets for suspension on frame profiles.
- Vessels:
    - Typically made of polymeric materials.
    - Allow installation of several plants in each element along the same row.
    - Have a significant visual impact on the building surface due to their form.
- Planter tiles:
    - Connected to each other by juxtaposition.
    - Often include a flat back fixed to the building surface and an area for individual plant insertion.
    - Can be made of lightweight or porous materials like plastic or ceramics.
    - May be glued to the vertical surface or fixed with mechanical fastening.

- Flexible bags:
  - Made of flexible polymeric materials.
  - Filled with growing media.
  - Cut to insert individual plants.

General support structure:

- Most modular LWS are fixed to a vertical and/or horizontal frame attached to the building surface.
- The frame provides the primary support for the entire system.
- It allows for the suspension of individual modules at various heights along the wall.

The choice of support structure for green facades depends on factors such as the building type, climatic conditions, desired aesthetic effect, and the specific requirements of the chosen plant species. The trend in recent developments has been towards systems that offer easier installation, maintenance, and plant replacement processes, while also considering the environmental impact of the materials used.

3.6.8 Conclusion

In the modeling process of forestry entities, such as plants, three key parameters among many others become very important: the modeling of root systems, the modeling of trunks, and the modeling of foliage. These elements all have to be included when trying to represent plant structures thoroughly in computer simulations and architectural designs.

Root system modeling means an advanced methodology comprising complex relationships with the neighborhood that need to be described with proper detail; this should be highly relevant for the effective representation of the main features shown by soil-root interactions. For example, in a micro-modeling framework, detailed features of soil-root interfaces and their mechanical behavior are specifically addressed. The opposite would represent an attempt to use a more general macro-modeling approach by idealizing the root system into a fixed boundary using beam elements. A meso-scale approach represents a compromise in which the root system would be modeled through equivalent spring interactions obtained from analyzes performed at the microscale. It is, consequently, the reason the multi-scale modeling approach is entirely pegged on comprehensive design, since this generally offers an efficient framework for the effective load transformation in the assessment of capacity.

Trunk modeling gives the general architecture of the woody plant, with biomechanical and growth dynamic concerns. It, therefore, enforces giving intensive attention to the wood mechanical properties, particularly anisotropy and appearance under different loading conditions. It may be different in the approach to modeling on different scales, from detailed fiber models to generalized beam models.

The third important element in the model is foliage modeling, covering leaves and branches; its key representation and visualization are primarily related to the different ways that plants show their interaction with light, air, and aesthetic appearance in the built environment. This dimension of the model has a very critical role with regard to an environmental assessment of forestry elements in cities, including its impact on air quality, microclimatic regulation, and biodiversity.

In turn, each of those would require an advanced modeling approach able to represent specific interactions with the immediate surroundings. Integrating these models on different scales, from micro to macro, allows a deep insight into plant behavior and its interaction with the built environment. The multi-scale modelling methodology lays a very strong basis in ensuring accuracy in the assessment of the load distribution, structural capabilities, and overall performance of systems related to the reinforced concrete edifices incorporating the forestry element.

3.7 COMFORT RELATED MODELS

3.7.1 Introduction

Comfort analysis encompasses many disciplines in order to address the needs of humans in various environments and condition interpretations. These are thermal, acoustic, visual, ergonomic, and psychological factors, which may affect human comfort and performance. For buildings with vertical forests, green envelopes, and those made with reinforced concrete, comfort analysis also considers the biophilic elements and their effects on the experience of the occupants. It regulates temperature and contributes to thermal regulation, improves air quality because of the plant filtration systems, and provides acoustic benefits supplied by the green surface itself, even a psychological impact thanks to increased exposure to natural environments. The embedding of biological systems in building façades raises a number of issues and opportunities regarding comfort modeling and involves dynamic variables acting over a range of timescales, from seasonal variations in vegetation to multi-year maturation dynamics in a building's vegetation component. Appropriately detailed comfort models are central to the successful design of buildings, workplaces, and products for human beings; green buildings, in particular, demand new metrics if the benefits accruing from vegetation in an integral form are to be captured fully. Therefore, this more long-term comfort analysis strategy in green concrete structures should arrive at an optimum synergy between conventional building materials and living systems in developing more sustainable, healthy, and comfortable urban environments. This is followed by the literature review.

3.7.2 Thermal Comfort Models (TCMs)

Comfort is primary concern in building design, due to its direct impact on both occupant satisfaction and energy consumption. In this direction, among the most important developments are those made by P.O. Fanger with the so-called Predicted Mean Vote (PMV) and Predicted Percentage Dissatisfied (PPD) models. The PMV model was developed in 1970 to predict the average thermal sensation for a large group of people based on a comprehensive set of factors including air temperature, mean radiant temperature, humidity, air velocity, clothing insulation, and metabolic rate. A companion model, PPD, provides a quantitative estimate of the percentage of occupants that are likely to feel thermally dissatisfied for a given set of environmental conditions (Fanger 1970). The models identified above have formed a part of the quantitative basis of the thermal environment assessment and have contributed to the development of international standards.

Building on the work of Fanger, adaptive models of thermal comfort emerged that could take into account dynamic interactions between occupants and their thermal environment. Realizing that people could adapt both behaviorally, physiologically, and psychologically, such models considered various modifications like changing clothes, changing metabolic rates, or changing environmental controls. The adaptive concept is particularly applicable in naturally ventilated buildings where there is quite a high degree of occupant control. This concept was further crystallized, in 1998, by de Dear and Brager, who developed an adaptive model of thermal comfort and preference, emphasizing the importance of occupants' feedback and environmental context when perceiving thermal comfort (de Dear & Brager, 1998).

These models, in turn, have been translated into standards and guidelines, providing design and evaluation frameworks for buildings. ASHRAE (American Society of Heating, Refrigerating and Air-Conditioning Engineers) Standard 55, developed by the American Society of Heating, Refrigerating and Air-Conditioning Engineers, provides detailed criteria regarding acceptable thermal environmental conditions for human occupancy. The specific standard harmonizes the PMV/PPD models with adaptive models and, therefore, provides a flexible approach to different design strategies for achieving thermal comfort in different building and climatic categories (ASHRAE Standard 55, 2020). Similarly, ISO (International Organization for

Standardization) 7730, which is an international standard developed by the International Organization for Standardization, describes how thermal sensation and discomfort can be predicted. It provides analytical procedures to determine thermal comfort by PMV and PPD indices and also criteria for local thermal comfort factors (ISO 7730, 2005).

With new design challenges, CFD (Computational Fluid Dynamics) models became one of the most needed tools for improving thermal comfort and HVAC (Heating, Ventilation, and Air-Conditioning) efficiency in modern design. Such CFD models simulate airflow and temperature within interior environments, giving a detailed analysis of how air circulation and heat transfer will affect the occupants concerning their comfort. This helps engineers and architects to create indoor environments that strictly meet comfort criteria with complete assurance of energy efficiency by allowing stringent control of environmental parameters.

Individually and in sum, these schemes and standards represent the move toward a holistic consideration of thermal comfort within the built environment. Integration of quantitative assessments with adaptive methodologies will enable designers to provide an environment that meets the occupants' thermal preference while enabling them to use energy in a sustainable manner. From fixed models, such as PMV/PPD to adaptive paradigms, this constitutes an evolution of comprehension of complex relations between occupants and their environment. With technological development, these tools can be driven further to provide, for instance, advanced predictive capability for thermal conditions and keep consolidating occupant well-being and building performance.

3.7.2.1 "Climate, Comfort & Natural Ventilation: A new adaptive comfort standard for ASHRAE Standard 55" (Brager and de Dearfd, 2001)

This peer-reviewed article investigates the development of an adaptive comfort standard for naturally ventilated buildings based on the largest database of thermal comfort field studies in naturally ventilated buildings. They compiled nearly 21000 sets of raw data from 160 buildings across four continents into two building categories: centrally air-conditioned-HVAC and naturally ventilated-NV. Using regression analysis, they tested the hypothesis that the indoor comfort temperatures are related to the outdoor climate.

The main deliverable is an adaptive model linking the accepted indoor temperatures with the outdoor climate. $T_{comf} = 0.31 \times T_{a,out} + 17.8$ (°C), where Tcomf is the optimum comfort temperature and Ta,out is the mean monthly outdoor air temperature. Results showed that a wider range of temperatures is accepted by the occupants of NV buildings and also preferred by them compared to the occupants of HVAC buildings. This has demonstrated the role of psychological adaptation and changing expectations. The authors defined 80% and 90% acceptability ranges around the optimum comfort temperature, giving practical design and operation guidance for buildings. The authors emphasized the need to focus on psychological adaptation, context, and individual agency in the use of the environment in developing comfort models in the future. The study also suggested focusing future research on direct assessment of thermal acceptability, individual differences, and integrating thermal comfort with other variables such as indoor air quality, productivity, and energy use. This adaptive model can be used in the design, operation, and evaluation of naturally ventilated buildings where energy gains can be made due to the wider acceptability of temperature. The authors have recommended extending its use for mixed-mode buildings and also for task-ambient conditioning systems. Future areas of research would involve thermal comfort outside the paradigm of neutrality, the role of thermal variability, development of more comprehensive models, and a finer investigation of the issue of personal control. The most important novelty of this present study is its dealing with the field-based adaptive model, contextual, and psychologically based, overstepping the traditional heat-balance approach so far adopted in laboratory studies, allowing naturally ventilated buildings to operate in a more flexible and energy-efficient way.

Note: Additional information can be found in (Brager and de Dearfd, 1998).

3.7.2.2 "Hybrid Ventilation with Innovative Heat Recovery—A System Analysis" (Davidsson et al. 2013)

This study investigates the energy performance of various ventilation systems for residential buildings through computer simulations using TRNSYS software. The research compares mechanical and hybrid ventilation systems with heat recovery against a baseline case of mechanical ventilation without heat recovery.

Key aspects of the study include:

- Baseline Case: Mechanical ventilation without heat recovery (Case 1).
- Comparison of different systems:
  - Hybrid ventilation with heat recovery (Case 2a)
  - Mechanical ventilation with heat recovery (Case 2b)
  - Hybrid systems with additional features like waste water heat recovery and ground source heat exchangers (Cases 3a-d)
  - A combined system with multiple heat sources (Case 4)
- Simulations were run for both a low-energy building and a standard insulated building.

Key findings:

- The efficiency of heat exchangers is the most critical factor for system performance.
- A hybrid system with 86% efficient heat exchangers performed comparably to a mechanical system with 75% heat recovery.
- Hybrid systems used about 400 kWh less electricity annually than mechanical systems with heat recovery.
- Adding a ground source heat exchanger provided minor energy savings (about 150 kWh/year).
- Waste water heat recovery saved 600-800 kWh/year.
- Combining multiple heat sources (ground, waste water) had limited additive benefit.

The researchers concluded that hybrid ventilation with efficient heat exchangers can achieve similar total energy performance to mechanical ventilation with heat recovery, while using significantly less electricity. They noted several technical challenges for practical implementation, including airflow control, heat exchanger cleaning, and noise mitigation. The study provides a quantitative analysis of the potential for hybrid ventilation with heat recovery in residential buildings, highlighting both energy-saving opportunities and areas needing further development. The simulations follow standard building energy modeling practices using TRNSYS software. This research contributes to the understanding of energy-efficient ventilation systems for low-energy and standard residential buildings, offering insights into the relative performance of different system configurations.

3.7.2.3 "A Review of Recent Literature on Systems and Methods for the Control of Thermal Comfort in Buildings" (Grassi et al. 2022)

The paper puts forward a review of the recent literature on systems and methodologies related to thermal comfort regulation in buildings. This work provides an overview of 166 relevant articles, published from 2017 to 2021, that describe different thermal comfort models and their indoor control strategies. Considering the kind of thermal comfort model used in each publication, the authors find that the Predicted Mean Vote method is the one most used, although often in more simplified ways. Other common Data-driven and adaptive models are also common alternatives to PMV. The major categories identified in this review for control strategies include: rule-based approaches, model predictive control, machine learning, optimization, and mathematical model approaches. In this study, a correlation is done on thermal comfort models and their control methods. The study shows that in many simulation studies, PMV models are combined with model predictive control, while prototypes combine non-PMV comfort models with simpler rule-based control strategies. The largest category of application sector considered relates to air conditioning systems for office and commercial buildings. The review also discusses implementation issues like required inputs, the level of readiness and estimated cost if available. It notes that while a large number of advanced control strategies are still limited to simulation study, prototype implementation and field deployments are becoming increasingly common. The authors indicate that not many studies have focused on the thermal comfort requirements for populations in vulnerable conditions, such as the elderly or the disabled. Some important standards include ASHRAE Standard 55 and EN ISO 7730/EN 16798-1 for thermal comfort models. This review paper presents a structured overview of the recent advances on comfort temperature control, highlighting the gap between thermal comfort research and its application to building technologies. The document comprises an additional spreadsheet database containing the analyzed papers, facilitating further investigation. In summary, the research identifies thermal comfort regulation as a dynamic field of study progressing towards real-world application; however, it emphasizes that additional efforts are necessary concerning individualized comfort and the consideration of specific requirements. The authors propose that enhanced cooperation among architects, energy professionals, and thermal comfort authorities may result in significant progress in the development of comfortable and energy-efficient indoor settings.

3.7.2.4 "Thermal comfort: use of controls in naturally ventilated buildings" (Raja et al. 2001)

The current study claims to study the reliance on controls over thermal comfort in self-cooled office buildings in the UK. It will review data from field surveys conducted in Oxford and Aberdeen to deduce how different controls like windows, doors, fans, and blinds are employed by the occupants in adapting their indoor thermal environment during the summer period. Data collection was performed through longitudinal surveys, whereby each respondent replied daily, and by transversal surveys, where single responses came from a larger population amounting to 15 different buildings. The authors examined the relationship among indoor and outdoor temperatures, comfort perception, and the use of different control strategies.

Key findings include:

- The most utilized control was the opening of windows, which increased both with indoor and outdoor temperature. On average, windows were reported to be opened in 62% of the responses.
- Fan use similarly increases with temperature but is less common overall - 38% of the responses.
- Blinds/curtains were used in about 24% of responses, but mostly to reduce glare rather than control heat.
- There was some effectiveness of cross-ventilation with opened windows and doors in reducing indoor temperatures.
- The use of controls was strongly correlated with reported thermal discomfort, suggesting occupants use them in response to uncomfortable conditions.
- Occupants with greater access to controls (e.g., those near windows) reported less discomfort than those with limited access.

When the indoor temperature rose to 20°C and the outdoor temperature rose to 15°C, occupants tended to open more windows and increase the usage of fans. In such studies conducted in Pakistan, similar results are presented, and hence consistency can be seen despite different climates. The authors conclude that availability and actual use of controls play a vital role in ensuring improved building performance and satisfaction with buildings designed for natural ventilation. The authors make a recommendation that in such structures, the increase of ventilation rates caused by opening windows when the referenced temperatures are surpassed is considered in the computer-simulated model. The present research increases the understanding of adaptive thermal comfort and gives valuable information that could help develop building design and management practices to increase comfort, probably reducing building energy consumption in naturally ventilated buildings.

3.7.2.5 "Thermal Environment Assessment Reliability Using Temperature —Humidity Indices" (D'ambrosio Alfano etal. 2011)

The article represents a comparison done between the Humidex index and established methodologies regarding thermal environments evaluation, both with hot and moderate indoor conditions. Comparisons will be performed for the Humidex index with methodologies covered by international standards: Wet Bulb Globe Temperature (WBGT) index, Predicted Heat Strain (PHS) model, and Predicted Mean Vote (PMV) index. They compared several environmental conditions, metabolic rates, and clothing insulation by using software specifically developed according to international standards. For hot environments, large discrepancies between Humidex and the results from standardized methods were apparent. In general, Humidex underestimated dangerousness of workplaces, especially for low metabolic rates and dry conditions. Very often the authors found that microclimatic situations assessed as dangerous by both PHS or WBGT were classified as just uncomfortable by Humidex. In indoor environments with moderate conditions, the Humidex showed coincidence with the PMV only within a narrow range of thermohygrometric parameter values. It worked well in high temperatures relevant to summer or low temperatures relevant to winter; however, this was possible only for very low values of metabolic activity rates. Moreover, it was also noted that the Humidex cannot factor in the effects of clothing insulation, varying metabolic rates, and temperature non-uniformities. Based on these easy interpretations, the researchers concluded that the Humidex index should be used only to give a general indication about outdoor clothing. They advised against the use of this index to assess either indoor thermal comfort or occupational thermal strain because the index is not valid outside the narrow range for which it has been validated and because it does not take into consideration individual physiological responses to different thermal exposures. The study recommends the use of appropriate rational approaches, like PHS and PMV methodologies from ISO Standards, for more reliable assessments, though noting that their application requires special software. The authors also state the intention to conduct further comparative studies with more promising metrics such as the Universal Thermal Climate Index (UTCI), based on a rational framework, validated for a wider range of microclimatic conditions. The present paper underlines the limitations in the use of simple bioclimatic indices, such as the Humidex, and emphasizes the importance of developing appropriate and standard methods necessary for accurate thermal environmental assessment both indoors and outdoors.

3.7.2.6 "Thermal comfort: A review paper" (Djongyang et al. 2010)

The present academic paper reviews thermal comfort based on its theoretical models, methods, and their applications in a critical way. Based on the two major approaches regarding thermal comfort, the rational or heat-balance method, and the adaptive method, Djongyang, Tchinda, and Njomo present a review. The rational approach can be explained in a very rational manner. Two popular models for the determination of indoor thermal comfort, namely the Predicted Mean Vote (PMV) and Predicted Percentage of Dissatisfied (PPD) models, are explained below. Each of these models takes into account the following factors: air temperature, mean radiant temperature, air velocity, relative humidity, metabolic rate, and insulation due to clothing. This paper will discuss in some detail the adaptive approach in relation to a variety of aspects: thermal comfort models and methodologies, comparative studies of traditional and modern living environments, techniques for analyzing building performances, and systems for energy-use minimization. Then, the paper will go into specifics of thermal comfort: in classrooms, in hospitals, and outdoors. The authors start with an analysis of the physiological basis of comfort; the human body is presented as a thermodynamic device, and a dynamic thermoregulatory system is explained. This chapter gives quite good insight into how the human body maintains its core temperature and copes with changes in the surroundings. Further, more than half of the paper is devoted to the mathematical modeling of heat exchange between the human body and the ambient environment. The various thermal effects discussed by the authors include conduction, convection, radiation, moisture, metabolism, and clothing. Equations and models are presented that quantify these effects with their resultant thermal comfort. Other topics reviewed here that relate to thermal comfort are gender differences in thermal perception, the outcomes of indoor climate on thermal perceptions, and adaptive algorithms for comfort prediction. The paper further considers new fields of research, such as thermal comfort outdoors and with respect to hospital patients. In general, the paper gives the broadest possible review of existing knowledge within the field of thermal comfort research, from basic conceptions to practical application. It therefore serves as a key sourcebook for researchers, engineers, and practitioners involved in designing buildings, developing Heating, Ventilation, and Air Conditioning (HVAC) systems, and improving the energy efficiency of buildings.

3.7.2.7 "Adaptive thermal comfort and sustainable thermal standards for buildings" (Nicol and Humphreys, 2002)

This paper investigates the adaptation methodology concerning thermal comfort in relation to architectural structure and its implication for developing sustainable thermal benchmarks. Results indicated that rational indicators based on controlled laboratory experiments cannot predict correctly thermal comfort in the real building environment. On the contrary, the adaptive approach provides a better framework that considers how people naturally adapt to a changing thermal environment for explaining comfort levels in real structures. Also, there is a very close relation in the free-running building between indoor comfort temperature and ambient temperature, which could be represented by a regression equation as $Tc = 13.5 + 0.54To$ for comfort temperature Tc and monthly mean ambient temperature To. It was seen to hold quite consistently over different sets of data. The internal comfort-outdoor temperature relation is thus complicated in those structures that are either heated or cooled, as internal temperatures are decoupled from those outdoors. Optimum indoor temperature may need to be established over time or for different population groups. In this work, the term "adaptive opportunity" will be introduced, defined as the ability of occupants to adjust either the environment or themselves to be comfortable. Buildings that are more flexible can accept a broader temperature tolerance band. For predicting the indoor comfort temperature, the authors propose the use of an exponentially-weighted running average for the outdoors temperature. The resulting process can then be considered an "adaptive algorithm," that can define variable indoor temperature setpoints based on recent outdoors conditions. Comfort standards are sustainable, the paper concludes, as long as they take into account energy use. Application of variable limits for indoor temperature according to the adaptive model would work to cut down energy consumption in air-conditioned buildings and encourage natural ventilation. It emerges from the study that about 2°C variation in temperature is acceptable in buildings, which can be extended provided the occupant has adequate control over the environment. Availability of effective and accessible controls to the occupants emerges as the key in achieving thermal comfort. In general, the present research espouses a transition from fixed and prescriptive temperature standards to adaptive standards, which depend on climate, building characteristics, and occupant behavior. According to them, this would ensure comfort and energy-efficient buildings, even sustainable ones.

Note: The paper refers to various standards such as ISO 7730 and ASHRAE Standard 55, proposing new guidelines based on the results from the adaptive model.

3.7.3 Acoustic Comfort Models (ACMs)

Acoustic comfort is a fundamental attribute in indoor space, and it influences health and productivity highly. It involves many factors which affect the sound of a room and its effects on the occupants. Amongst such terms, one is reverberation; it is the time the sound can stay alive inside the room after the original sound has stopped. There are different kinds of rooms with different characteristics of reverberation. For example, less reverberation in lecture halls helps achieve distinct speech, while increased reverberation in concert halls makes the musical performance better. Another important factor is sound insulation. It deals with the obstruction of sound by the walls, floors, and other structural elements of buildings from passing from one space to another. Good sound insulation is a basis for privacy and minimum disturbance arising from space neighborhood or external noise. Background noise level greatly affects acoustic comfort. Noise levels should be managed such that ambient sounds will not prevent a person from performing his or her activities like talking, learning, or resting. This becomes highly essential in places where maximum concentration is needed, like the office and classroom. The design of the building system, mainly the heating, ventilation, and air conditioning (HVAC), affects acoustic comfort tremendously. These can be major noise and vibration contributors, and careful planning is required to limit their acoustic impact. When acoustic issues are integrated into the process of building design and construction, architects and engineers can create an environment best fostering communication, enhancing concentration, and assuring privacy. This is a comprehensive approach to acoustic design that will not only enhance operational effectiveness but also play a very important role in maintaining the overall wellbeing, efficiency, and contentment of its occupants.

3.7.3.1 “A model predicting the effect of speech of varying intelligibility on work performance“ (Hongisto, 2005)

This paper develops a model for predicting the impact of speech intelligibility on work performance in open-plan offices. The authors did a review of the literature of studies investigating speech and its impact on task performance in offices. They showed that speech-especially intelligible speech-seriously degrades the performance of different cognitively demanding tasks, such as remembering lists, comprehension of read material, and proofreading. The authors therefore created a predictive model based on such analysis to show the loss of work performance as a function of an increase in speech intelligibility levels. In this paper, speech intelligibility is quantified by the Speech Transmission Index, ranging from 0-completely unintelligible-to 1-perfectly intelligible. According to the model, performance on complex tasks can decrease by up to 7% when speech is highly intelligible-an STI above 0.60-which just happens to be very common in open-plan offices which are poorly designed. However, losses in performance, whenever speech intelligibility is low-less than 0.20-are expected to be small to insignificant, as would typically occur in a well-designed private office. The authors indicate that the greatest loss in performance occurs in the range of STI between 0.30 and 0.50 and note that the exact form of this relationship is still in need of further research, most specifically within this critical range. It discusses practical implications: STI should be maintained below 0.50 to improve acoustics and reduce performance decrements in open-plan offices. This will be achieved by several acoustic treatments in combination, including highly absorbing rooms, tall cubicle partitions, and an appropriate speech masking system. The authors would go further in presenting the model as a tool for quantifying possibly large productivity gains due to acoustic improvements in a manner through which companies may estimate return on investment for upgrades. They provide an example calculation showing how the model could be applied. For this current model, limitations are accepted, and further empirical analysis is recommended, in particular the consequences of performance for varying levels of STI. Future Research - Further extension and validation of the model should combine controlled laboratory experiments with field studies. This manuscript introduces an innovative methodology for forecasting the impact of speech distraction in workplace environments, integrating prior studies into a functional framework that has significant ramifications for office architecture and employee productivity. The authors assert that this work serves as an initial platform for continued exploration of the intricate interplay between auditory conditions and cognitive functioning.

3.7.3.2 “Combined effects of environmental factors on human perception and objective performance: a review of experimental laboratory works“ (Torresina et al., 2018)

This research paper presents a comprehensive literature review on the combined effects of multiple indoor environmental factors (acoustic, thermal, visual, and air quality) on human perception and performance in buildings. The key aims were to:

- Explore how different environmental factors interact to affect occupants' comfort and productivity.

- Review methodological approaches used in experimental laboratory studies investigating these interactions.
- Identify patterns of interaction between environmental factors and potential practical implications for building design.
- Highlight limitations, potential improvements, and future research opportunities in this field.

The authors collected and analyzed 45 recent laboratory studies that examined the combined effects of two or more indoor environmental factors. They reviewed the experimental designs, exposure conditions, and methods used to assess perception and performance.

Key findings include**:**

- Most studies focused on interactions involving thermal conditions, followed by visual, acoustic, and air quality factors.
- Interactions between factors were observed in some cases, but results were often inconsistent across studies.
- Some clear trends emerged, such as high temperature and humidity negatively affecting perceived air quality.
- Performance impacts were less frequently studied than perceptual effects.
- Methodological differences made comparison across studies challenging.

The paper highlights the need for more standardized approaches to studying factor interactions. It notes that deeper understanding of these interactions could improve indoor environmental quality models and inform human-centered building design practices. The authors suggest future research should aim to develop integrated models that account for combined environmental effects, individual occupant characteristics, and dynamic behaviors over time. They advocate for incorporating this knowledge into building standards to promote designs that reduce negative impacts and enhance positive effects on occupants. Overall, this review synthesizes current knowledge on indoor environmental factor interactions, identifies key research gaps, and provides a foundation for future studies aiming to better understand and predict how indoor environments holistically impact human comfort and performance.

3.7.3.3 "Stress Hormones in the Research on Cardiovascular Effects of Noise" (Babisch, 2003)

This research reviews and synthesizes findings on the effects of noise exposure on stress hormone levels in humans. The paper examines both laboratory studies and epidemiological research investigating how various types of noise (e.g., occupational, traffic, aircraft) impact the secretion of stress hormones like adrenaline, noradrenaline, and cortisol. The author, W. Babisch, provides an overview of the physiological stress response and explains how stress hormones act as bio-messengers in regulating autonomic functions. The paper discusses the potential links between chronic noise exposure, elevated stress hormone levels, and increased cardiovascular health risks. It summarizes results from numerous studies measuring stress hormone levels in urine, blood, and saliva samples from subjects exposed to different noise conditions. The review finds fairly consistent evidence from occupational noise studies showing higher levels of stress hormones, particularly noradrenaline, in workers exposed to louder environments. Results for community noise sources like traffic and aircraft are less conclusive, with some studies showing elevated hormone levels and others finding no effect or even decreases. The paper explores various methodological challenges in this research, such as accounting for circadian rhythms in hormone secretion and distinguishing chronic effects from acute responses. Babisch discusses how stress hormone measurements can be useful for identifying at-risk groups, investigating combined exposures, and examining factors that modify individual noise responses. However, he notes that interpreting the health significance of observed hormone changes remains challenging. The paper concludes that while noise-induced stress responses are well-established, more standardized methods and clinical data are needed to quantitatively assess long-term health risks. Overall, this review synthesizes a large body of research on noise and stress hormones, highlighting key findings, methodological issues, and areas needing further study. It provides a comprehensive overview of the state of knowledge in this field as of 2003, when the paper was published.

3.7.3.4 Towards an Urban Vibrancy Model: A Soundscape Approach“ (Aletta and Kang, 2018)

This paper investigates the perception of "vibrancy" in urban soundscapes and proposes a predictive model to determine the degree of vibrancy from the physical parameters. The authors have used a two-part data collection methodology: first, a focus group discussion to understand how vibrancy is interpreted, and then a controlled laboratory experiment where perceptual data related to vibrancy was collected. The findings of the group interview indicated that the perception of vibrancy would result from auditory elements like human voices, sound variability, loudness, and music, and also visual components comprising the presence of people and actions. Based on this, they developed some probable physical indicator variables that could act as predictors of vibrancy. These include acoustic properties like Roughness, Fluctuation Strength, and Loudness, and visual aspects such as the Presence of People and Music. The researchers collected audio-visual data from 46 urban sites in the UK and China. The same locations were rated by 35 participants in a controlled laboratory experiment using audio-visual stimuli for their vibrancy, pleasantness, and eventfulness. They did a stepwise linear regression on five parameters - Roughness, Presence of People, Fluctuation Strength, Loudness, and Presence of Music - to come up with a predictive model of vibrancy. This model accounted for 76% of the variance observed in vibrancy scores. Principal findings:

- Vibrancy was strongly correlated with eventfulness, but not with pleasantness
- Visual context appears important for pleasantness ratings
- The association between vibrancy and variability in loudness was non-linear

The research findings suggest that vibrancy is a multivariate perceptual variable determined by both auditory and visual components. The predictive model developed can be a useful tool in the design of urban soundscapes. The research conformed to the ISO 12913-1:2014 requirements concerning the definition of soundscape and its conceptual framework. It furthers the development of quantitative tools meant to assess specific features of soundscapes, going beyond the general assessment of soundscape quality.

3.7.4 Visual Comfort Models (VCMs)

Visual comfort in buildings encompasses both natural and artificial lighting and is an important aspect of occupants' well-being and productivity. Daylighting models, analyzing natural light penetration into the building, apply metrics such as the Daylight Factor for optimum window location and sizing. These models try to maximize the intake of natural light with minimal glare and thermal discomfort, adding to the energy efficiency within the buildings.

Glare, being a significant concern in lighting design, is quantified by certain indices, one of which is the Daylight Glare Probability (DGP). DGP predicts the probability of discomfort due to excessive brightness contrast, taking into consideration factors such as luminance of glare sources and their position with respect to the observer's position. Some researchers, like Wienold and Christoffersen (2006), have come up with better evaluation methods and glare prediction models that have increased the accuracy of glare assessments in daylit environments.

The visual comfort criteria can be ensured according to the established norms, such as EN 12464-1. EN 12464-1 is the European Standard that gives detailed prescriptions for indoor lighting in view of intensity of illuminance, limitation of glare, illuminating uniformity, and color rendition. For such set standards, a designer will be capable of proposing, with the help of visual comfort models, lighting solutions supporting occupants' activities, enhancing their comfort and well-being, and raising indoor environmental quality without compromising energy efficiency.

3.7.4.1 The 'adaptive zone' – A concept for assessing discomfort glare throughout daylit spaces (Jakubiec and Reinhart, 2012)

The present work reviews and performs a comparison of the various measures existing at present that quantify discomfort glare in daylit settings, with the purpose of guiding architects and designers in best assessment and mitigation of glare concerns The key aspects of the study include:

- Comparison of five glare metrics: Daylight Glare Index (DGI), CIE Glare Index (CGI), Visual Comfort Probability (VCP), Unified Glare Rating (UGR), and Daylight Glare Probability (DGP). In this, the authors, through Radiance simulation quantified these metrics under different daylight conditions in three typical environments.
- Introduction of the "adaptive zone" concept, which considers an occupant's ability to adjust their position and view direction to minimize glare. This approach provides a more realistic assessment of glare in real-world scenarios.
- Development of a new visualization method using cylindrical image projections overlaid with view direction-dependent glare evaluations. This allows designers to quickly understand glare conditions throughout a space and over time.
- Implementation of the enhanced simplified DGP (eDGPs) method for annual glare simulations, combining DAYSIM illuminance predictions with fast Radiance simulations to efficiently evaluate glare over an entire year.
- Integration of glare predictions with the modeling of occupant behavior in simulating blind usage patterns and their interaction with daylight availability and energy use.

This present study identified DGP as the strongest and most reliable predictor of discomfort glare for daylight environments, particularly when direct sunlight is present. This investigation recommends the application of DGP when performing quantitative glare analyses, both during the design stage and in later post-occupancy assessments. With respect to adaptive zones, the authors show how the freedom afforded occupants to adjust seat location and viewing direction can be utilized to strongly reduce predicted glare occurrence. It was found, for instance, that in a sidelit office, ± 45° of rotational freedom reduced average glare by about 10% and eliminated intolerable glare for hundreds of occupied hours. The paper also discussed the importance of considering glare in concert with other daylighting metrics, such as daylight autonomy. By combining glare predictions with models of occupancy behavior**, the study demonstrated how adaptive glare analysis can lead to** better predictions of daylight availability and, therefore, higher energy savings. The key outputs of this research compose inputs and tools for architects and lighting designers in the handling of glare concerns in daylit spaces within the context of offering higher occupant comfort and energy efficiency.

3.7.4.2 "Daylighting offices: A first step toward an analysis of photobiological effects for design practice purposes" (Bellia et al., 2014)

This study characterizes the features of natural light in three different Naples offices, Italy, for their visual and, non-visual-for example, circadian-effects. This study had twin objectives: in-depth daylight characterization and the investigation of its possible circadian effect on the occupants in an office setting, focusing on providing recommendations on daylight quality characterization in spaces. Three offices in various orientations with individual peculiarities were in focus. The researchers measured a number of facets of the daylight in those spaces: spectral power distributions, correlated color temperatures, and irradiances at eye-level. They also analyzed the potential circadian consequences of that daylight-using several established metrics that had been developed for the quantification of circadian impact. Key findings from the research include:

- The spectral distributions and CCTs of light reaching an occupant's eye at desk level were similar across the three offices, despite differences in office characteristics such as dimensions, surface reflectances, and external obstructions.
- These spectral properties remained consistent under various sky conditions.
- The eye-level irradiances and their calculated circadian impact were found to be similar to those of CIE standard illuminants D50 and D55.

The researchers explained that indoor natural light is essential to promote occupants' well-being, enhance productivity, and reduce consumption of electric power. They added that light is the most important time cue for the endogenous circadian system of humans and thus possibly may have potential health and sleep-wake cycle effects. This manuscript shortly describes how the historical context of human adaptation to natural light came into being and what kind of disorders the discovery of electric illumination, especially for night-time conditions, may have brought with it. Such contextual analysis underlines the need for recognition of the circadian effects of daylight in today's architectural situations. The authors intend to extend the present study by performing similar measurements in other seasons and comparing the experimental results with those obtained using computer simulations. The said tendency is further to constantly work out for more detailed standardization that might go well beyond the assessment and optimization of daylight quality in architectural design, considering the visual and non-visual effects.

3.7.4.3 "Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras" (Wienold and Christoffersen, 2006)

This research focuses on evaluating and developing glare prediction models for daylight environments using CCD cameras. The main objectives were to:

- Provide new insights into how luminance distributions impact glare perception
- Assess existing glare prediction models
- Develop a new, more accurate glare prediction model

The researchers used CCD camera-based luminance mapping technology to record luminance distributions in daylit office spaces. They developed a RADIANCE-based tool called "evalglare" to analyze glare according to various prediction models and contrast ratios. User assessments were conducted with over 70 subjects in Copenhagen and Freiburg under different daylighting conditions. The results were compared to existing glare models, revealing significant room for improvement in glare prediction. For example, the window luminance model had a squared correlation factor of only 0.12, while the daylight glare index (DGI) achieved 0.56. Because these models were poorly predictive, the authors have developed a new metric, called daylight glare probability (DGP). This new model relies on the vertical eye illuminance, which is itself related with the luminance of the glare source and its solid angle and position index. This new DGP reached a very high positive correlation with the subjective response: 0.94 squared correlation coefficient. It indicates that accurate glare prediction is of prime importance in sustainable building design through effective daylighting strategies. The study addresses the challenges associated with integrating daylight utilization along with visual comfort regarding increasing glass use in recent architectural designs and the development of new glazing technologies, together with novel shading systems. In fact, the obtained outcomes give important lights to the architects and designers who are dealing with the development of building envelopes and lighting systems. It indicates that a number of dimensions related to comfort and energy needs, particularly those about discomfort glare from windows, are pending; therefore, the development of reliable assessment instruments and descriptors is required.

3.7.4.4 "Daylight glare evaluation with the sun in the field of view through window shades" (Konstantzos and Tzempelikos, 2016)

This research investigates the evaluation of daylight glare for conditions in which sunlight is visible through window shades. 41 participants performed office tasks using 14 different shade products mounted on windows. Primary goals and findings of the study were:

- The relationships of discomfort glare to many factors measured and simulated were studied by the investigators.
- They evaluated the existing glare indices for their effectiveness when sunlight is perceptible through window coverings.
- The study presented alternative illuminance-based criteria for assessing glare through fabrics by extracting discomfort thresholds and proposing a new related index.
- The authors proposed modifications to the coefficients in the Daylight Glare Probability (DGP) equation for cases when the sun is visible through shading devices.

The best accordance with the experimental data has been achieved by the modified DGP equation. Such result would mean that while the general structure of the DGP equation is viable, it can be adjusted for specific environmental conditions or different fenestration systems using different values of the coefficients. One of the most important contributions in this work concerns the development of an alternative glare discomfort index. This index is based on direct and total-to-direct vertical illuminance reaching the eye and therefore captures not only the impact of sunlight but also the interplay between fabric coloration, overall brightness, and the apparent intensity of visible sun. The authors indicate that the new index has the potential to simplify annual simulations by eliminating the need for detailed luminance mappings of interior environments. Besides, it can be directly related to the optical properties of fabrics and, therefore, has value in developing design guidelines and glare-based shading controls. Different shading products with different openness factors and visible transmittance values were used in the experiment, considering direct and total light transmission properties. Thus, the impact of various fabric properties on glare perception when direct sunlight is in the field of view was studied in depth. This research, in brief, provides important insights into evaluating daylight glare when window shades are in use, improving the current glare metrics and offering new tools for assessing visual comfort in built environments.

3.7.4.5 Development and implementation of an adaptive lighting and blinds control algorithm" (Gunay et al., 2017)

This paper presents the development and testing of an adaptive lighting and blind control algorithm for office buildings. Researchers recorded the switch-on and blind closing behaviors related to light sources in ten private offices, complemented by monitoring data for solar irradiance, ceiling illuminance, and space occupancy. Using this data, the authors have developed an algorithm that is designed to learn about occupant illuminance preferences based on the light switch-on and blind closing behaviors. The learned preferences are then used by an adaptive algorithm to select suitable photosensor setpoints at which to turn lights off and open blinds. In their testbed, the authors implemented the algorithm on controllers serving five private offices and one shared office space with its own network of controls. Several control scenarios were studied using integrated daylighting and occupant behavior simulations. The challenge is to develop effective systems for daylight-integrated lighting and automated blinds in view of large variability in the factors influencing visual comfort and in the preferences of individual occupants. Previous research documented that preferred workplane light levels for different occupants may range from 91 to 1000 lux, while illuminance levels that trigger the closure of blinds may be as low as 3 klux or as high as 9 klux. Traditional approaches often use conservative photo-sensor setpoints; for example, closing the shades at 2 klux on the window or 1.8 klux on the work plane and turning lights off when over 500 lux on the work plane. But the conservative set-points may not be liked by all the occupants*, as* some feel the automated blind closure is too early or too late according to their individual preference. The adaptive algorithm developed herein is designed to learn and adapt to such occupant individual behaviors in order to avoid such issues. Results have shown the ability to potentially reduce lighting demand in office buildings without sacrificing the comfort of the occupants. This paper contributes to the literature on building automation and energy efficiency by providing a new, more personalizable and responsive approach to the control of lighting and window blinds. It discusses the challenges in varying occupant preferences and environmental variables that may lead to increased occupant satisfaction and energy efficiency in office buildings.

3.7.5 Indoor Air Quality Models (IAQMs)

Indoor air quality models are major elements in assessing and improving environmental quality within buildings since indoor air quality level has a great effect on both health and comfort, as well as the productivity of the occupants. Poor indoor air quality could expose many people to a variety of health issues including respiratory diseases and allergies, thus reducing cognition and overall well-being. One important class of Indoor Air Quality (IAQ) models includes the Volatile Organic Compounds (VOC) model. These models consider the characteristic emission rates of organic chemicals from a variety of building materials such as paints, adhesives, carpets, and furnishings, and characterizes their impacts on indoor air quality. Once knowledgeable about VOC behavior and concentration, building professionals are in a position to better make appropriate material choices and to take other actions which reduce the exposure of building occupants to the most harmful chemicals.

Various standards and guidelines have thus been laid down to ensure acceptable IAQ levels, such as ASHRAE Standard 62.1 and ISO 16000. Such standards are the most important references among architects, engineers, and facility managers because they give the minimum ventilation rates to be adopted and specify the demands for a healthy and comfortable indoor environment. This avoids the buildup of indoor pollutants, controls moisture levels, and ensures adequate oxygen supply-all factors related to the health and comfort of the occupants.

IAQ models play an important role in building design and operation by providing comprehensive insights into the behavior of indoor pollutants and helping in facilitating the realization of efficient ventilation strategies coupled with air purification. These models allow one to find those spaces where air quality might get degraded, for the purpose of adjustment in ventilation strategies so that adequate quantities of fresh air could be provided and/or effectively dilute or remove contaminants from the occupied space. Emphasizing indoor air quality by applying these models, together with adhering to recognized standards, contributes much to the health, comfort, and productivity of the occupants, while fostering the overall sustainability and operational efficiency of the building.

3.7.5.1 “Providing Better Indoor Environmental Quality Brings Economic Benefits“ (Fisk and Seppanen, 2007)

This research paper examines the economic benefits of improving indoor environmental quality (IEQ) in non-industrial workplaces and homes. The authors review and analyze existing scientific literature to quantify relationships between IEQ factors and human health, work performance, and absence rates. The paper focuses on two main aspects of IEQ: thermal conditions and air quality. For thermal conditions, it finds that work performance peaks at temperatures around 21-22°C, with performance decreasing at higher and lower temperatures. For air quality, higher ventilation rates are associated with improved health outcomes, reduced absence rates, and better work and school performance. The authors develop quantitative relationships between these IEQ factors and outcomes like work performance and absence rates. For example, they estimate that doubling ventilation rates from 6.5 to 13 L/s per person increases work performance by about 1.5%. They also quantify the health costs associated with environmental tobacco smoke exposure and dampness/mold in buildings. Using these quantitative relationships, the paper presents several example cost-benefit analyses for IEQ improvement measures. These include night-time ventilative cooling, various building cooling strategies, adding economizer systems, and increasing ventilation rates. The analyses account for energy costs, equipment costs, and the economic value of improved work performance and health. The results consistently show that many IEQ improvement measures are highly cost-effective when accounting for productivity and health benefits, with benefit-cost ratios up to 80 and annual economic benefits as high as 500€ per person. The authors argue this indicates more investment should be made in IEQ improvements, as the benefits often far outweigh the costs. The paper acknowledges limitations in the current research, including uncertainties in quantifying impacts on real-world work performance. It identifies priority research needs, such as studying effects on high-level cognitive performance and developing energy-efficient methods to achieve IEQ benefits. Overall, this research synthesizes existing evidence on IEQ impacts, develops quantitative relationships for use in economic analyses, and demonstrates through example calculations that many IEQ improvements can be highly cost-effective when accounting for all benefits. The authors argue this information should be used to inform building design and operation decisions.

3.7.5.2 "Indoor air pollutants in office environments: Assessment of comfort, health, and performance" (Wolkoff, 2012)

This research paper reviews indoor air pollutants in office environments and assesses their impacts on comfort, health, and performance. The study examines various indoor air pollutants, focusing on volatile organic compounds (VOCs), particles, and ozone-initiated reaction products. It evaluates their effects on sensory irritation, lung function, cardiovascular health, and overall air quality perception. The researchers found that VOC concentrations in typical office environments are generally too low to cause significant sensory irritation in the eyes and airways based on estimated thresholds. However, some VOCs, including formaldehyde, may contribute to reported sensory irritation under certain conditions when combined. The odor thresholds of several VOCs are low enough to influence perceived air quality, potentially resulting in acute effects and performance deterioration. Regarding particles, the study indicates that office dust particles, even when combined with substances like glucans, aldehydes, or phthalates, do not appear to cause significant sensory or lung effects in most individuals. However, some inflammatory effects may be observed in asthmatics. Ambient particles, especially from sources like traffic emissions and candle smoke, may have cardio-pulmonary effects, particularly in susceptible populations such as the elderly and those with pre-existing conditions. The paper highlights concerns about ozone-initiated terpene reaction products, especially in environments with elevated ozone levels (≥0.1 mg/m3) and high limonene concentrations. These reactions can produce formaldehyde, which may be problematic. Secondary organic aerosols generated from these reactions appear less likely to cause adverse airway effects compared to their gaseous counterparts. The researchers recommend measuring specific compounds to assess indoor air quality and minimize reports of irritation symptoms, performance deterioration, and cardiovascular and pulmonary effects. These recommendations are based on an analysis of thresholds for odor and sensory irritation. Overall, the study emphasizes the complexity of indoor air quality issues in office environments and the need for targeted measurement and mitigation strategies to ensure occupant comfort and health. The research underscores the importance of considering multiple factors, including chemical interactions and individual susceptibilities, when evaluating indoor air quality and its potential health impacts.

3.7.5.3 "Performance, acute health symptoms and physiological responses during exposure to high air temperature and carbon dioxide concentration" (Liu et al. 2017)

The present research sets out to investigate human performance, acute health symptoms, and physiological responses to high air temperature (35°C) and high CO2 concentration. Human subjects were exposed to various environmental conditions in fixed 3-hr time periods in a climate chamber where environmental conditions were controlled. The researchers chose 35°C as an action level because it is a threshold in China where outdoor workers are required to reduce their work intensity and take measures to prevent heat-related diseases. They compared the responses at this temperature with those at a base temperature of 26°C. The authors also discuss the possible effects of increasing CO2 concentration to 3000 ppm at 35°C on the responses measured. Measurements included physiological parameters like tympanic membrane temperature, cutaneous temperature, heart rate, body weight loss, arterial oxygen saturation, and cardiac intervals. Further, thermal comfort, air quality, sleepiness, and acute symptoms related to health were recorded based on subjective self-reported measures. The cognitive performance was determined in terms of the performance of addition and subtraction tasks. The findings obtained from these experiments after exposure to temperature in the range of 35°C compared with 26°C significantly altered physiological parameters. The subjects recorded a rise in eardrum temperature, skin temperature, heart rate, and body weight loss. Arterial oxygen saturation fell, while the percentage of adjacent inter-beat cardiac intervals differing by more than 50 ms (pNN50) also fell, reflecting heightened stress levels. Subjectively, the participants felt uncomfortably warm, perceived worse air quality and greater sleepiness and higher intensity of several acute health symptoms at 35°C. Cognitive performance, measured with addition and subtraction tasks, was significantly reduced during exposure at 35°C. The elevated CO_2 level of 3000 ppm at 35°C did not result in significant added response changes compared with 35°C alone. The results from this study confirm that selecting 35°C as an action level is appropriate for the initiation of both working time reduction and protective measures for outdoor workers. The findings further indicate that simultaneously high CO_2 levels of up to 3000 ppm have no modifying effects on the negative effects of high temperatures. The present study contributes valuably to the knowledge on physiological and cognitive responses to high-temperature exposures, which is of vital importance in the light of the expected rise in frequency and intensity of extreme heat events under global climate change. The study's findings can inform occupational health and safety guidelines, especially for outdoor workers exposed to high temperatures.

3.7.6 Integrated Comfort Models (ICMs)

Integrated comfort models signify a more modern and integrated approach to building design and assessment, as many aspects of environmental comfort are interdependent. Thermal comfort, acoustic quality, visual comfort, and indoor air quality have conventionally been treated as separate issues, with potential solutions being optimized for one or more of these factors at the expense of others. It has only recently emerged that all these factors together contribute to the general satisfaction and well-being of the occupants. Integrated Comfort Models are models (ICMs) that combine several comfort parameters into one evaluative framework. This approach therefore realizes that perfection in an indoor environment is a function of not overemphasizing one particular aspect, but rather balancing all the different contributing factors in a given space in harmony toward the creation of a comfortable environment for its occupants. The ICMs involve evaluating how different environmental parameters interact and affect occupants simultaneously.

For instance, while larger windows may be installed to increase natural daylight usage, improving visual comfort and saving energy on lighting, they may also lead to thermal problems of solar heat gains or glare, thus negatively impacting both visual and thermal comfort. In the same vein, increased insulation meant to improve thermal efficiency may incidentally affect acoustics, altering the way sound propagates in space. The aim of integrated comfort models is to recognize and manage these inter-relationships in a manner such that with improvement in one aspect, negativity in the other is avoided. The derivation and application of an integrated comfort model requires developing building performance simulation tools.

Models such as EnergyPlus, and TRNSYS are of the computer software packages available that have the capability to simultaneously simulate various building performance issues. These models represent the complicated interactions among the building systems, environmental conditions, and occupants' behaviors. By way of inputting various design parameters and environmental data, these models will allow the professional to predict how a building will perform regarding energy efficiency, thermal comfort, lighting levels, acoustic quality, and IAQ for whatever situation one can imagine. This predictive capability enables informed decision-making during the design process, allowing modifications to be made that enhance overall comfort while achieving sustainability and energy goals.

3.7.6.1 "A Review of Field Measurement Studies on Thermal Comfort, Indoor Air Quality and Virus Risk" (Kakoulli et al., 2022)

This research provides a comprehensive review of field measurement studies conducted during the last two decades, which have been used to assess indoor environmental quality, with a special emphasis on indoor air quality. The current paper reviews 41 carefully selected field measurement studies conducted across a range of indoor environments including but not limited to offices, schools, residences, care environments, and other building types. Additionally, the parameters measured, the measurement methodologies used, and the main findings of these studies are presented. The review provides background on thermal comfort, indoor air quality, and virus risk first, including the indices and standards used in the studies. It then collates statistics on the types of buildings studied, parameters measured, and IEQ factors. Among the measured parameters, temperature took precedence at 75.6%, followed by CO2 at 73.2%, and then relative humidity at 70.7%. This study also points out that as many as 49% of the field studies are conducted within educational establishments, while 14.5% are conducted within offices and residences. It also remarks that there is a lack of research studies on other types of indoor environments such as hospitals, shopping centers, and public transportation facilities. The paper discusses different methods of data collection across studies, including sensors at 87.8%, passive samplers at 31.7%, and occupant questionnaires at 29.3%. The study also points out that these calibration methods vary and most of the studies lack long-term, continuous monitoring. The paper outlines the following as the main results of the studies reviewed: statistical data analysis, 87.2%; comparison with standards, 61.5%; ventilation effect evaluation, 28.2%. It also establishes that health effects were addressed by only 17.9% of these studies and productivity and cognitive performance effects were discussed by 10.3% of them. This manuscript has focused on many inadequacies and challenges of the existing field measurement studies, including the need for standardization, consideration of a wider range of pollutants, and the implementation of real-time monitoring and control systems. It emphasizes that universal standards and protocols about the execution of field measurement studies need to be developed for better comparability and derivation of meaningful results. Overall, this research provides a valuable overview of the present status of the IEQ field measurement studies for pinpointing the trends, gaps, and future research needs in this important area of indoor environmental science.

3.7.6.2 "A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices" (Huang et al., 2012)

The current study examined the interaction between the thermal, luminous, and acoustic factors on indoor environmental quality and comfort in offices. The authors conducted a controlled field survey to evaluate the acceptable parameters of each environmental variable and its combined effect on the overall general indoor environmental quality. The concerns about productivity, coupled with an increased sensitivity to the characteristics of office space, have driven this study. While existing benchmarks tend to consider the different environmental parameters singly, this research emphasized their interactions, as indicated in the recommendations of ASHRAE Guideline 10P. The field study measured parameters of thermal, luminous, and acoustic environments. Assessment of satisfaction of participants in relation to the indoor environment by questionnaires was also performed. Development of a quantitative evaluation criterion for office environments where responses from occupants are expected was the aim of this study. In this respect, the study investigated the indoor environmental parameters: the level of comfort concerning the given thermal condition (temperature and humidity), indoor air quality, acoustic, and lighting. In the same vein, it mentioned conditions of poor indoor environmental quality related to health problems, low productivity, and individuals' discomfort. Key findings of the study include:

- Satisfaction of temperature and noise is one of the important influential attributes in general satisfaction because both of them have one-vote veto power over the general satisfaction.

- Chart analysis was performed for classifying indoor environmental quality by investigating interactions among several environmental factors.

- The study emphasized that in establishing an acceptable indoor environment, all environmental parameters should be considered together rather than separately.

The present research may help to develop the understanding of interaction effects among key environmental factors and their impacts on occupant comfort and satisfaction in office environments. The paper offers relevant insights into indoor environmental quality optimization and productivity improvement in office settings through joint effect analyses. The results will imply potential impacts on future design guidelines and standards for indoor environmental quality in office spaces.

3.7.6.3 "Office layout affecting privacy, interaction, and acoustic quality in LEED-certified buildings" (Lee et al., 2010)

This paper addresses how different office configurations in LEED-certified buildings impact employee satisfaction and perceived job performance in respect of the factors of privacy, interaction, and acoustic quality. The five office types tested were: enclosed private, enclosed shared, high-cubicle, low-cubicle, and bullpen (open-plan without partitions) offices; statistically significant differences among those office types exist. Workers at higher cubicles reported lower satisfaction and lesser perception of job performance related to visual privacy and interpersonal relationships with coworkers than workers in enclosed private and shared offices. Workers at high cubicles also reported lower satisfaction with noise condition and auditory privacy, and a lower perception of performance due to acoustic quality than workers in enclosed private, enclosed shared, and bullpen offices. Amazingly enough, bullpen users expressed higher satisfaction with the level of noise and higher perceived performance related to acoustic qualities than both high and low cubicle workers. The bullpen layout also demonstrated a higher level of satisfaction regarding sound privacy compared to high-cubicle plans, revealing that tall panels do not create a safe haven for private conversations. The bullpen layout did not show significant deviations in measurement from enclosed open offices for the criteria of privacy, interaction and acoustic quality, thus it may be a feasible alternative for smaller office settings. This study was motivated by previous studies which showed that the LEED-certified buildings do not necessarily and constantly improve employee satisfaction and productivity over conventional buildings, particularly in terms of office space and acoustic design. Given that offices constitute the predominant category of commercial projects pursuing LEED certification, it is essential for organizations focused on sustainable work environments to comprehend the influence of office layouts on employee experiences. This study adds to the expanding corpus of literature concerning sustainable construction methodologies and their implications for those who inhabit these spaces. It has highlighted that office layout is a critical link in the design process for LEED-certified spaces since this design should support environmental sustainability goals in a way that marries productive and satisfying work experiences. The findings may inform office design decisions for the organizations that want both sustainability and workers' well-being in the built environment.

3.7.6.4 "Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone" (Candido et al, 2010)

This research focuses on identifying air movement acceptability levels inside naturally ventilated buildings in Brazil's hot humid climate zone. The study aims to determine minimal air velocity values corresponding to 80% and 90% air movement acceptability (V80 and V90) in these buildings. The researchers conducted field experiments during hot and cool seasons, collecting 2075 questionnaires from subjects while simultaneously recording microclimatic observations with laboratory precision. The study was motivated by the importance of natural ventilation as a passive strategy for maintaining thermal comfort and reducing cooling loads in hot humid climates. The main findings indicate that the minimal required air velocity was at least 0.4 m/s for operative temperatures of 26°C, increasing to 0.9 m/s for temperatures up to 30°C. Importantly, the results show that subjects not only prefer higher air speeds but also demand air velocities close to or exceeding the 0.8 m/s limit set by ASHRAE Standard 55. These findings challenge the notion of draft in hot humid climates and support the broader theory of alliesthesia, which describes the physiological pleasure associated with increased air movement in warm environments. The study highlights the discrepancy between occupant preferences in naturally ventilated buildings in hot humid climates and the guidelines set for air-conditioned spaces, where 0.2 m/s is considered the threshold for draft perception. The research builds upon previous studies on thermal comfort and air velocity ranges but specifically addresses the question of air movement acceptability. It considers factors such as air velocity, air velocity fluctuations, air temperature, and personal factors like overall thermal sensation, clothing insulation, and physical activity level. By providing evidence for higher acceptable air velocities in hot humid climates, this study contributes to the development of more appropriate design strategies for naturally ventilated buildings in these regions. The results suggest that current standards may be overly restrictive for such climates and that higher air velocities can be both acceptable and desirable for occupant comfort.

3.7.7 Psychological and Subjective Comfort Models (PSCMs)

Understanding the psychological and subjective dimensions of comfort will be important in developing environments that can respond properly to the needs of their occupants. Traditional comfort analyses tend to focus on physical variables that are readily measurable, such as temperature, humidity, and light. However, these in themselves do not capture the complex manner whereby people actually perceive and respond to their environment. Models of psychological and subjective comfort address this by focusing on how occupants perceive, feel about, and are satisfied with their environment.

One key approach in this respect is Post-Occupancy Evaluation (POE), which deals with the feedback of the occupants after they have stayed in the building. Through questionnaires, interviews, and observation, POE researches several dimensions of the occupants' satisfaction, that is, thermal comfort, acoustic performance, lighting conditions, spatial configuration, and aesthetic quality. The valuable information of this nature about the performance of the building from the users' point of view highlights those aspects which require further improvement. With occupants' feedback integrated, the designer or facility manager will be better positioned to make data-informed decisions toward enhancing comfort and functionality for improved user experiences of current and future projects.

Environmental psychology contributes to our understanding of subjective comfort by studying the effect of design elements on occupants' behavior and well-being. The discipline examines the most different interrelations between a person and his physical environment, including color scheme, use of materials, textures, layouts, and natural exposure. Models from environmental psychology show how specific design features can have significant impacts on emotional states, productivity of work, interpersonal interactions, and levels of stress. For instance, access to natural light and outside views have been shown to improve one's concentration and reduce fatigue, while thoughtfully designed communal spaces may spur collaboration and a sense of community.

By incorporating these concepts of environmental psychology into architectural design, architects and engineers are able to construct an environment that meets functional requirements but also promotes psychological comfort and well-being. This integrated approach acknowledges that comfort is a multidimensional experience of physical parameters and affective responses. It encourages the creation of environments attuned to the manifold needs and likings of the individual because cultural background, personal experience, and even personal sensitivity make differences in perceiving comfort.

3.7.7.1 “A Meta-Synthesis Review of Occupant Comfort Assessment in Buildings (2002–2022)“ (Faraji et al., 2023)

This research provides a comprehensive meta-synthesis review of studies on occupant comfort assessment in buildings published between 2002-2022. The review analyzes 154 selected papers from the Web of Science database, examining various aspects of indoor occupant comfort including thermal, visual, acoustic, and indoor air quality (IAQ) satisfaction.

The study categorizes and analyzes the papers based on several factors:

- Types of studies (single-factor vs. multi-factor approaches)
- Geographical locations and climate zones of case studies
- Building types used in case studies (e.g. educational, commercial, residential)
- Decision-making models for occupant comfort assessment
- Assessment indicators and criteria used
- Data collection methods and tools
- Data analysis strategies

The review finds that thermal comfort has received the most research attention, followed by visual comfort, acoustic comfort, and IAQ. Most studies focused on a single aspect of comfort, with fewer examining multiple aspects simultaneously. Educational buildings were the most common case study type. The authors note an increasing trend toward multi-criteria decision-making approaches and the use of machine learning algorithms for data analysis since 2016. However, they identify gaps in research on certain building types and tropical climate zones. Data collection methods included simulations, physical measurements, and questionnaires, with simulation being the most common approach. The review discusses various comfort models and indicators used, such as Predicted Mean Vote (PMV) and adaptive models for thermal comfort. Based on their analysis, the authors provide several recommendations for future research directions. These include studying more diverse building types, examining all four comfort aspects simultaneously, incorporating physiological factors into comfort models, and conducting long-term measurements to validate existing models. The review aims to provide a useful guide for researchers in determining future research directions in the field of indoor occupant comfort assessment. It highlights the growing importance of this area in creating energy-efficient buildings that also prioritize occupant well-being.

3.7.7.2 “Driving factors for occupant-controlled space heating in residential buildings“ (Wei et al., 2014)

This paper provides a review of factors driving the space-heating behavior of occupants in residential buildings, while exploring its representation in building performance simulations. The authors identify and assess several factors as drivers in space-heating behavior through an extensive literature review. The study identified 27 factors that could potentially affect occupants' control of space heating, classifying them into the following categories: environmental, such as outdoor climate; building and systems-related, for example, dwelling type and insulation; occupant-related, including age and income; and other factors, among them time of day and energy awareness. Drawing from the review, the researchers evaluated the existing evidence for each of the listed factors, which indicated some of them, such as outdoor climate and dwelling type, to be established facts, while others still needed further investigation. The paper then surveyed how space-heating behavior is normally modeled within building performance simulations. According to them, most simulations are based on simplified models of heating behavior, assuming constant temperature setpoints or very basic schedules. Indeed, they found that only a subset of the 27 factors identified here were ever included within simulation models. The authors suggest that increasing the number of these influencing factors in simulation models would result in greater accuracy. However, they also acknowledge the trade-offs between model complexity and other pragmatic factors such as time and data availability. For this reason, the authors go on to recommend that future behavioral studies continue examining these factors in greater detail to better quantify their impact on energy use within buildings. The paper follows the usual procedure of an academic study, through a systematic literature review and critical analysis of the existing studies and simulation practices. The influencing factors were categorized in a structured way and evaluated; they were then presented in tables and figures in order to make the information more understandable. This research highlights that occupant space-heating behavior is complex and modeling this behavior in building performance simulations has its limits up to date. This work provides a thorough overview of the current level of knowledge in the subject area, while it also defines the most important directions of future research that will help to enhance our understanding and modeling of occupant behavior in residential buildings.

3.7.7.3 "Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning" (Kima et al., 2018)

The study herein presents the development and validation of personal comfort models that can be used to predict the thermal preference of occupants in office buildings. The researchers developed, in this regard, personal comfort models employing techniques of machine learning to predict the individual occupant's thermal preferences rather than generic one-size-fits-all comfort models. Data were collected from a total of 38 office workers who, over several months, used heated/cooled chairs-personal comfort systems or PCS. The dataset included the interactions of the occupants with the PCS chairs, environmental measurements, surveys from occupants, data on HVAC systems, and weather data. The development of the personal comfort models employed six machine learning algorithms: the Classification Tree, Gaussian Process Classification, Gradient Boosting Method, Kernel Support Vector Machine, Random Forest, and Regularized Logistic Regression. The models were evaluated based on prediction accuracy, prediction variability, and model convergence. The results showed that the personal comfort models achieved a median accuracy of 0.73 in predicting individual thermal preferences, which was a significant improvement over conventional comfort models like PMV and adaptive models (median accuracy of 0.51). Among the tested algorithms, Random Forest performed the best overall. Importantly, the study found that models based solely on occupants' interactions with their PCS chairs (heating/cooling behavior) produced the best prediction accuracy compared to other categories of collected data. This suggests that PCS control behavior could potentially replace survey feedback as a way to understand occupants' thermal preferences. The researchers also determined that about 60 data points (e.g., survey responses) per occupant were typically needed for the models to converge and produce stable predictions. However, the amount of data required varied between individuals. The study was conducted in accordance with thermal comfort standards such as ISO 7730, EN 15251, and ANSI/ASHRAE Standard 55. Overall, this research demonstrates the potential of personal comfort models to improve thermal comfort predictions for individuals in office buildings, which could lead to improved occupant satisfaction and energy efficiency in building operations. The study also highlights the value of using occupants' interactions with personal comfort systems as a key input for understanding and predicting individual thermal preferences.

3.7.7.4 "Occupant satisfaction in LEED and non-LEED certified buildings" (Altomonte and Schiavon, 2013)

This research investigates whether LEED (Leadership in Energy and Environmental Design) certified buildings lead to higher, equal, or lower occupant satisfaction with indoor environmental quality (IEQ) compared to non-LEED rated buildings. The study analyzes occupant satisfaction data from the Center for the Built Environment (CBE) Occupant Indoor Environmental Quality Survey database. The dataset includes 144 buildings, of which 65 are LEED certified, and 21,477 individual occupant responses, with 10,129 from LEED buildings. The researchers compare mean satisfaction scores between LEED and non-LEED buildings for overall building satisfaction, workspace satisfaction, and 15 other IEQ parameters. They use statistical analysis to determine the significance of any differences found. The results show that occupants of LEED certified buildings have equal satisfaction with the building overall and with their workspace compared to occupants of non-LEED rated buildings. For the other 15 IEQ parameters investigated, the difference in mean satisfaction scores between LEED and non-LEED buildings is always less than 6%, with a negligible effect size. The study concludes that LEED certification does not have a significant influence on occupant satisfaction with indoor environmental quality. However, a detailed analysis of mean satisfaction votes reveals that occupants of LEED buildings tend to be slightly more satisfied with air quality and slightly more dissatisfied with the amount of light. This research is important because occupant satisfaction has been positively correlated with self-estimated job performance and potentially overall company productivity. The findings contribute to the ongoing discussion about the effectiveness of green building certification programs in improving the indoor environment for occupants. The study follows standard scientific research methods, using a large dataset and statistical analysis to draw its conclusions. It provides an objective assessment of LEED certification's impact on occupant satisfaction, which can be valuable for building designers, managers, and policymakers in the sustainable building industry.

3.7.7.5 "Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts" (Zhang et al., 2010)

This research develops models for predicting local thermal comfort of individual body parts in non-uniform and transient thermal environments. The paper is Part II of a three-part series that aims to create comprehensive models for predicting both local and whole-body thermal sensation and comfort. The researchers developed a thermal comfort model with coefficients for 19 individual body parts. For each body part, the model predicts local comfort based on local and whole-body thermal sensations. These sensation inputs come from models described in Parts I and III of the series, or from direct measurements. The models were developed using data from literature and from body-part-specific human subject tests conducted in a climate chamber. They were then validated against tests with automobile passengers. The researchers intend for others to be able to test and further develop these models as more empirical data becomes available. A key motivation for this work is that asymmetrical thermal environments may require less energy to produce than uniform ones, while potentially being equally or more comfortable for occupants. However, comfort quantification in non-uniform conditions has been challenging since it depends on comfort at the individual body parts level rather than whole-body comfort. The paper presents a comparison of their approach against earlier ones like Equivalent Homogeneous Temperature (EHT), which has limitations in addressing physiological parameters and the combined effects of body parts under different temperatures. Besides, for a non-uniform or transient environment, the relation between thermal sensation and comfort is far more complex compared to uniform conditions. This study aims to provide a more detailed, flexible approach toward the prediction of thermal comfort and, in turn, enable various environmental designs for buildings and vehicles to attain higher energy efficiency with comfort. The developed models apply to several thermal conditions, including uniform and non-uniform, as well as transient and stable environments.

3.7.8 Conclusion

A critical review of comfort-related frameworks identified the holistic nature of occupant comfort in the built environment. In that respect, optimal comfort would be considered an integrated approach involving thermal, acoustic, visual, indoor air quality, and psychological parameters. While existing traditional models deal with each of these elements in isolation from one another, complex, multi-dimensional interactions between the several environmental factors participating in general occupant satisfaction and well-being can hardly be addressed.

Thermal Comfort Models (TCMs) span from static indices such as Fanger's PMV and PPD to adaptive models, taking as input the dynamic way occupants interact with their thermal environment. Brager and de Dear (2001) and Nicol and Humphreys (2002) provided evidence of the role of psychological adaptation and personal control in naturally ventilated buildings. Their inclusion in recent standards, such as ASHRAE Standard 55 and ISO 7730, reflects the fact that, due to occupants' behavioral adaptations and expectations, occupants are able to accept a wider temperature range.

Acoustic Comfort Models (ACMs) identify sound as a significant parameter on occupant health and productivity. The model by Hongisto (2005), proved that speech intelligibility in open-plan offices decreases cognitive performance. According to Babisch, 2003, with chronic noise exposure, the amount of stress hormones is increased, creating cardiovascular risks. This synthesis of acoustic comfort with other environmental variables, according to Torresin et al. (2018), indicates that acoustic metrics cannot be considered in isolation but interrelate to thermal and visual contexts

Visual Comfort Models (VCMs) focus on both natural and artificial lighting and deal with glare, daylighting, and other circadian issues, as well. New metrics for evaluation such as the DGP developed by Wienold and Christoffersen (2006) offer reliable tools for assessing discomfort glare in rooms lit by daylight. Analyses by Jakubiec and Reinhart (2012) and Bellia et al. (2014) have brought out the need to consider a balance in the use of daylight between utilization and visual comfort, taking into account both visible and non-visible (photobiological) effects of the light on occupants.

Indoor Air Quality Models (IAQMs) are important tools used in assessing and improving environmental conditions that have a direct effect on the occupants' health and comfort. As Fisk and Seppanen (2007) noted, improving indoor environmental quality leads to significant economic benefits due to improved health and increased productivity. Wolkoff's 2012 review on indoor air pollutants highlights the complexity brought about by indoor air quality problems and furthers stresses the need for accurate measurement and mitigation methods grounded in standards such as ASHRAE Standard 62.1 and ISO 16000.

Integrated Comfort Models (ICMs) represent a holistic approach where a number of comfort variables are interrelated. According to Huang et al. (2012) and Kakoulli et al. (2022), research has shown that cumulative effects are needed since both thermal and noise variables have a great combined effect on general satisfaction with the indoor environment. Employment of building performance simulation tools like EnergyPlus and TRNSYS enhances modeling of complicated interactions, enabling designers to project and optimize multiple elements of comfort at the same time.

Psychological and Subjective Comfort Models (PSCMs) focus on occupant perceptions and satisfaction, recognizing that individual preferences and behaviors significantly influence comfort. Faraji et al. (2023) highlight that while thermal comfort has been extensively studied, there is a growing need to consider all aspects of comfort collectively. Kima et al. (2018), demonstrates that personal comfort models using machine learning for predicting individual thermal preference result in better occupant satisfaction. POE and principles of environmental psychology are also useful in understanding design elements affecting occupants' well-being.

Analysis results highlight standards and guidelines as the key drivers of comfort models and construction methodologies. Important standards and guidelines, such as ASHRAE Standards 55 and 62.1 and ISO 7730 and EN 12464-1, provide a critical framework of assessment and design with respect to comfort. Indeed, these standards involve both conventional and adaptive models, which, upon consideration, offer flexibility toward meeting comfort standards in an expansive range of buildings and climatic conditions.

In conclusion, comfort and sustainability in built environments are a result of an integral approach in understanding the dynamic and interacting features of various comfort variables. Future research would do well to continue exploring how these environmental factors interact; develop occupant-specific comfort interventions; and refine modeling approaches to capture occupant diversity and adaptive behaviors. This means that by applying advanced modeling tools and adhering to evolving standards, designers and engineers can maximize a building's systems' interactions on behalf of the occupants to produce a positive effect on well-being and productivity.

4 CONCLUSIONS

The document reviews Vertical Forest buildings and their modeling, focusing on the innovative approach developed within the GREENERGY project for urban building renovation. In this sense, it differs from other projects operating within conventional concepts of zero-energy consumption by pursuing integration of real forest growth into urban buildings. This ambitious initiative encompasses the important challenge of combining structural retrofitting with green infrastructure in existing buildings in order to reach the final objective of a more sustainable urban environment due to high-density urban forestation.

From a technical perspective, the use of advanced 3D finite element modeling with Explicit Dynamics in ANSYS Workbench, with sophisticated material models for concrete, steel, and composites, is proposed for detailed modeling. The holistic approach treats structural integrity and environmental benefits under the same heading with comprehensive modeling for the renovation of urban buildings. Moreover, the project takes advantage of the OpenSees framework, which is a powerful platform for implementation of various modeling approaches. The wide variety of material models for concrete and steel can account for linear, nonlinear, and inelastic behavior. This framework, when combined with the systematic classification system, enables practitioners to balance computational efficiency with accuracy requirements, thus enabling them to choose the most suitable modeling approach in terms of specific project needs, available resources, and desired analysis outcomes. The categorization of RCMs has a broad scope, including material properties, dimensionality, behavior characteristics, and methods of analysis. The systematic approach will eventually provide engineers and researchers with methodology to choose appropriate modeling strategies, ranging from simple one-dimensional elements to complex three-dimensional representations, considering the composite nature of reinforced concrete and the diversity of analysis requirements for a wide range of structural applications.

In particular, given the importance of integration in energy system modeling, especially concerning low-carbon transition modeling techniques, it appears that balancing model development in accounting for the complexity of intricate energy systems in recent times has taken place in conjunction with elements of transparency as well as communication of uncertainty against the backdrop of making policy and investment decisions on urban forestry initiatives. Open data and reproducible analysis increase the credibility and collaborate development of models in energy, but has to continue working with the intrinsic uncertainties of long-term energy projections. Since Vertical Forest buildings represent an innovative concept for sustainable urban development, it is necessary to adapt these models for energy to include the unusual nexus between building systems and integrated vegetation, keeping in mind aspects such as natural shading, evaporative cooling, and seasonal fluctuations of energy demand.

Adding to the complexity are three main parameters of forestry modeling: root system, the trunk, and foliage. Special attention will have to be paid in the modeling of the root system, because this intricate system plays a crucial role in structural stability and the interaction soil-structure. Detailed modeling of soil-root interfaces and their mechanical behaviors at the microscale provides very important insight into the foundation needs of Vertical Forest buildings. Biomechanical modeling of woody plants regarding various loading conditions and growth patterns is covered under trunk modeling. Also, in foliage modeling, seasonal variation, wind loads, and dynamic nature have to be taken into account on the living systems. Therefore, it is a multiscale approach, from micro-level soil-root interaction up to macro levels with regards to structural considerations providing insight into the behavior of integrated forest elements in the built environment.

Comfort modeling then is another important dimension, since all parameters of thermal, acoustic, visual, and air quality are all interrelated within a building with integrated forest elements. The concept has evolved from one based on static indices toward adaptive models reflecting the increasing insight of occupant-environment interaction. TCMs should also consider that this integrated vegetation will be in contact with different microclimates concerning humidity, air movements, and radiant temperature. VCMs have to balance the benefits from natural daylighting with dynamic shading patterns from the foliage, while IAQMs have to incorporate biological processes of living plants and impacts on air quality.

Integration of these comfort parameters through integrated comfort models represents the state-of-the-art development in understanding the holistic impact of Vertical Forest buildings on occupant well-being. Such models have to consider seasonal variations in comfort parameters and dynamic natures of living building elements. The development of PSCMs further enriches such understanding by incorporating the perceptions and behaviors of occupants, especially for the unique environment created by integrated vegetation. These synthesis models, in turn, represent the structural, energy, forestry, and comfort modeling approaches combined as a step toward greater methodology in sustainable urban development. This overall framework enables the practitioner to address the various challenges of incorporating living forest elements in urban buildings while maintaining structural integrity, energy efficiency, and occupant comfort. Incorporation of the framework requires careful considerations of a range of temporal scales, from an instantaneous structural response to the longer-term growth patterns of vegetation.

By integrating nature with built infrastructure, more sustainable urban environments can be achieved. This calls for further refinement in the modeling approaches, validation by post-occupancy studies, and further development of best practices in designing and implementing Vertical Forest buildings. Such an ambitious undertaking will succeed by appropriately fusing multidisciplinary inputs with the proper balancing of technical, environmental, and human factors in the modeling and design processes.

5 REFERENCES

Ai D, Luo H, Wang C, Zhu H. Monitoring of the load-induced RC beam structural tension/compression stress and damage using piezoelectric transducers. Engineering Structures 2018; 154:38–51. DOI: https://doi.org/10.1016/j.engstruct.2017.10.046.

Ai D, Luo H, Zhu H. Numerical and experimental investigation of flexural performance on prestressed concrete structures using electromechanical admittance. Mechanical Systems and Signal Processing 2019; 128: 244–265. DOI: https://doi.org/10.1016/j.ymssp.2019.03.046.

Akyildiz, A. T., Kowalska-Koczwara, A., & Hojdys, Ł. (2021). Seismic Protection of RC Buildings by Polymeric Infill Wall-Frame Interface. Polymers, 13(10), 1577. https://doi.org/10.3390/polym13101577

Aletta, F., & Kang, J. (2018). Towards an Urban Vibrancy Model: A Soundscape Approach. International Journal of Environmental Research and Public Health, 15(8), 1712. https://doi.org/10.3390/ijerph15081712

ALFANO, F. R. d'AMBROSIO, Palella, B. I., & Riccio, G. (2011). Thermal environment assessment reliability using temperature—Humidity indices. Industrial Health, 49(1), 95–106.

Al-Osta, M. (2019). Behavior of RC beam retrofitted using ultra high-performance concrete under impact loads. 10th International Structural Engineering and Construction Conference, ISEC 2019.

Al-Saawani, M. A., Al-Negheimish, A. I., El-Sayed, A. K., & Alhozaimy, A. M. (2022). Finite Element Modeling of Debonding Failures in FRP-Strengthened Concrete Beams Using Cohesive Zone Model. Polymers, 14(9), 1889. https://doi.org/10.3390/polym14091889

Altomonte, S., & Schiavon, S. (2013). Occupant satisfaction in LEED and non-LEED certified buildings. Building and Environment, 68, 66–76. https://doi.org/10.1016/j.buildenv.2013.06.008

Aly, A. M., Fossati, F., Muggiasca, S., Argentini, T., Bitsuamlak, G., Franchi, A., Longarini, N., Crespi, P., & Chowdhury, A. G. (2013). Wind loading on trees integrated with a building envelope. Wind and Structures, 17(1), 69–85. https://doi.org/10.12989/WAS.2013.17.1.069

ANSI. (1997). ANSI S3.5-1997 Methods for Calculation of the Speech Intelligibility Index [Standard]. American National Standards Institute.

ASCE/SEI 41-17. (2017). Seismic Evaluation and Retrofit of Existing Buildings. American Society of Civil Engineers.

ASCE/SEI 7-16. (2016). Minimum Design Loads and Associated Criteria for Buildings and Other Structures. American Society of Civil Engineers.

ASHRAE. (2011). ASHRAE Guideline 10P: Interactions Affecting the Achievement of Acceptable Indoor Environments [Guideline]. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. (2019). ANSI/ASHRAE Standard 62.1-2019: Ventilation for Acceptable Indoor Air Quality [Standard]. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

ASHRAE. (2020). ANSI/ASHRAE Standard 55-2020: Thermal Environmental Conditions for Human Occupancy [Standard]. American Society of Heating, Refrigerating and Air-Conditioning Engineers.

Assad, M., Hawileh, R., & Abdalla, J. (2022). Finite Element Simulation of FRP-Strengthened Thin RC Slabs. Journal of Composites Science, 6(9), 263. https://doi.org/10.3390/jcs6090263

Attard, M. M., & Setunge, S. (1996). Stress-strain relationship of confined and unconfined concrete. Material Journal ACI, 93(5), 432–444.

Babisch, W. (2003). Stress hormones in the research on cardiovascular effects of noise. Noise and Health, 5(18), 1–11.

Bathe, K.-J. (1996). Finite Element Procedures. Prentice Hall.

Bauschinger, J. (1886). On the change of the position of the elastic limit of iron and steel. Mitt. Mech.-Tech. Lab., 13, 1–115.

Bažant, Z. P., & Planas, J. (1997). Fracture and Size Effect in Concrete and Other Quasibrittle Materials. CRC Press.

Beer, F. P., Johnston, E. R., DeWolf, J. T., & Mazurek, D. F. (2014). Mechanics of Materials. McGraw-Hill Education.

Belarbi, H., & Hsu, T. C. C. (1994). Constitutive Laws of Concrete in Tension and Reinforcing Bars Stiffened by Concrete. ACI Structural Journal, 91(4), 465–474.

Bellia, L., Pedace, A., & Barbato, G. (2014). Daylighting offices: A first step toward an analysis of photobiological effects for design practice purposes. Building and Environment, 74, 54–64. https://doi.org/10.1016/j.buildenv.2013.12.021

Bhattacharyya, S. C., & Timilsina, G. R. (2010). A review of energy system models. International Journal of Energy Sector Management, 4(4), 494–518. https://doi.org/10.1108/17506221011092742

Bisby, L., & Ranger, M. (2010). Axial-flexural interaction in circular FRP-confined reinforced concrete columns. Construction and Building Materials, 24(9), 1672–1681.

Bodig, J., & Jayne, B. A. (1982). Mechanics of Wood and Wood Composites. Van Nostrand Reinhold.

Braga, F., Gigliotti, R., & Laterza, M. (2006). Analytical stress-strain relationship for concrete confined by steel stirrups and/or FRP jackets. Journal of Structural Engineering ASCE, 132(9), 1402–1416.

Brager, G. S., & De Dear, R. (2001). Climate, comfort, & natural ventilation: A new adaptive comfort standard for ASHRAE standard 55.

Breyer, D. E., Fridley, K. J., Cobeen, D., & Pollock, K. E. (2014). Design of Wood Structures-ASD/LRFD. McGraw-Hill.

Bruneau, M., Uang, C. M., & Sabelli, S. R. (2011). Ductile Design of Steel Structures (2nd ed.). McGraw-Hill Education.

Bruneau, M., Uang, C.-M., & Whittaker, A. (1997). Ductile Design of Steel Structures. McGraw-Hill Professional.

Butenweg, C., & Marinković, M. (2018). Damage reduction system for masonry infill walls under seismic loading. Ce/Papers, 2(4), 267–273. https://doi.org/10.1002/cepa.863

Calvi, G. M., & Priestley, M. J. N. (2006). Seismic Design and Retrofit of Bridges. John Wiley & Sons.

Cândido, C., De Dear, R. J., Lamberts, R., & Bittencourt, L. (2010). Air movement acceptability limits and thermal comfort in Brazil's hot humid climate zone. Building and Environment, 45(1), 222–229. https://doi.org/10.1016/j.buildenv.2009.06.005

Cao, P., Cao, L., Chen, G., Zhi, Z., Wang, J., Yuan, Z., & Tan, Z. (2024). Numerical modelling of flexural performance of textile reinforced mortar strengthened concrete beams. Materials & Design, 244, 113227. https://doi.org/10.1016/j.matdes.2024.113227

CEB-FIP. (2010). CEB-FIP Model Code 2010. Thomas Telford Services Ltd.

CEN. (2007). EN 15251:2007 Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics [Standard]. European Committee for Standardization.

CEN. (2019). EN 16798-1:2019 Energy performance of buildings—Ventilation for buildings—Part 1: Indoor environmental input parameters for design and assessment of energy performance of buildings addressing indoor air quality, thermal environment, lighting and acoustics [Standard]. European Committee for Standardization.

Chalioris C, Voutetaki M, Liolios A. Structural Health Monitoring of Seismically Vulnerable RC Frames under Lateral Cyclic Loading. Earthquakes and Structures 2020; 19(1): 29–44.

Chalioris CE, Kytinou VK, Voutetaki ME, Karayannis CG. Flexural Damage Diagnosis in Reinforced Concrete Beams Using a Wireless Admittance Monitoring System—Tests and Finite Element Analysis. Sensors 2021; 21(3). DOI: https://doi.org/10.3390/s21030679.

Chang, G. A., & Mander, J. B. (1994). Seismic Energy Based Fatigue Damage Analysis of Bridge Columns: Part I – Evaluation of Seismic Capacity (NCEER Technical Report No. NCEER-94-0006). State University of New York.

Chopra, A. K. (2012). Dynamics of Structures. Prentice Hall.

CIE. (2011). CIE S 017/E:2011 ILV: International Lighting Vocabulary [Standard]. International Commission on Illumination.

Clair, B., Fournier, M., Prevost, M. F., Beauchêne, J., & Bardet, S. (2003). Biomechanics of buttressed trees: Bending strains and stresses. American Journal of Botany, 90(9), 1349–1356.

Clough, R. W., & Penzien, J. (2003). Dynamics of Structures. Computers & Structures, Inc.

Coleman, A. F., Harper, R. W., Eisenman, T. S., Warner, S. H., & Wilkinson, M. A. (2022). Street Tree Structure, Function, and Value: A Review of Scholarly Research (1997–2020). Forests, 13(11), 1779. https://doi.org/10.3390/f13111779

Committee 209, A. C. I. (1992). Prediction of Creep, Shrinkage, and Temperature Effects in Concrete Structures. American Concrete Institute.

Committee 318, A. C. I. (2019). Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary. American Concrete Institute.

Connolly, D., Lund, H., & Mathiesen, B. V. (2016). Smart Energy Europe: The technical and economic impact of one potential 100% renewable energy scenario for the European Union. Renewable and Sustainable Energy Reviews, 60, 1634–1653. https://doi.org/10.1016/j.rser.2016.02.025

Connolly, D., Lund, H., Mathiesen, B. V., & Leahy, M. (2010). A review of computer tools for analysing the integration of renewable energy into various energy systems. Applied Energy, 87(4), 1059–1082. https://doi.org/10.1016/j.apenergy.2009.09.026

Cook, R. D., Malkus, D. S., Plesha, M. E., & Witt, R. J. (2007). Concepts and Applications of Finite Element Analysis. John Wiley & Sons.

Crespi, P., Franchi, A., Longarini, N., Aly, A. M., & others. (2013). An experimental investigation of the wind forces on trees. Changing Needs, Adaptive Buildings, Smart Cities. Proceedings of the 39th International Association for Housing Science (IAHS) World Congress, 319–324.

D'Amato, M. (2009). Analytical models for non linear analysis of RC structures: Confined concrete and bond-slips of longitudinal bars [Doctoral Thesis]. University of Basilicata.

D'Amato, M., Braga, F., Gigliotti, R., Kunnath, S., & Laterza, M. (2012). A numerical general-purpose confinement model for non-linear analysis of R/C members. Computers and Structures Journal, 102–103, 64–75.

D'Ambrisi, A., Feo, L., & Focacci, F. (2013). Experimental and analytical investigation on bond between Carbon-FRCM materials and masonry. Composites Part B: Engineering, 46, 15–20. https://doi.org/10.1016/j.compositesb.2012.10.018

Dagoumas, A. S., & Koltsaklis, N. E. (2019). Review of models for integrating renewable energy in the generation expansion planning. Applied Energy, 242, 1573–1587. https://doi.org/10.1016/j.apenergy.2019.03.194

Dalley S. Ancient Mesopotamian Gardens and the Identification of the Hanging Gardens of Babylon Resolved. Garden History 1993; 21(1): 1. DOI: https://doi.org/10.2307/1587050.

Davidsson, H., Bernardo, R., & Hellström, B. (2013). Hybrid Ventilation with Innovative Heat Recovery—A System Analysis. Buildings, 3(1), 245–257. https://doi.org/10.3390/buildings3010245

De Dear, R., & Brager, G. S. (1998). Developing an adaptive model of thermal comfort and preference.

DeCarolis, J. F., Hunter, K., & Sreepathi, S. (2012). The case for repeatable analysis with energy economy optimization models. Energy Economics, 34(6), 1845–1853. https://doi.org/10.1016/j.eneco.2012.07.004

Desch, H., & Dinwoodie, J. (1996). Timber: Its Structure, Properties and Utilization. Macmillan Press.

Djongyang, N., Tchinda, R., & Njomo, D. (2010). Thermal comfort: A review paper. Renewable and Sustainable Energy Reviews, 14(9), 2626–2640. https://doi.org/10.1016/j.rser.2010.07.040

Dodd, L. L., & Restrepo-Posada, J. I. (1995). Model for Predicting Cyclic Behaviour of Reinforcing Steel. ASCE Journal of Structural Engineering, 121(3), 433–445.

Dounar, S., Iakimovitch, A., Mishchanka, K., Jakubowski, A., & Chybowski, L. (2020). FEA Simulation of the Biomechanical Structure Overload in the University Campus Planting. Applied Bionics and Biomechanics, 2020, 1–13. https://doi.org/10.1155/2020/8845385

Dupuy, L. X., Fourcaud, T., Lac, P., & Stokes, A. (2007). A generic 3D finite element model of tree anchorage integrating soil mechanics and real root system architecture. American Journal of Botany, 94(9), 1506–1514.

Ekonomou, L. (2010). Greek long-term energy consumption prediction using artificial neural networks. Energy, 35(2), 512–517. https://doi.org/10.1016/j.energy.2009.10.018

European Committee for Standardization. (2011). Light and lighting—Lighting of work places—Part 1: Indoor work places (Standard No. EN 12464-1). CEN.

Fanaradelli, T. D., & Rousakis, T. C. (2020). 3D Finite Element Pseudodynamic Analysis of Deficient RC Rectangular Columns Confined with Fiber Reinforced Polymers under Axial Compression. Polymers, 12(11), 2546. https://doi.org/10.3390/polym12112546

Fanger, P. O. (1970). Thermal comfort. Analysis and applications in environmental engineering.

Faraji, A., Rashidi, M., Rezaei, F., & Rahnamayiezekavat, P. (2023). A Meta-Synthesis Review of Occupant Comfort Assessment in Buildings (2002–2022). Sustainability, 15(5), 4303. https://doi.org/10.3390/su15054303

Fardis MN. Design provisions for masonry-infilled RC frames. Proceedings of 12th World Conference on Earthquake Engineering, Auckland, New Zeland: 2000.

Fardis, M. N. (2009). Seismic Design, Assessment and Retrofitting of Concrete Buildings. Springer Science & Business Media.

Filippou, F. C., Popov, E. P., & Bertero, V. V. (1983a). Effects of bond deterioration on hysteretic behavior of reinforced concrete joints. Report EERC, 83(19), 1–229.

Filippou, F. C., Popov, E. P., & Bertero, V. V. (1983b). Effects of Bond Deterioration on Hysteretic Behavior of Reinforced Concrete Joints (Report No. EERC 83-19). Earthquake Engineering Research Center, University of California, Berkeley.

Fisk, W., & Seppanen, O. (2007). Providing better indoor environmental quality brings economic benefits.

Forest Products Laboratory. (2021). Wood Handbook—Wood as an Engineering Material (General Technical Report No. FPL-GTR-282; p. 543). U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. https://www.fpl.fs.fed.us

Forest Products Laboratory. (2024). Forest Inventory and Analysis Database. https://data-usfs.hub.arcgis.com/documents/bc09d4e07dbb4d539a8e46dd3639b5fe/explore

Foster KP. The Hanging Gardens of Nineveh. Iraq 2004; 66: 207. DOI: https://doi.org/10.2307/4200575.

Fragkos, P., Tasios, N., Paroussos, L., Capros, P., & Tsani, S. (2017). Energy system impacts and policy implications of the European Intended Nationally Determined Contribution and low-carbon pathway to 2050. Energy Policy, 100, 216–226. https://doi.org/10.1016/j.enpol.2016.10.023

Galambos, T. V., & Surovek, A. E. (2008). Structural Stability of Steel: Concepts and Applications for Structural Engineers. John Wiley & Sons.

Gallardo-Zafra, R., & Kawashima, K. (2009). Analysis of CFRP RC Bridge Columns under Lateral Cyclic Loading. Journal of Earthquake Engineering, 13, 129–154. https://doi.org/10.1080/13632460802347455

Gams M, Tomaževič M, Berset T. Seismic strengthening of brick masonry by composite coatings: an experimental study. Bulletin of Earthquake Engineering 2017; 15(10): 4269–4298.

GB 50010-2010. (2010). Code for Design of Concrete Structures. China Architecture & Building Press.

Gere, J. M., & Timoshenko, S. P. (1997). Mechanics of Materials. PWS Publishing Company.

Gergely, P., & Lutz, L. A. (1968). Maximum crack width in reinforced concrete flexural members. Ca Cemento e Calcestruzzo, 4, 291–300.

Ghali, A., & Neville, A. M. (1997). Structural Analysis: A Unified Classical and Matrix Approach. Chapman & Hall.

Golias E, Zapris AG, Kytinou VK, Osman M, Koumtzis M, Siapera D, Chalioris CE, Karayannis CG. Application of X-Shaped CFRP Ropes for Structural Upgrading of Reinforced Concrete Beam–Column Joints under Cyclic Loading–Experimental Study. Fibers 2021; 9(7).

Grassi, B., Piana, E. A., Lezzi, A. M., & Pilotelli, M. (2022). A Review of Recent Literature on Systems and Methods for the Control of Thermal Comfort in Buildings. Applied Sciences, 12(11), 5473. https://doi.org/10.3390/app12115473

Greenergy, 2024. Catalog of plant species for VF buildings. Resilient Vertical Forest Renovation of Reinforced Concrete Structures in Seismic Prone Areas (H.F.R.I. Project Number 015376). Deliverable D1.4 Democritus University of Thrace, Xanthi.

Guan, Q., Yang, M., Shi, K., & Zhang, T. (2022). Experimental Study and Finite Element Analysis on the Flexural Behavior of Steel Fiber Reinforced Recycled Aggregate Concrete Beams. Materials, 15(22), 8210. https://doi.org/10.3390/ma15228210

Gulinelli, P., Aprile, A., Rizzoni, R., Grunevald, Y.-H., & Lebon, F. (2020). Multiscale Numerical Analysis of TRM-Reinforced Masonry under Diagonal Compression Tests. Buildings, 10(11), 196. https://doi.org/10.3390/buildings10110196

Gunay, H. B., O'Brien, W., Beausoleil-Morrison, I., & Gilani, S. (2017). Development and implementation of an adaptive lighting and blinds control algorithm. Building and Environment, 113, 185–199. https://doi.org/10.1016/j.buildenv.2016.08.027

Hall, L. M. H., & Buckley, A. R. (2016). A review of energy systems models in the UK: Prevalent usage and categorisation. Applied Energy, 169, 607–628. https://doi.org/10.1016/j.apenergy.2016.02.044

Heard, B. P., Brook, B. W., Wigley, T. M. L., & Bradshaw, C. J. A. (2017). Burden of proof: A comprehensive review of the feasibility of 100% renewable-electricity systems. Renewable and Sustainable Energy Reviews, 76, 1122–1133. https://doi.org/10.1016/j.rser.2017.03.114

Helman D, Yungstein Y, Mulero G, Michael Y. High-Throughput Remote Sensing of Vertical Green Living Walls (VGWs) in Workplaces. Remote Sensing 2022; 14(14): 3485.

Hibbeler, R. C. (2015). Engineering Mechanics: Statics. Pearson Prentice Hall.

Hibbeler, R. C. (2017). Structural Analysis. Pearson Prentice Hall.

Hinton, E., & Owen, D. R. J. (1984). Finite Element Programming. Academic Press.

Hojdys Ł, Krajewski P, Kwiecien A, Rousakis T, Vanian V, Marcin T, Viskovic A, Ilki A, Gams M, Rakicevic Z, Zajac B, Bogdanovic A. Quick Repair of Damaged Infill Walls with Externally Bonded FRPU Composites: Shake Table Tests. Journal of Composites for Construction ASCE, Accepted and Proofread.

Hongisto, V. (2005). A model predicting the effect of speech of varying intelligibility on work performance. Indoor Air, 15(6), 458–468. https://doi.org/10.1111/j.1600-0668.2005.00391.x

Hou S, Zhang H, Han X, Ou J. Damage monitoring of the RC frame shaking table test and comparison with FEM results. Procedia Engineering 2017; 210: 393–400.

Hsieh, W. A., & Mau, S. T. (2005). Schaum's Outline of Structural Analysis. McGraw-Hill.

Hu, X., Tao, W., & Guo, Y. (2008). Using FEM to predict tree motion in a wind field. Journal of Zhejiang University-SCIENCE A, 9(7), 907–915. https://doi.org/10.1631/jzus.A0720035

Huang, L., Zhu, Y., Ouyang, Q., & Cao, B. (2012). A study on the effects of thermal, luminous, and acoustic environments on indoor environmental comfort in offices. Building and Environment, 49, 304–309. https://doi.org/10.1016/j.buildenv.2011.07.022

International Organization for Standardization. (2004). ISO 16000: Indoor air [Standard]. ISO.

ISO. (2005). ISO 7730:2005 Ergonomics of the thermal environment – Analytical determination and interpretation of thermal comfort using calculation of the PMV and PPD indices and local thermal comfort criteria [Standard]. International Organization for Standardization.

ISO. (2014). ISO 12913-1:2014 Acoustics – Soundscape – Part 1: Definition and conceptual framework [Standard]. International Organization for Standardization.

Jackson, T., Shenkin, A., Wellpott, A., Calders, K., Origo, N., Disney, M., Burt, A., Raumonen, P., Gardiner, B., Herold, M., Fourcaud, T., & Malhi, Y. (2019). Finite element analysis of trees in the wind based on terrestrial laser scanning data. Agricultural and Forest Meteorology, 265, 137–144. https://doi.org/10.1016/j.agrformet.2018.11.014

Jakubiec, J., & Reinhart, C. (2012). The 'adaptive zone' – A concept for assessing discomfort glare throughout daylit spaces. Lighting Research & Technology, 44(2), 149–170. https://doi.org/10.1177/1477153511420097

James, K. R., Dahle, G. A., Grabosky, J., Kane, B., & Detter, A. (2014). Tree biomechanics literature review: Dynamics. Arboric. Urban For, 40, 1–15.

James, K. R., Moore, J. R., Slater, D., & Dahle, G. A. (2018). Tree biomechanics. CABI Reviews, 1–11. https://doi.org/10.1079/PAVSNNR201712038

Jian, Z., Bo, L., & Mingyue, W. (2018). Study on windbreak performance of tree canopy by numerical simulation method. The Journal of Computational Multiphase Flows, 10(4), 259–265. https://doi.org/10.1177/1757482X18791901

Jirásek, M., & Bažant, Z. P. (2002). Inelastic Analysis of Structures. John Wiley & Sons.

Kaddoura, M. F. (2022). Simulation and Optimization of Energy Systems. In M. Fathi, E. Zio, & P. M. Pardalos (Eds.), Handbook of Smart Energy Systems (pp. 1–17). Springer International Publishing. https://doi.org/10.1007/978-3-030-72322-4_146-1

Kakoulli, C., Kyriacou, A., & Michaelides, M. P. (2022). A Review of Field Measurement Studies on Thermal Comfort, Indoor Air Quality and Virus Risk. Atmosphere, 13(2), 191. https://doi.org/10.3390/atmos13020191

Kaldellis, J. K., Kapsali, M., Kaldelli, El., & Katsanou, Ev. (2013). Comparing recent views of public attitude on wind energy, photovoltaic and small hydro applications. Renewable Energy, 52, 197–208. https://doi.org/10.1016/j.renene.2012.10.045

Karabinis, A. I., Rousakis, T. C., & Manolitsi, G. E. (2008). 3D Finite-Element Analysis of Substandard RC Columns Strengthened by Fiber-Reinforced Polymer Sheets. Journal of

Composites for Construction, 12(5), 531–540. https://doi.org/10.1061/(ASCE)1090-0268(2008)12:5(531)

Karantzikis M, Papanicolaou CG, Antonopoulos CP, Triantafillou TC. Experimental Investigation of Nonconventional Confinement for Concrete Using FRP. Journal of Composites for Construction 2005; 9(6):480–487. DOI: https://doi.org/10.1061/(ASCE)1090-0268(2005)9:6(480).

Karapetkov, S., Uzunov, H., Dechkova, S., & Uzunov, V. (2023). Impact of Inertial Forces on Car Occupants in a Vehicle-Fixed Barrier Front Crash. Symmetry, 15(11), 1998. https://doi.org/10.3390/sym15111998

Karayannis CG, Voutetaki ME, Chalioris CE, Providakis CP, Angeli GM. Detection of flexural damage stages for RC beams using Piezoelectric sensors (PZT). Smart Structures and Systems, An International Journal 2015; 15(4): 997–1018.

Karlos, K., Tsantilis, A., & Triantafillou, T. (2020). Integrated Seismic and Energy Retrofitting System for Masonry Walls Using Textile-Reinforced Mortars Combined with Thermal Insulation: Experimental, Analytical, and Numerical Study. Journal of Composites Science, 4(4), 189. https://doi.org/10.3390/jcs4040189

Karsan, I. D., & Jirsa, J. O. (1969a). Behavior of concrete under compressive loadings. Journal of the Structural Division, 95(12), 2543–2563.

Karsan, I. D., & Jirsa, J. O. (1969b). Behaviour of concrete under compressive loadings. Journal of Structural Division ASCE, 95(12), 2543–2563. https://doi.org/10.1061/JSDEAG.0002424

Kent, D. C., & Park, R. (1971). Flexural members with confined concrete. Journal of the Structural Division, 97(7), 1969–1990.

Kim, J., Zhou, Y., Schiavon, S., Raftery, P., & Brager, G. (2018). Personal comfort models: Predicting individuals' thermal preference using occupant heating and cooling behavior and machine learning. Building and Environment, 129, 96–106. https://doi.org/10.1016/j.buildenv.2017.12.011

Knaack, A. M. (2013). Sustainable concrete structures using recycled concrete aggregate: Short-term and long-term behavior considering material variability [PhD Dissertation]. University of Notre Dame.

Knaack, A. M. (2023). Manual describing the use of the model and sample files.

Knaack, A. M., & Kurama, Y. C. (2018). Modeling Time-Dependent Deformations: Application for Reinforced Concrete Beams with Recycled Concrete Aggregates. ACI Structural Journal, 115, 175–190. https://doi.org/10.14359/51701153

Kolozvari, K., Orakcal, K., & Wallace, J. W. (2015). Shear-Flexure Interaction Modeling of reinforced Concrete Structural Walls and Columns under Reversed Cyclic Loading (PEER Report No. 2015/12). Pacific Earthquake Engineering Research Center, University of California, Berkeley.

Konstantzos, I., & Tzempelikos, A. (2017). Daylight glare evaluation with the sun in the field of view through window shades. Building and Environment, 113, 65–77. https://doi.org/10.1016/j.buildenv.2016.09.009

Koutas L, Triantafillou TC, Bousias SN. Analytical Modeling of Masonry-Infilled RC Frames Retrofitted with Textile-Reinforced Mortar. Journal of Composites for Construction 2015; 19(5): 04014082.

Kumar, P., & Mosalam, K. M. (2015). Shaking Table Evaluation of Reinforced Concrete Bridge Columns Repaired Using Fiber-Reinforced Polymer Jackets. Journal of Bridge Engineering, ASCE, 20(12), 04015025. https://doi.org/10.1061/(ASCE)BE.1943-5592.0000780

Kwiecień A, de Felice G, Oliveira DV, Zając B, Bellini A, De Santis S, et al. Repair of composite-to masonry bond using flexible matrix. Materials and Structures 2016; 49(7): 2563–2580.

Kwiecień A, Gams M, Rousakis T, Viskovic A, Korelc J. Validation of a New Hyperviscoelastic Model for Deformable Polymers Used for Joints between RC Frames and Masonry Infills. Engineering Transactions 2017; 65(1): 113–121.

Kwiecień A, Zając B. Dynamic response of the cracked masonry building repaired with the flexible joint method – an innovative earthquake protection. In: Brennan MJ, editor. Proceedings of the 7th European Conference on Structural Dynamics, 7-9 July 2008, Southampton: University of Southampton. Institute of Sound & Vibration Research; 2008.

Kwiecień A. Shear bond of composites-to-brick applied with highly deformable, in relation to resin epoxy, interface materials. Materials and Structures 2014; 47(12): 2005–2020.

Kytinou, V. K., Kosmidou, P.-M. K., & Chalioris, C. E. (2022). Numerical Analysis Exterior RC Beam-Column Joints with CFRP Bars as Beam's Tensional Reinforcement under Cyclic Reversal Deformations. Applied Sciences, 12(15), 7419. https://doi.org/10.3390/app12157419

Lam, L., & Teng, J. G. (2003). Design-oriented stress-strain model for FRP-confined concrete. Construction and Building Materials, 17(6), 471–489.

Lam, L., & Teng, J. G. (2009). Stress-strain model for FRP-confined concrete under cyclic axial compression. Engineering Structures, 31(2), 308–321.

Lee, H., Oh, M., Seo, J., & Kim, W. (2021). Seismic and Energy Performance Evaluation of Large-Scale Curtain Walls Subjected to Displacement Control Fasteners. Applied Sciences, 11(15), 6725. https://doi.org/10.3390/app11156725

Lee, Y. S. (2010). Office layout affecting privacy, interaction, and acoustic quality in LEED-certified buildings. Building and Environment, 45(7), 1594–1600. https://doi.org/10.1016/j.buildenv.2010.01.007

Leopold, A. (2016). Energy related system dynamic models: A literature review. Central European Journal of Operations Research, 24(1), 231–261. https://doi.org/10.1007/s10100-015-0417-4

Li, H., Sun, Q., Zhang, Q., & Wallin, F. (2015). A review of the pricing mechanisms for district heating systems. Renewable and Sustainable Energy Reviews, 42, 56–65. https://doi.org/10.1016/j.rser.2014.10.003

Lin, G. (2016). Seismic Performance of FRP-confined RC Columns: Stress-Strain Models and Numerical Simulation [PhD Thesis]. The Hong Kong Polytechnic University.

Lin, G., & Teng, J. G. (2015). Numerical simulation of cyclic/seismic lateral response of square RC columns confined with fibre-reinforced polymer jackets. Proceedings, Second International Conference on Performance-Based and Life-Cycle Structural Engineering (PLSE 2015), 481–489. http://plse2015.org/cms/USB/pdf/full-paper_7408.pdf

Lin, G., Teng, J. G., & Lam, L. (2012). Numerical simulation of FRP-jacketed RC columns under cyclic loading: Modeling of the strain penetration effect. First International Conference on Performance-Based and Life-Cycle Structural Engineering (PLSE2012).

Liu, W., Zhong, W., & Wargocki, P. (2017). Performance, acute health symptoms and physiological responses during exposure to high air temperature and carbon dioxide concentration. Building and Environment, 114, 96–105. https://doi.org/10.1016/j.buildenv.2016.12.020

Logan, D. L. (2012). A First Course in the Finite Element Method. Cengage Learning.

Lund, H., & Mathiesen, B. V. (2009). Energy system analysis of 100% renewable energy systems—The case of Denmark in years 2030 and 2050. Energy, 34(5), 524–531. https://doi.org/10.1016/j.energy.2008.04.003

Luo, Y. (2022). Microstructure-Free Finite Element Modeling for Elasticity Characterization and Design of Fine-Particulate Composites. Journal of Composites Science, 6(2), 35. https://doi.org/10.3390/jcs6020035

MacGregor, J. G., & Wight, J. K. (2012). Reinforced Concrete: Mechanics and Design. Prentice Hall.

MacLeod, I. A. (1997). Design of Structural Masonry. Taylor & Francis.

Maekawa, K., Pimanmas, A., & Okamura, H. (2003). Nonlinear Mechanics of Reinforced Concrete. CRC Press.

Mander, J. B., Priestley, M. J. N., & Park, R. (1988). Theoretical stress-strain model for confined concrete. Journal of Structural Engineering ASCE, 114(8), 1804–1825.

Marugg C. Vertical Forests: The Impact of Green Balconies on the Microclimate by Solar Shading, Evapotranspiration and Wind Flow Change 2018.

Mazzoni, S., McKenna, F., Scott, M. H., & Fenves, G. L. (2006). OpenSees command language manual. Pacific Earthquake Engineering Research (PEER) Center.

McGuire, W., Gallagher, R. H., & Ziemian, R. D. (2015). Matrix Structural Analysis. John Wiley & Sons.

McKenna, F. (2011). OpenSees: A Framework for Earthquake Engineering Simulation. Computing in Science & Engineering, 13(4), 58–66. https://doi.org/10.1109/MCSE.2011.66

McPherson, E. G., Van Doorn, N. S., & Peper, P. J. (n.d.). Urban tree database [Dataset]. Forest Service Research Data Archive. https://doi.org/10.2737/RDS-2016-0005

Megalooikonomou, K. G. (2019). Modeling the behavior of shear-critical reinforced concrete columns under lateral loads [PhD Thesis, University of Cyprus]. https://doi.org/10.12681/eadd/47504

Megalooikonomou, K. G. (2023, June). Inelastic Time-History Analyses of FRP-Retrofitted Bridge Columns Subjected to Near-Field Ground Motions. Proceedings of the 9th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2023). https://doi.org/10.7712/120123.10754.20021

Megalooikonomou, K. G., & Monti, G. (2015). Numerical Modeling of FRP-Retrofitted Circular RC Columns Including Shear. Proceedings of the 5th International Conference on Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2015). https://doi.org/10.7712/120115.3663.400

Megalooikonomou, K. G., & Papavasileiou, G. S. (2019). Analytical stress-strain model for FRP-confined rectangular RC columns. Frontiers in Built Environment, 5, 39. https://doi.org/10.3389/fbuil.2019.00039

Megalooikonomou, K. G., Monti, G., & Santini, S. (2012). Constitutive Model for Fiber-Reinforced Polymer- and Tie-Confined Concrete. ACI Structural Journal, 109(4), 569–578. https://doi.org/10.14359/5168387

Megson, T. H. G. (2014). Structural and Stress Analysis. Butterworth-Heinemann.

Mehta, P. K., & Monteiro, P. J. M. (2014). Concrete: Microstructure, Properties, and Materials. McGraw-Hill Education.

Menegotto, M., & Pinto, P. E. (1973). Method of analysis of cyclically loaded RC plane frames including changes in geometry and non-elastic behavior of elements under normal force and bending. Preliminary Report IABSE, 13.

Mickovski, S. B., Stokes, A., Van Beek, R., Ghestem, M., & Fourcaud, T. (2011). Simulation of direct shear tests on rooted and non-rooted soil using finite element analysis. Ecological Engineering, 37(10), 1523–1532. https://doi.org/10.1016/j.ecoleng.2011.06.001

Mindess, S., Young, J. F., & Darwin, D. (2003). Concrete. Prentice Hall.

Moore, J. R., & Maguire, D. A. (2008). Simulating the dynamic behavior of Douglas-fir trees under applied loads by the finite element method. Tree Physiology, 28(1), 75–83.

Moravčík, Ľ., Vincúr, R., & Rózová, Z. (2021). Analysis of the Static Behavior of a Single Tree on a Finite Element Model. Plants, 10(7), 1284. https://doi.org/10.3390/plants10071284

Mortar, N. A. M., Al Bakri Abdullah, M. M., Hussin, K., Razak, R. A., Hamat, S., Hilmi, A. H., Shahedan, N. N., Li, L. Y., & Aziz, I. H. A. (2022). Finite Element Analysis on Structural Behaviour of Geopolymer Reinforced Concrete Beam using Johnson-Cook Damage in ABAQUS. Archives of Metallurgy and Materials, 1349–1354. https://doi.org/10.24425/amm.2022.141061

Nacht, T., Pratter, R., Ganglbauer, J., Schibline, A., Aguayo, A., Fragkos, P., & Zisarou, E. (2023). Modeling Approaches for Residential Energy Consumption: A Literature Review. Climate, 11(9), 184. https://doi.org/10.3390/cli11090184

Naser, M. Z., Hawileh, R. A., & Abdalla, J. (2021). Modeling Strategies of Finite Element Simulation of Reinforced Concrete Beams Strengthened with FRP: A Review. Journal of Composites Science, 5(1), 19. https://doi.org/10.3390/jcs5010019

Neville, A. M. (1996). Properties of Concrete. Longman.

Nicol, J. F., & Humphreys, M. A. (2002). Adaptive thermal comfort and sustainable thermal standards for buildings. Energy and Buildings, 34(6), 563–572. https://doi.org/10.1016/S0378-7788(02)00006-3

Nilson, A. H., & Darwin, D. (1997). Design of Concrete Structures. McGraw-Hill.

Nilson, A. H., Darwin, D., & Dolan, C. W. (2010). Design of Concrete Structures. McGraw-Hill.

Orakcal, K. (2004). Nonlinear Modeling and Analysis of Slender Reinforced Concrete Walls [PhD Dissertation]. University of California.

Ozden S, Akguzel U, Ozturan T. Seismic strengthening of infilled reinforced concrete frames with composite materials. ACI Structural Journal 2011; 108(4): 414–422.

Padanattil A, Karingamanna J, K.M M. Novel hybrid composites based on glass and sisal fiber for retrofitting of reinforced concrete structures. Construction and Building Materials 2017; 133: 146–153.

Palermo, D., & Vecchio, F. J. (2003). Compression Field Modeling of Reinforced Concrete Subjected to Reversed Loading: Formulation. ACI Structural Journal, 100(5), 616–625.

Park, R., & Paulay, T. (1975). Reinforced Concrete Structures. John Wiley & Sons.

Pfenninger, S., & Keirstead, J. (2015). Renewables, nuclear, or fossil fuels? Scenarios for Great Britain's power system considering costs, emissions and energy security. Applied Energy, 152, 83–93. https://doi.org/10.1016/j.apenergy.2015.04.102

Pfenninger, S., DeCarolis, J., Hirth, L., Quoilin, S., & Staffell, I. (2017). The importance of open data and software: Is energy research lagging behind? Energy Policy, 101, 211–215. https://doi.org/10.1016/j.enpol.2016.11.046

Pfenninger, S., Hawkes, A., & Keirstead, J. (2014). Energy systems modeling for twenty-first century energy challenges. Renewable and Sustainable Energy Reviews, 33, 74–86. https://doi.org/10.1016/j.rser.2014.02.003

Priestley, M. J. N., Calvi, G. M., & Kowalsky, M. J. (2007). Displacement-Based Seismic Design of Structures. IUSS Press.

Providakis C, Tsistrakis S, Voutetaki M, Tsompanakis J, Stavroulaki M, Agadakos J, Kampianakis E, Pentes G, Liarakos E. An Innovative Active Sensing Platform for Wireless Damage Monitoring of Concrete Structures. Current Smart Materials 2016; 1(1): 49–62.

Providakis C, Tsistrakis S, Voutetaki M, Tsompanakis Y, Stavroulaki M, Agadakos J, Kampianakis E, Pentes G. A new damage identification approach based on impedance-type measurements and 2D error statistics. Structural Monitoring and Maintenance 2015; 2(4): 319–338.

Raja, I. A., Nicol, J. F., McCartney, K. J., & Humphreys, M. A. (2001). Thermal comfort: Use of controls in naturally ventilated buildings. Energy and Buildings, 33(3), 235–244. https://doi.org/10.1016/S0378-7788(00)00087-6

Ramberg, W., & Osgood, W. R. (1943). Description of stress-strain curves by three parameters (No. Technical Note No. 902). National Advisory Committee For Aeronautics.

Raumonen, P., Kaasalainen, M., Åkerblom, M., Kaasalainen, S., Kaartinen, H., Vastaranta, M., Holopainen, M., Disney, M., & Lewis, P. (2013). Fast Automatic Precision Tree Models from Terrestrial Laser Scanner Data. Remote Sensing, 5(2), 491–520. https://doi.org/10.3390/rs5020491

Reade J. Alexander the Great and the Hanging Gardens of Babylon. Iraq 2000; 62: 195. DOI: https://doi.org/10.2307/4200490.

Rebelatto, B. G., & Frandoloso, M. A. L. (2020). Energy Modelling: Methods and Applications. In W. Leal Filho, A. M. Azul, L. Brandli, P. G. Özuyar, & T. Wall (Eds.), Affordable and Clean Energy (pp. 1–12). Springer International Publishing. https://doi.org/10.1007/978-3-319-71057-0_62-1

Reddy, J. N. (2006). An Introduction to the Finite Element Method. McGraw-Hill.

Ren, X. D. (2010). Multi-scale based stochastic damage constitutive theory for concrete [PhD Thesis]. Tongji University.

Ringkjøb, H.-K., Haugan, P. M., & Solbrekke, I. M. (2018). A review of modelling tools for energy and electricity systems with large shares of variable renewables. Renewable and Sustainable Energy Reviews, 96, 440–459. https://doi.org/10.1016/j.rser.2018.08.002

Rouka D, Kaloudaki A, Rousakis T, Fanaradelli T, Anagnostou E, Kwiecień A, et al. Response of RC buildings with Low-strength Infill Walls Retrofitted with FRP sheets with Highly Deformable Polymer- Effects of Infill Wall Strength. 25th International Conference on Composites/Nano Engineering, Rome 2017.

Rousakis T, Anagnostou E, Fanaradelli T. Advanced Composite Retrofit of RC Columns and Frames with Prior Damages—Pseudodynamic Finite Element Analyses and Design Approaches. Fibers 2021; 9(9).

Rousakis T, Ilki A, Kwiecien A, Viskovic A, Gams M, Triller P, Ghiassi B, Benedetti A, Rakicevic Z, Colla C, Halici OF, Zając B, Hojdys Ł, Krajewski P, Rizzo F, Vanian V, Sapalidis A, Papadouli E, et al. Deformable Polyurethane Joints and Fibre Grids for Resilient Seismic Performance of Reinforced Concrete Frames with Orthoblock Brick Infills. Polymers 2020; 12(12). DOI: https://doi.org/10.3390/polym12122869.

Rousakis T, Vanian V, Fanaradelli T, Anagnostou E. 3D FEA of Infilled RC Framed Structures Protected by Seismic Joints and FRP Jackets. Applied Sciences 2021; 11(14).

Rousakis TC, Panagiotakis GD, Archontaki EE, Kostopoulos AK. Prismatic RC columns externally confined with FRP sheets and pre-tensioned basalt fiber ropes under cyclic axial load. Composites Part B: Engineering 2019; 163: 96–106. DOI: https://doi.org/10.1016/j.compositesb.2018.11.024.

Rousakis TC, Tourtouras IS. RC columns of square section – Passive and active confinement with composite ropes. Composites Part B: Engineering 2014; 58: 573–581.

Rousakis TC. Reusable and recyclable nonbonded composite tapes and ropes for concrete columns confinement. Composites Part B: Engineering 2016; 103: 15–22.

Rousakis, T. C., Karabinis, A. I., Kiousis, P. D., & Tepfers, R. (2008). Analytical modelling of plastic behaviour of uniformly FRP confined concrete members. Composites Part B: Engineering, 39(7–8), 1104–1113. https://doi.org/10.1016/j.compositesb.2008.05.001

Rousakis, T., Vanian, V., Fanaradelli, T., & Anagnostou, E. (2021). 3D FEA of Infilled RC Framed Structures Protected by Seismic Joints and FRP Jackets. Applied Sciences, 11(14), 6403. https://doi.org/10.3390/app11146403

Saadatmanesh, H., Ehsani, M., & Jin, L. (1997). Seismic retrofitting of rectangular bridge columns with composite straps. Earthquake Spectra, 13(2), 281–304.

Sagi, P. V. (2016). Foundation effects of trees under wind loads [PhD Thesis]. The University of Western Ontario (Canada).

Salmon, C. G., Johnson, J. E., & Malhas, F. A. (2009). Reinforced Concrete Design. John Wiley & Sons.

Sellier, D., Fourcaud, T., & Lac, P. (2006). A finite element model for investigating effects of aerial architecture on tree oscillations. Tree Physiology, 26(6), 799–806.

Sezen, H., & Moehle, J. P. (2004). Shear strength model for lightly reinforced concrete columns. Journal of Structural Engineering, 130(11), 1692–1703.

Sinha, B. P., Gerstle, K. H., & Tulin, L. G. (1964). Stress-strain relations for concrete under cyclic loading. Journal of the American Concrete Institute, 61(2), 195–210.

Standardization, E. C. for. (2004). Eurocode 2: Design of Concrete Structures—Part 1-1: General Rules and Rules for Buildings. CEN.

Standardization, E. C. for. (2005). Eurocode 3: Design of Steel Structures—Part 1-2: General Rules—Structural Fire Design. CEN.

Stanton, J. F., & McNiven, H. D. (1979). The Development of a Mathematical Model to Predict the Flexural Response of Reinforced Concrete Beams to Cyclic Loads, Using System Identification (EERC Report No. 79/02). Earthquake Engineering Research Center.

Subramanian, A. S. R., Gundersen, T., & Adams, T. A. (2018). Modeling and Simulation of Energy Systems: A Review. Processes, 6(12), 238. https://doi.org/10.3390/pr6120238

Suganthi, L., & Samuel, A. A. (2012). Energy models for demand forecasting—A review. Renewable and Sustainable Energy Reviews, 16(2), 1223–1240. https://doi.org/10.1016/j.rser.2011.08.014

Swan, L. G., & Ugursal, V. I. (2009). Modeling of end-use energy consumption in the residential sector: A review of modeling techniques. Renewable and Sustainable Energy Reviews, 13(8), 1819–1835. https://doi.org/10.1016/j.rser.2008.09.033

Talakokula V, Bhalla S, Gupta A. Corrosion assessment of reinforced concrete structures based on equivalent structural parameters using electro-mechanical impedance technique. Journal of Intelligent Material Systems and Structures 2014; 25(4): 484–500. DOI: https://doi.org/10.1177/1045389X13498317.

Talakokula V, Bhalla S. Reinforcement corrosion assessment capability of surface bonded and embedded piezo sensors for reinforced concrete structures. Journal of Intelligent Material Systems and Structures 2015; 26(17): 2304–2313. DOI: https://doi.org/10.1177/1045389X14554133.

Tankut, N., Tankut, A. N., & Zor, M. (2014). Finite Element Analysis of Wood Materials. Drvna Industrija, 65(2), 159–171. https://doi.org/10.5552/drind.2014.1254

Tedeschi C, Kwiecień A, Valluzzi MR, Zając B, Garbin E, Binda L. Effect of thermal ageing and salt decay on bond between FRP and masonry. Materials and Structures 2014; 47(12): 2051–2065.

Teng, J. G., Lam, L., Lin, G., Lu, J. Y., & Xiao, Q. G. (2015). Numerical Simulation of FRP-Jacketed RC Columns Subjected to Cyclic and Seismic Loading. Journal of Composites for Construction, ASCE, 20(1), 04015021.

Thomoglou, A., Rousakis, T., & Karabinis, A. (2018). Numerical modeling of shear behavior of URM strengthened with FRCM or FRP subjected to seismic loading. Proceedings of the 16th European Conference on Earthquake Engineering, Thessaloniki, Greece, 18–20.

Torresin, S., Pernigotto, G., Cappelletti, F., & Gasparella, A. (2018). Combined effects of environmental factors on human perception and objective performance: A review of experimental laboratory works. Indoor Air, 28(4), 525–538. https://doi.org/10.1111/ina.12457

Triantafillou TC, Papanicolaou CG, Zissimopoulos P, Laourdekis T. Concrete confinement with textile- reinforced mortar jackets. ACI Structural Journal 2006; 103(1): 28.

TRNSYS. (2024). TRNSYS: A Transient System Simulation Program. http://www.trnsys.com/

Tsai, W. T. (1988). Uniaxial Compressional Stress-Strain Relation of Concrete. ASCE Journal of Structural Engineering, 114(9), 2133–2136.

Tsantilis, A. V., & Triantafillou, T. C. (2018). Innovative seismic isolation of masonry infills using cellular materials at the interface with the surrounding RC frames. Engineering Structures, 155, 279–297. https://doi.org/10.1016/j.engstruct.2017.11.025

U.S. Department of Energy. (2024). EnergyPlus: Simulation Software. U.S. Department of Energy. https://energyplus.net/

Ugural, A. C., & Fenster, S. K. (2011). Mechanics of Materials. John Wiley & Sons.

Urban, F., Benders, R. M. J., & Moll, H. C. (2007). Modelling energy systems for developing countries. Energy Policy, 35(6), 3473–3482. https://doi.org/10.1016/j.enpol.2006.12.025

Vanian, V., Akyildiz, A. T., Rousakis, T., & Kwiecien, A. (2024). Dynamic Modeling and Analysis of RC Frames Filled with URM Panels Protected with Flexible Connectors. Proceedings of the 18th World Conference on Earthquake Engineering.

Voutetaki ME, Naoum MC, Papadopoulos NA, Chalioris CE. Cracking Diagnosis in Fiber-Reinforced Concrete with Synthetic Fibers Using Piezoelectric Transducers. Fibers 2022; 10(1).

Voutetaki ME, Papadopoulos NA, Angeli GM, Providakis CP. Investigation of a new experimental method for damage assessment of RC beams failing in shear using piezoelectric transducers. Engineering Structures 2016; 114: 226–240. DOI: https://doi.org/10.1016/j.engstruct.2016.02.014.

Wang, C. K., & Salmon, C. G. (1998). Reinforced Concrete Design. John Wiley & Sons.

Wang, C. K., Salmon, C. G., & Pincheira, J. A. (2007). Reinforced Concrete Design. John Wiley & Sons.

Wang, D., Chen, D., Wang, S., Chen, Z., & Zhang, F. (2017). Analysis on vibratory harvesting mechanism for trained fruit tree based on finite element method. Transactions of the Chinese Society of Agricultural Engineering, 33.

Weaver, W., & Gere, J. M. (1990). Matrix Analysis of Framed Structures. Springer Science & Business Media.

Wei, S., Jones, R., & De Wilde, P. (2014). Driving factors for occupant-controlled space heating in residential buildings. Energy and Buildings, 70, 36–44. https://doi.org/10.1016/j.enbuild.2013.11.001

Wienold, J., & Christoffersen, J. (2006). Evaluation methods and development of a new glare prediction model for daylight environments with the use of CCD cameras. Energy and Buildings, 38(7), 743–757. https://doi.org/10.1016/j.enbuild.2006.03.017

Wolkoff, P. (2013). Indoor air pollutants in office environments: Assessment of comfort, health, and performance. International Journal of Hygiene and Environmental Health, 216(4), 371–394. https://doi.org/10.1016/j.ijheh.2012.08.001

Wu, J. Y., Li, J., & Faria, R. (2006). An energy release rate-based plastic-damage model for concrete. International Journal of Solids and Structures, 43(3), 583–612.

Yang, M., Défossez, P., Danjon, F., & Fourcaud, T. (2014). Tree stability under wind: Simulating uprooting with root breakage using a finite element method. Annals of Botany, 114(4), 695–709. https://doi.org/10.1093/aob/mcu122

Yassin, M. H. (1994). Nonlinear analysis of prestressed concrete structures under monotonic and cyclic loads. PhD Dissertation, University of California, Berkeley.

Yassin, M. H. M. (1994). Nonlinear Analysis of Prestressed Concrete Structures under Monotonic and Cyclic Loads [PhD Thesis]. University of California at Berkeley.

Yuksel E, Ilki A, Erol G, Demir C, Karadogan HF. Seismic retrofit of infilled reinforced concrete frames with CFRP composites. In: Wasti ST, Ozcebe G, editors. Advances in Earthquake Engineering for Urban Risk Reduction, Dordrecht: Springer Netherlands; 2006.

Zeng, S. J. (2012). Dynamic Experimental Research and Stochastic Damage Constitutive Model for Concrete [PhD Thesis]. Tongji University.

Zhang, H., Arens, E., Huizenga, C., & Han, T. (2010). Thermal sensation and comfort models for non-uniform and transient environments, part II: Local comfort of individual body parts. Building and Environment, 45(2), 389–398. https://doi.org/10.1016/j.buildenv.2009.06.015

Zhang, H., Cai, C., & Wang, R. (2017). Fatigue life prediction of reinforced concrete beams under cyclic loading. Engineering Structures, 140, 61–72.

Zhang, P. (2024). Large deformation of trees in a strong wind. Applied Mathematical Modelling, 131, 381–402. https://doi.org/10.1016/j.apm.2024.04.007

Zhao, J., & Sritharan, S. (2007). Modeling of strain penetration effects in fiber-based analysis of reinforced concrete structures. ACI Structural Journal, 104(2), 133–141.

Zienkiewicz, O. C., Taylor, R. L., & Zhu, J. (2005). The Finite Element Method: Its Basis and Fundamentals. Butterworth-Heinemann.