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)

Guidelines for the renovation of existing buildings to VFs considering combined structural, energy, forestry and comfort aspects

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LIST OF ACRONYMS

CO_2	Carbon Dioxide
BSO	EU Building Stock Observatory
CoM	European Covenant of Mayors
EEA-38	European Environment Agency network, Eionet
EED	Energy Efficiency Directive
ELSTAT	Hellenic Statistical Authority
EPBD	European Energy Performance of Buildings Directive
ES	Ecosystem Service
HVAC	Heating, Ventilation, and Air Conditioning
IEA	International Energy Agency
LCA	Life Cycle Assessment
LWS	Living Wall System
NBS	Nature Based Solutions
NOK	National Construction Regulation
RED	Renewable Energy Directive
TIR	Thermal Insulation Regulation
UHI	Urban Heat Island
UN	United Nations
VF	Vertical Forests
VG	Vertical Green
RC	Reinforced Concrete
PZT	Piezoelectric sensors or piezoelectric transducers
3D	3 Dimensions
etc	et cetera
e.g.	exempli gratia
SHM	Structural Health Monitoring
EMI	Electromechanical Impedance
DUTH	Democritus University of Thrace
NTUA	National Technical University of Athens
SAs	Smart aggregates
AUTH	Aristotle University of Thessaloniki

ΠΕΡΙΛΗΨΗ

Το πρώτο κεφάλαιο των Οδηγιών παρουσιάζει τα αποτελέσματα μιας διεξοδικής αξιολόγησης της επίδρασης της ενσωμάτωσης των κατασκευών Κάθετου Δάσους (κατακόρυφου πρασίνου, κάθετων ζωντανών τοίχων, γλαστρών με φυτά κλπ) στο μικροκλίμα και την ενεργειακή απόδοση των κτιρίων. Σχεδιάζονται και αποτιμώνται διαφορετικά πραγματικά σενάρια, βασισμένα σε πραγματικές συγκεκριμένες συνθήκες αστικής περιοχής της Θεσσαλονίκης με κίνδυνο φαινομένων αστικής θερμικής νησίδας. Παράλληλα, οι Οδηγίες του έργου Greenenergy προσφέρουν ένα ολοκληρωμένο πλαίσιο για τη μετατροπή νέων και υφιστάμενων κτηρίων σε κατακόρυφα πράσινες κατασκευές, συνδυάζοντας γνώσεις από τη δομική μηχανική, την αρχιτεκτονική και την διαχείριση αστικού πρασίνου. Λαμβάνονται υπόψην πτυχές δομοστατικές, ενεργειακές, δασοκομικές και θερμικής άνεσης. Στόχος είναι τα κτήρια να διατηρούν τη δομική τους ακεραιότητα και την αισθητική τους αρμονία, να αποκτούν μεγαλύτερη οικολογική αξία και, παράλληλα, να συμβάλλουν σε μια καλύτερη περιβαλλοντική ποιότητα και ανθεκτικότερες πόλεις μέσω της ενσωμάτωσης της βλάστησης.

Οι Οδηγίες παρουσιάζουν το πλαίσιο αποτίμησης και ενίσχυσης υφιστάμενων κτηρίων ώστε να ενσωματώσουν κατακόρυφα δάση, κατά την ανακαίνισή τους. Συνδυάζονται βασικά ζητήματα, όπως οι μέθοδοι κατασκευής, τα υλικά και η επιλογή φυτών, και προσφέρονται πρακτικές κατευθυντήριες για τον σχεδιασμό, την αναβάθμιση, τον προγραμματισμό, την εφαρμογή και την παρακολούθηση των συστημάτων. Οι οδηγίες συνδέουν αυτές τις πτυχές σχεδιασμού με στόχο να υποστηρίξουν τους επαγγελματίες στον σχεδιασμό και την κατασκευή κτηρίων που πληρούν τα τεχνικά και αρχιτεκτονικά πρότυπα, περιλαμβάνοντας και την βλάστηση.

Επιπρόσθετα, οι Οδηγίες αναδεικνύουν τα οικολογικά, λειτουργικά και αισθητικά οφέλη της ενσωμάτωσης της βλάστησης στα κτίρια, συμβάλλοντας στη δημιουργία πιο υγιεινών και ευχάριστων χώρων διαβίωσης και εργασίας. Επιπλέον, περιλαμβάνονται κατευθύνσεις για τη διαχείριση κινδύνου καταστροφών και την ευαισθητοποίηση της κοινωνίας, με ενεργό συμμετοχή όλων των εμπλεκόμενων φορέων.

SUMMARY

The first chapter of this deliverable presents the results of a thorough assessment regarding the influence of VGS integration on the microclimate and buildings' energy efficiency. Different real case scenarios are designed, based on the specific conditions of urban district in Thessaloniki, related to thermal island effects. In addition, the Greenergy Guidelines provide a comprehensive framework for transforming new or existing buildings into vertical forest structures. They combine knowledge from structural engineering, architecture, and urban forestry to ensure that buildings maintain structural integrity, energy efficiency, human comfort, aesthetic harmony, and ecological value. By linking these disciplines, the guidelines aim to help professionals design and construct buildings that meet technical and architectural standards while improving environmental quality and urban resilience through the integration of vegetation.

The Greenergy Guidelines provide a comprehensive framework for the renovation of existing buildings into structures incorporating vertical forest. They highlight the ecological, functional, and aesthetic advantages of incorporating greenery into buildings, promoting healthier living and working environments. It covers a range of systems, from simple green solutions to complex vertical forest designs, addressing key aspects such as construction methods, materials, and plant selection. The guidelines outline essential principles for the design, retrofitting, planning, implementation, and monitoring of vertical forest systems, offering practical direction based on current knowledge and best practices. The main focus is on structural, forestry, energy and comfort engineering, supported by complementary design and construction guidance, and is intended for professionals working across related fields. It introduces disaster risk management and society awareness, involving all involved stakeholders.

1 ASSESSMENT OF THE VGS INFLUENCE ON URBAN MICROCLIMATES AND BUILDINGS' COOLING DEMANDS BY THEODORIDOU I., MALLINIS G., VATITSI K.

1.1 GENERAL FRAMEWORK FOR THE INFLUENCE OF GREEN WALLS ON URBAN AREAS

Various studies have investigated the effect of green walls on microclimatic conditions. The results suggest a moderate effect, with the cooling of air temperature having a small and local effect just in front of the green surfaces. On the other hand, green walls, due to their strong insulating properties, significantly reduce the surface temperature of the walls of the buildings they cover, and subsequently the internal temperature of the buildings.

In detail, Thomas et al. (1) argued that the introduction of green walls, in a humid-tropical climate, shows a reduction in the ambient air temperature (on average) by 1.3–1.6 °C during the winter season and 0.4–0.5 °C during the summer season, with the maximum cooling effect reaching -1.9 °C and -0.8 °C respectively.

The benefits are more pronounced at denser plantings, but the absolute value remains low. In particular, a simulation in an urban canyon that was fully planted on both sides showed a reduction in external air temperature by 1.2 °C with the benefits being local, close to the green facades (2).

The benefits are much greater on building surfaces. Maintaining external building surface temperature 8.5 °C less, under sunny conditions. Regarding the effect of different planting systems on the microclimate, the differences are small. Liu et al. (2) in a comparative study of various green wall systems argued that different systems do not significantly change the external air temperature, with the type of substrate having a smaller influence and with the parameters related to the planting -foliage density (Leaf Area Density/Index) and the optical properties of the leaves- being more critical. The study by Li et al. (3) compared three green wall systems and concluded that all systems had a small effect on the air temperature with the greatest cooling caused by the living wall system with the densest foliage with the reduction reaching – 0.25 °C.

Ramadhan and Mahmoud et al. (4), on the basis of green wall impact on the energy performance of buildings, concluded that the energy saving was up to 75%. This is a result of increased insulation, shading and cooling from evapotranspiration of vegetation layer.

Against this background, this chapter aims at evaluating the effect of Vertical Forests-VGS on urban built environments in typical Mediterranean cities. The assessment follows a dual path, namely the evaluation of the effect of green walls on the urban microclimate and on the buildings energy performance. This advanced approach satisfies simultaneously energy, forestry and human comfort standards, while it contributes to the identification and quantification of the relevant benefits, based on real case scenarios for buildings and urban regions-districts.

1.2 PROPOSED METHODOLOGY

In order to holistically assess the VGS implementation benefits, a series of methodological steps have been adopted.

Firstly, a typical urban environment was chosen in the city of Thessaloniki, the second largest city in northern Greece. Specific selection criteria were applied, analyzed in the following chapter.

Secondly, the available vertical building areas were calculated and located so as to integrate the VGS. The criteria for this were based upon previous Deliverables, statistical and building related aspects, explain in the following chapters.

Thirdly, the effect of the VGS on the microclimatic area was assessed using the ENVI-met software.

Finally, the energy consumption of the buildings is assessed with the EnergyPlus software in order to explore possible cooling load reductions after the integration of VGS.

The flow diagram below depicts the steps of the assessment approach.

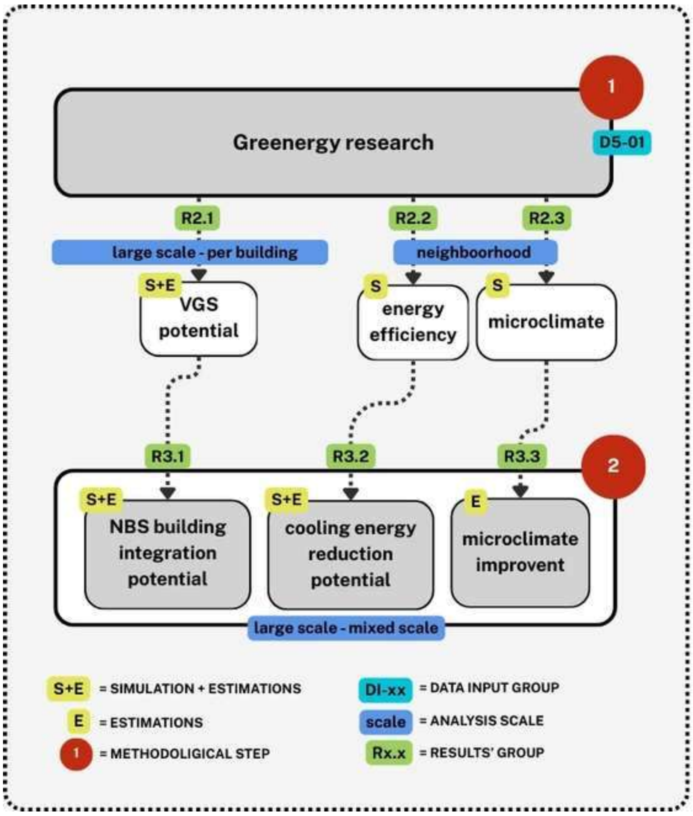


Figure 1.2-1 Flow diagram of the research procedure

1.2.1 Case study area and available surfaces

1.2.1.1 Method for the selection of the case study area

For the selection of the case study area, a specific approach was applied. Since existing CFD tools don't offer the ability to simulate the microclimatic conditions in greater urban areas and whole cities, an LST analysis was performed to identify neighborhoods with high Land Surface Temperature (LST). More specifically, the identification and analysis of urban thermal islands in Thessaloniki were conducted using satellite-based remote sensing data and cloud-based geospatial processing techniques. The analysis relied on Landsat-8 OLI/TIRS imagery, exploiting both optical and thermal information to derive Land Surface Temperature (LST) as the primary indicator of surface heat patterns

Landsat-8 data were accessed through the Google Earth Engine (GEE) platform, enabling efficient handling of large image collections and reproducible processing workflows. Two standardized products were used:

- LANDSAT/LC08/C02/T1_L2, providing atmospherically corrected surface reflectance and surface temperature data, and
- LANDSAT/LC08/C02/T1_TOA, providing top-of-atmosphere reflectance and thermal brightness temperature data.

The study focused on the summer period (July–August 2024), when urban heat island effects are most pronounced.

Pre-processing steps included temporal filtering, spatial subsetting to the Thessaloniki urban area, and systematic cloud and cloud-shadow masking using the QA_PIXEL quality band. This ensured that only reliable, cloud-free observations were retained for analysis.

Land Surface Temperature was derived through a physically based approach. First, the Normalized Difference Vegetation Index (NDVI) was calculated from surface reflectance bands, followed by estimation of Fractional Vegetation Cover (FVC).

$$FVC = \left(\frac{NDVI - NDVI_{bare}}{NDVI_{veg} - NDVI_{bare}}\right)^2 \quad (1)$$

where NDVI_veg and NDVI_bare are the NDVI values of vegetation and bare soil pixels, for which the critical threshold values of 0.86 and 0.2 were defined, respectively (Ermida et al., 2020).

FVC was then used to compute Land Surface Emissivity (ε), accounting for variations in surface materials and vegetation cover (Sobrino et al., 2004).

$$\varepsilon = 0.004FVC + 0.986 \quad (2)$$

Finally, LST was retrieved from thermal infrared data by correcting brightness temperature values for surface emissivity effects and converting results from Kelvin to degrees Celsius

$$LST = \frac{BT}{\left\{1 + \left[\frac{W \times BT}{\rho} \times \ln(\varepsilon_i)\right]\right\}} \quad (3)$$

where

BT is the brightness temperature (K),

W is the wavelength of the emitted radiation,

ε_i is the land surface emissivity, and

ρ is the constant 1.438×10^{-2} m·K

To reduce the influence of residual noise and short-term variability, median composite LST images were generated for the full study period. These composites provided stable representations of spatial temperature patterns across the city, allowing the identification of persistently warmer zones corresponding to urban thermal islands.

Figure 1.2-2 Spatial distribution of Land Surface Temperature (LST) over the pilot study area in Toumpa, Thessaloniki, overlaid with building footprints. Warmer surface temperatures are indicated by red tones, while cooler areas are shown in green to blue shades. The building outlines provide urban context, highlighting the relationship between built-up density and elevated LST values.

1.2.1.2 Description of the case study *area*

Based on these data, a neighbourhood in the area of Toumba within the Municipality of Thessaloniki was chosen. The selected area comprises typical MF-buildings mostly constructed before 1980 and the first Thermal Insulation Regulation. The area is considered as densely built with narrow streets and multistorey buildings (with minimum 4 storeys). By means of the existing vegetation is dispersed, with scattered acacia and citrus aurantium trees.

The study area is located in the city of Thessaloniki, Greece and more specifically in the wider district of Upper Toumba, above the Toumba Stadium (40.62, 22.98) (Figure 1.2-3 and Figure 1.2-4). Its dimensions are 150x120m (33.750m^2). and is surrounded by street axes Tirolois, Praxagora, Efesou, Mikras Asias streets. The district consists of 161 buildings with a relatively compact mid-rise morphology with a predominantly residential character. Most blocks are apartment buildings, where the ground floors function mainly as entrance lobbies and pilotis with parking spaces for the residents, while local commercial uses and public assembly functions (e.g. small shops, cafés, gathering spaces) occur partially.

The average number of floors (including the ground floor) ranges between 5 to 6 storeys. Total building height varies between roughly 4.6 m and 25.2 m, with an average height of approximately 16.2 m, suggesting medium-height blocks. Individual roof areas range from 36 m² for the smallest structures up to 1086 m² for the largest, with the average surface area of around 147 m². Overall, the building stock corresponds to a total build surface area of approximately 23,700 m², providing a large envelope area for assessing the impact of facade greening and other mitigation measures on the local microclimate (Table 1.2-1).

In terms of age, the building stock is relatively old. 50% of the buildings were constructed before 1980, 11.49% in 1981–1990, 21.84% in 1991–2000, and only 16.67% after 2001, indicating a mixture of older and more recent construction (Table 1.2-2).

Table 1.2-1 Study area main characteristics

Parameters	Study Area
Location	Upper Toumba, Thessaloniki, Greece (40.62 °N, 22.98 °E)
Existing vegetation	Trees across all street axes
Surrounded streets	Tirolois, Praxagora, Efesou, Mikras Asias
Area rotation from north (0°)	25° (counterclockwise)
Total area [m^2]	33.750 (225x150m.)
Total built surface area [m^2]	23,700
Non built area [m^2]	10,050
Building coverage ratio	70%
Total building floor area [m^2]	124,700 (12.5 ha)
Building blocks	13
Building units	161

Table 1.2-2 Buildings stock's construction time period

Construction time period	Construction time period of buildings [%]
before 1980	50.00
1981 - 1990	11.49
1991 - 2000	21.84
2001 +	16.67
Total	100.00

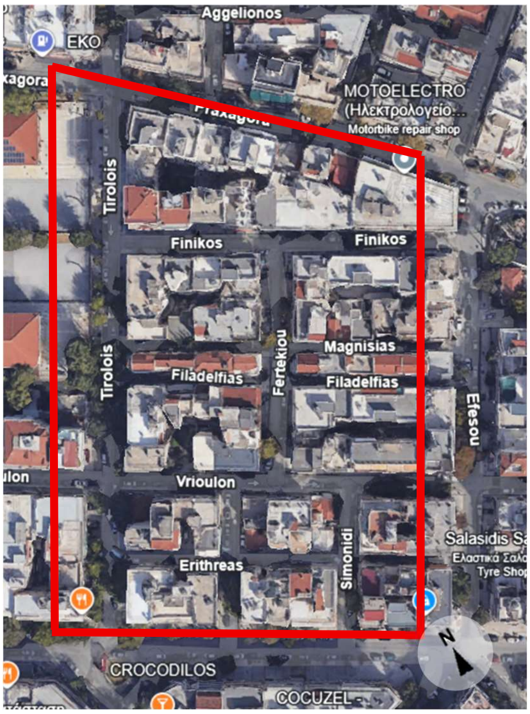


Figure 1.2-3 Study area plan

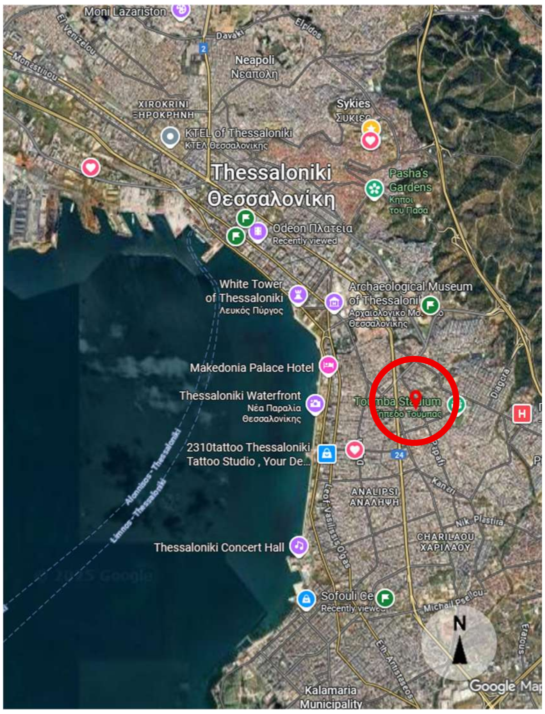


Figure 1.2-4 Location of study area in the greater area of Thessaloniki

1.3 MICROCLIMATIC MODEL

To assess the microclimatic conditions of the study area in the baseline state and after the integration of green walls, ENVI-met V5 tool was used. ENVI-met is a three-dimensional, non-hydrostatic, prognostic model that simulates surface-plant-air interactions based on fundamental laws of fluid dynamics and thermodynamics with a typical resolution of 0.5 m in space and 1-5 sec. Most recent advancements include the introduction of simple and full forcing (v4) that allows dynamic changes in atmospheric boundary conditions. Additionally, the Lindenmayer-System tree (v5) that describes a more realistic position and arrangement of leaf clusters and a hierarchical tree branching system and the vegetated wall and roof systems (v5) (5) (6).

Green walls, in particular, are simulated through the Green Wall System (GWS) as an additional planted layer that lays upon the top of the dynamic wall model and is simultaneously connected to the vegetation model and the soil/substrate model. GWS solves the energy balance of the leaves (radiation, sensible and latent flux) and the substrate at each time step, calculating shading, evapotranspiration and heat conduction to the wall, while the vegetation is defined by LAI, foliage thickness (ΔC) and angular leaf distribution (7).

For living wall systems, the three substrate layers (moisture/conductivity properties) and a watering coefficient ζw are additionally declared, which keeps the water content constant, so that there is realistic evapotranspiration. GWS modifies the radiation fields and heat/water vapor fluxes in the adjacent air cells, returning updated shortwave/longwave fluxes and a source/sink temperature term to the main 3D solver of ENVI-met. In this way, the model can clearly differentiate (a) the temperature and energy flux inside the wall and (b) the local microclimatic effect of the facade (air cooling, PET change), for different types of green walls (climbing vs. living walls with substrate and/or airgap). ENVI-met simulates the green wall through a layer on the surface of the building wall, taking into account critical physical processes such as evapotranspiration, thermal mass and shading. To create a green wall system, a series of basic parameters are defined; The leaf area index (LAI) and the thickness of the plant layer. Also, the substrate and its properties, thickness and composition, degree of irrigation, among others.

1.3.1 Model data input and setup

For setting up the area in the three-dimensional space of ENVI-met, the basic morphological parameters were defined including building heights, environmental materials, their thermophysical characteristics, area dimensions, cell sizes, etc. (Figure 1.3-1 and Figure *1.3-2*). For the x and y axis a resolution of 1.5x1.5m. was selected, and the model was created on the basis of 100x150 grids. On the z axis, the number of cells was set to 20 with a 3m. resolution. Six nesting grids were assigned to the model that surround the main area to reduce the boundary effects and assure the model's stability. The assigned material of nesting grids is asphalt road, as a most representative material found in the main area. The simulation configuration inputs are included in

Table 1.3-1-1. The physical properties of the materials and ground surfaces and the assigned construction and soil profiles are presented in Table 1.3-21.3-2. The materials' values reflect the construction period of the buildings, mostly dated before 1980.

The geometry and foliage characteristics of the modeled plants are designed in ENVI-met's "Albero" tool. For this study, Citrus Aurantium (bitter orange) evergreen tree species was selected as the main tree type for both study areas. LAD value was defined as 2 m^2/m^3 to correspond to the tree's dense crown. The tree height is 4.5 m. and the crown diameter 3 m (Table 1.3-3). These values correspond to mature trees based on field study and relevant measurements that are reported in the existing literature (8).

The simulation was performed for a critical summer day (24h, start time 00:00), with an hourly timestep (60min). The climate data was obtained from the nearest meteorological station, GRC - IWEC 166220 WMO. In ENVI-met, simple forcing was selected and hourly values for air temperature and relative humidity were incorporated. The average wind speed and direction were set to 2.21 m/s and

0°, respectively. Model initialization parameters are included in Table 1.3-4. Finally, the climatic data reflects an extremely hot day during the historical period 1984-1990. The climatic data used for the simulations are included in

Table 1.3-5. Average wind speed will be 2.24 m/s.

Figure 1.3-1 ENVI-met model setup (plan view)

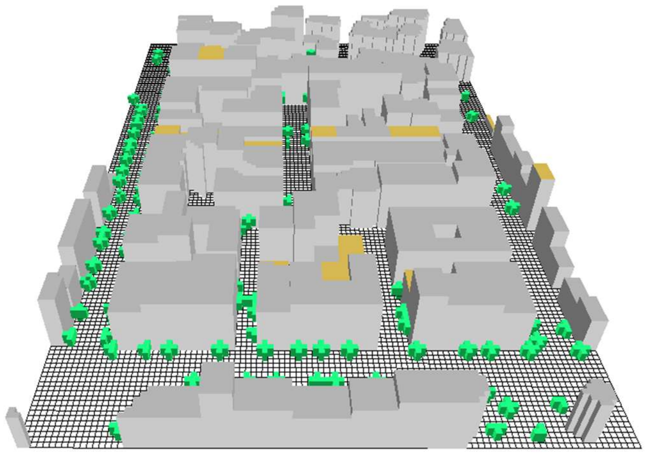


Figure 1.3-2 ENVI-met model setup (3D view)

Table 1.3-1 ENVI-met Model Specifications

Model Specifications/Parameters	Study Area
Simulation Model Size (m)	150x225x60
Model Area (Number of Grids) xyz-Grids	100x150x20
Size of grid cell (m) dx, y, z	1.5x1.5x3
Geographic Location	40.612830, 22.974371
Nesting grids	6
Reference time zone	GMT+2
Model rotation out of grid north	25°

Table 1.3-2 Thermal and optical properties of the building envelope and ground surface materials, wall/roof constructions and soil profiles

Wall/Roof Materials						
Name	Default Brick: burned	Default Plaster	Default Reinforced concrete	Cement Mortar	Concrete tiles	Roofing: tile
Default thickness (m)	0.19	0.01	0.20	0.02	0.035	0.03
Thermal conductivity (W/m*K)	0.51	0.87	2.5	1.4	1.5	1
Reflection (Frac.)	-	0.4	-	0.3	0.3	0.3
Soils/Ground Materials						

Name	Asphalt (with Basalt)	Cement Concrete: tiles	Loam
Thermal conductivity (W/m*K)	0.7	1.5	1.45
Reflection (Frac.)	0.12	0.3	0.2
Wall/Roof Constructions			
Database-ID	0101B2	0101RF	0101R1
Name	Brick wall (burned)	Roofing: Concrete	Roofing: Tile
Layers (outside to inside)	0101PL-0101BR-0101PL	0101CT-0101CM-0101FC	0101R1-0101CM-0101FC
Layers thickness (m)	0.02-0.19-0.01	0.035-0.02-0.15	0.03-0.02-0.15
Soil Profiles			
Database-ID	0101ST	0101PG	0101LO
Name	Asphalt road	Concrete pavement gray	Loamy Soil
Upper layer	0101AB	0101ZB	0100LE
Albedo	0.12	0.3	0.2

Table 1.3-3 Parameters of reference tree

Tree parameters	Values
Name	Citrus aurantium – Bitter orange
Symbol	TZ
Type	Evergreen
Tree height (m)*	4.5
Crown diameter (m)*	3*
LAD value (m2/m3)	2

Table 1.3-4 Model initialization parameters and meteorological input boundary conditions

Parameters	Values
Simulation duration	24h
Start time	00:00
Timestep (min)	60
Mean wind speed at 10m above ground	2.24
Prevailing wind direction	N (0°)
Roughness length of the site	0.1*
Air temperature forcing	Hottest Summer Day (SKG epw)
Relative humidity forcing	Hottest Summer Day (SKG epw)
Cloud coverage	0, No clouds
Specific humidity at 2500m	8g/kg*
Adjustment factor for solar radiation	1
Soil upper layers initial temperature	20 °C*
Soil upper layers moisture content	65% - 75%*

**ENVI-met default values*

Table 1.3-5 Climatic Data for ENVI-met simulation, Extreme Hot Day

Hour	Air Temperature – Tair (°C)	Relative Humidity – RH (%)
1	24.1	59
2	23.4	55
3	24.1	52
4	24.7	48
5	25.4	45
6	25.3	53
7	25.1	61
8	25	68
9	26.1	65
10	27.3	61
11	28.4	57
12	29.6	53
13	30.8	49
14	32	46
15	32.9	38
16	33.7	30
17	34.6	23
18	33.4	25
19	32.2	27
20	31	29
21	29.3	33
22	27.7	37
23	26	42
24	25.8	44

1.3.2 Green Wall Scenarios

After the basic geometric and material design of the study area was completed in ENVI-met, the vertical planting scenarios were developed. At the master-plan level, the entire area was examined and the surfaces on which the vertical planting systems would be installed were selected. The surfaces primarily include the blind walls of the buildings and the walls that enclose the vertical circulations of the buildings (stairwells and elevators).

Three alternative planting scenarios were developed. In Scenario A, a soil-based Living Wall with soil substrate and evergreen climbing plants was installed on selected surfaces, reflecting a realistic state of green wall integration in an urban environment. In Scenario B, the same greening pattern as Scenario A was followed, with a different greening system to evaluate the effect of different green wall systems. In detail, a hydroponic system was applied, consisting of closed-cell panels where plants grow in a foam substrate supported by continuous nutrient and water supply. Finally, a third scenario was introduced to test the effect of high greening coverage at district scale. In Scenario C, the same Living Wall system configuration as in Scenario A was adopted, but it was deployed on a substantially larger portion of the urban fabric: all facades facing the interior of the building blocks (internal courtyards) and all main facades of buildings facing the principal road axes of the area, namely Finikos, Vrioulon, Mikras Asias, Torolois, Fertekiou and Efesou. The aim is to study (a) the comparison between two alternative green wall technologies under moderate application and (b) the impact of increased green wall application.

1.3.2.1 Scenario A – Living Wall

The first scenario considers the installation of a planted wall system with an 8cm thick soil mixture substrate. The panel consists of a lightweight metal frame, geotextile pockets filled with organic soil and planting of Hedera helix (evergreen ivy), a species adapted to the Mediterranean climate with a high leaf area index (LAD=2m²/m³). Irrigation factor is set to 0.50, suggesting two daily applications (06:00&18:00), which maintain adequate substrate moisture (Table 1.3-61.3-6, Figure 1.3-3, Figure 1.3-4).

Table 1.3-6 Scenario A – Living Wall System's Parameters

Parameters	Value
Plant	Ivy (Hedera helix) 0.3m
LAI [m2/m2]	2
Leaf Area Distribution [0-1]	0.50
Root depth	0.08m. (in substrate)
Substrate	0.08 m sandy loam + 0.5m styrofoam
Emissivity	0.95
Albedo	0.30
Water coefficient of substrate for plant	0.50
Air gap between substrate and wall	0.20

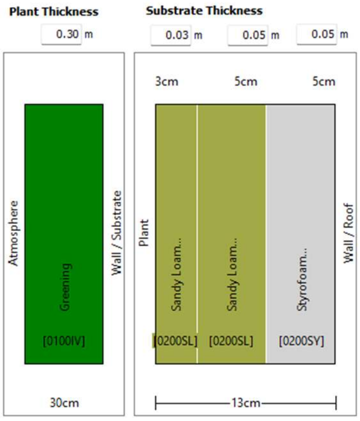


Figure 1.3-3 Living wall system layers – ENVI_met

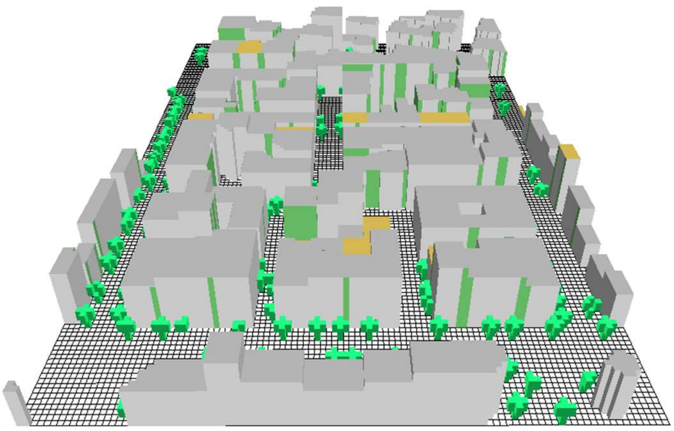


Figure 1.3-4 Study Area – Scenario A

1.3.2.2 Scenario B – Hydroponic Green Wall

Scenario B refers to a hydroponic living wall system. The design includes an upper vegetation layer of fern, with a leaf area distribution of 0.8 and LAD of 3. The substrate constitutes of 8cm of Peat material, as the closest default material for a hydroponic growth mat (e.g., rockwool/coir) because of its very high water-holding capacity and porosity. The water coefficient was set to 1.00, reflecting the constant supply of nutrients that a hydroponic system requires. For a second layer, Styrofoam (EPS), 5cm, was selected as a closed-cell insulation board placed directly behind the wet substrate. Finally, an airgap of 20 cm was left between the green wall system and the building's surface to aid ventilation and limit risk of moisture at the wall. Styrofoam layer and air gap, match scenario A's system for comparability across simulations (Table 1.3-7, Figure 1.3-5, Figure 1.3-6). For the simulation, the base wall construction is kept identical to Scenario A to isolate the effect of the hydroponic wall. All comparisons therefore reflect only the added greening assembly and its moisture/thermal behavior.

Table 1.3-7 Scenario B – Hydroponic Foam Wall System's Parameters

Parameters	Value
Plant	Fern (Nephrolepis)
LAI [m2/m2]	3
Leaf Area Distribution [0-1]	0.80
Root depth	0.03m.
Substrate	0.08m. peat
Emissivity	0.95
Albedo	0.30
Water coefficient of substrate for plant	1 (constant supply of nutrients for vegetation layer)
Air gap between substrate and wall	0.20

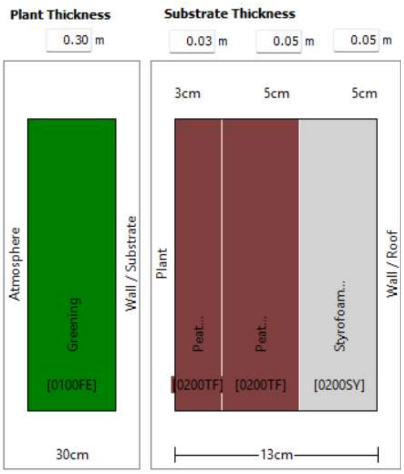


Figure 1.3-5 Hydroponic foam wall system layers – ENVI-met

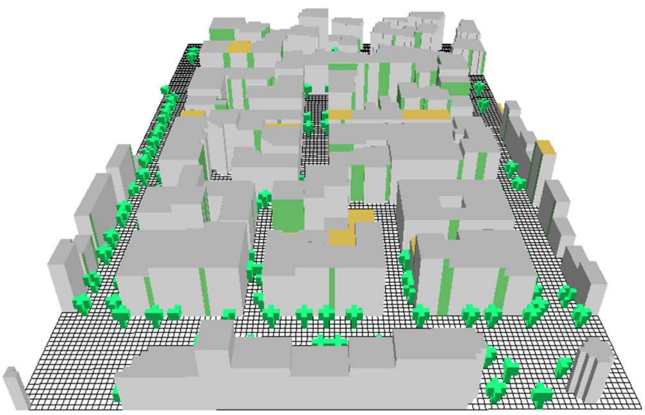
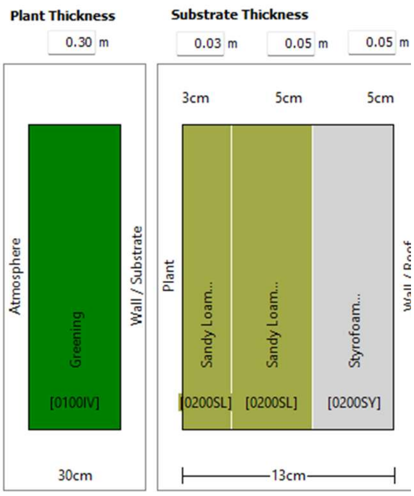


Figure 1.3-6 Study Area – Scenario B

1.3.2.3 Scenario C – High density Living Wall

Scenario C represents the high-intensity facade greening configuration and was developed to test the maximum microclimatic potential of vertical greenery within the selected urban district (Figure 1.3-7 and Figure 1.3-8). Scenario C follows the same Living Wall system definition used in Scenario A (i.e., identical vegetation type and living-wall set-up). Therefore, the difference between Scenario A and Scenario C is the extent and spatial distribution of greening. In Scenario C, the Living Wall system was applied on a substantially larger share of the building stock: (a) all facade surfaces facing the interior of the building blocks (inner courtyards) were vegetated to maximize cooling in semi-enclosed spaces, where reduced ventilation and higher radiant heat storage can intensify local heat stress; (b) all main facades of buildings facing the major road axes of the study area were also vegetated (Finikos, Vrioulon, Mikras Asias, Torolois, Fertekiou and Efesou streets), as the most frequently used public spaces and the primary urban corridors.

Overall, Scenario C represents a significant increase in vegetated vertical surface area compared to Scenario A, while keeping the same Living Wall configuration. This allows the analysis to isolate the effect of coverage density and placement on near-surface air temperature and humidity, and to evaluate whether large-scale deployment can produce measurable district-level improvements beyond the localized cooling observed in more moderate interventions.



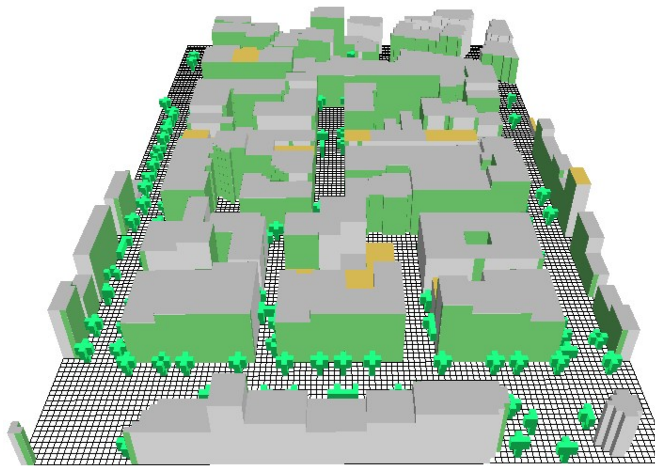


Figure 1.3-7 Living wall system layers – ENVI_met

Figure 1.3-8 Study Area – Scenario C

1.4 BUILDING ENERGY CONSUMPTION

The next stage of the work focuses on investigating the impact of green walls on the energy profile of buildings, by coupling the results of microclimate simulation with dynamic building energy simulation. Specifically, the results of the microclimate simulation from ENVI-met, for the two scenarios considered (Baseline, Scenario A and Scenario C), were integrated into the EnergyPlus software, in order to assess the impact of green walls on the energy requirements for cooling, during summer.

A five-story apartment building with exclusive residential use on all floors, including the ground floor, was selected as a representative building (Figure 1.4-1, Figure 1.4-2 and Table 1.4-1). In the first phase of the analysis (Baseline Scenario), the building was simulated using climatic data corresponding to the existing situation, without the presence of green walls in the building block. In the second phase (Scenario A), the same building was studied under moderate facade greening conditions, where the living wall system is applied only on selected blind facades. In the third phase (Scenario C), an intensive facade greening strategy was examined, where the living wall system of scenario A is applied to all facades facing internal courtyards and to the facades of the main streets; additionally, the case-study building is assumed to be fully covered by the green wall construction. At this stage, the assessment of green wall's impacts on the buildings' energy profile focuses only on living wall system, since it constitutes the most representative and fully developed facade-greening option, with the hydroponic scenario exhibiting only marginal changes in the ENVI-met outputs.

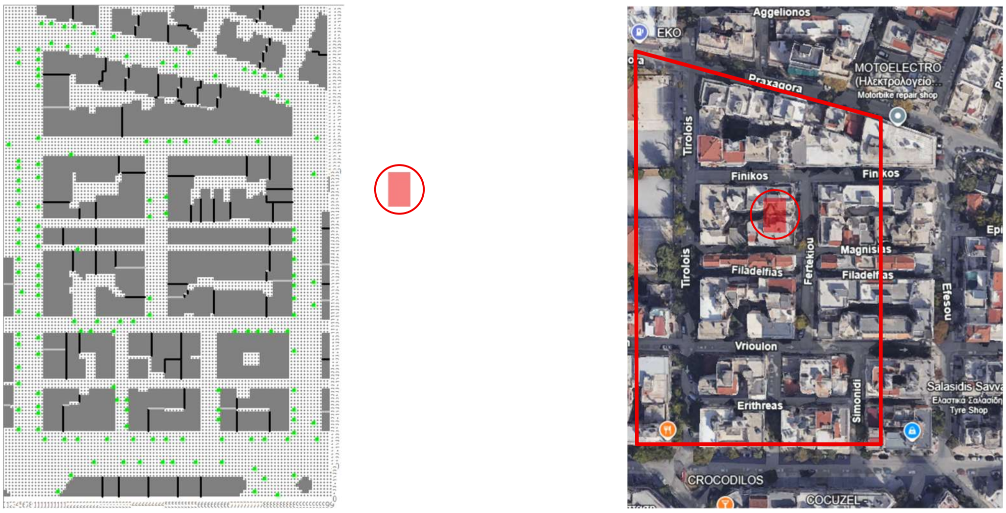


Figure 1.4-1 Location of building in the study area

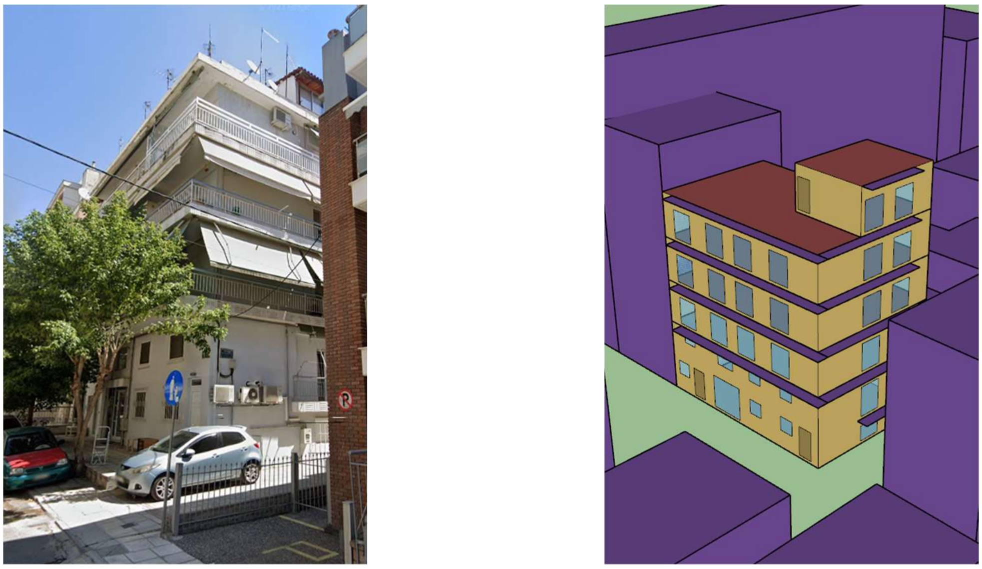


Figure 1.4-2 Representative building of the study area, (a) current state and (b) 3D model in EnergyPlus

Table 1.4-1 Building Specification

Parameter	Value
Building use	Multi-family residential (all floors, including ground floor)
Number of floors	5
Conditioned floor area	535.87 m²
Conditioned volume	1,859.70 m³
Location / weather file	Thessaloniki (IWEC file), microclimate adjusted with ENVI-met
Total above-ground gross wall area	623.39 m²
Total window glass area	97.63 m²
Overall Window-to-Wall Ratio (WWR)	≈ 15.6 %

External wall construction (baseline)	"EXTERIOR WALL" – U-factor with film: 1.85 W/m²K
External wall construction with green wall system	"EXTERIOR GREEN WALL" – U-factor with film: 1.045 W/m²K
Roof construction	"EXTERIOR ROOF" – U-factor with film: 2.126 W/m²K
Zone lighting power density	5.6 W/m² (all zones)
Plug and process load density	2.0 W/m² (all zones)
Occupancy density	20 m²/person (i.e. 0.05 persons/m²)
Zone status	All zones conditioned and part of total floor area

The integration of the green wall in the building energy model was achieved by adding an external layer of material to the structural element of the external wall, which simulates the thermal behavior of the vertical vegetation system equivalently. This layer was defined in EnergyPlus as an additional material with a specific thickness, thermal conductivity, density, specific heat and optical/thermal absorptivities, in order to represent the total thermal resistance and absorption of solar radiation by the green system (Table 1.4-2). In the baseline scenario, the exterior facades are modeled without this layer. In Scenario A, the modified construction is applied only to the eastern "blind" wall, reflecting the realistic scenario of green wall integration. In Scenario C, the green wall construction is applied to all exterior facades of the case-study building, representing full-facade coverage. In this way, the comparison of the results between the three scenarios captures both the impact of the green walls on the local microclimate (through the ENVI-met climate data), and the change in the thermal behavior of the building envelope (through the modified wall construction).

Table 1.4-2 Green wall material physical properties

Property	Value
Roughness	Very Rough
Thickness {m}	0.10
Conductivity {W/m-K}	0.24
Density {kg/m3}	300
Specific Heat {J/kg-K}	2500
Thermal Absorptance	0.9
Solar Absorptance	0.8
Visible Absorptance	0.8

1.4.1 Climatic Data

The boundary conditions used in the daily building energy simulations were not taken directly from a standard weather file but were extracted from the ENVI-met outputs for both the Baseline Scenario (existing conditions), Scenario A (moderate facade greening), and Scenario C (intensive facade greening). Hourly air temperature (Tair), relative humidity (RH), and wind speed values were adopted as the external climatic inputs, so that the EnergyPlus model integrates the locally modified microclimate produced by each greening configuration rather than relying on generic meteorological conditions. To maintain consistency between the outdoor and indoor modelling stages, the simulated day corresponds to the same extreme hot day used in the ENVI-met microclimate assessment. The resulting hourly boundary-condition dataset for all cases is presented in Table 1.4-3.

Table 1.4-3 Hourly boundary conditions for Baseline and Scenario A

Hour	Air Temperature (°C)			Relative Humidity (%)			Wind Speed (m/s)		
	Ref. State	Scen. A	Scen. C	Ref. State	Scen. A	Scen. C	Ref. State	Scen. A	Scen. C
1	24.67	24.63	24.62	50.20	50.41	50.57	0.59	0.59	0.59
2	24.87	24.83	24.80	48.72	48.97	49.17	0.59	0.59	0.59
3	25.16	25.12	25.08	46.58	46.85	47.09	0.58	0.58	0.58
4	25.53	25.48	25.43	44.70	44.98	45.24	0.58	0.58	0.58
5	25.54	25.49	25.44	48.52	48.80	49.06	0.57	0.57	0.57
6	25.49	25.43	25.38	53.37	53.63	53.90	0.56	0.56	0.56
7	25.66	25.59	25.50	57.34	57.71	58.18	0.55	0.55	0.55
8	26.55	26.46	26.32	56.13	56.72	57.37	0.52	0.52	0.53
9	27.71	27.57	27.39	53.21	53.97	54.86	0.50	0.50	0.50
10	28.86	28.70	28.50	49.68	50.52	51.48	0.47	0.47	0.47
11	29.97	29.82	29.60	46.24	47.01	47.96	0.48	0.48	0.47
12	30.97	30.81	30.57	43.69	44.42	45.39	0.47	0.48	0.47
13	31.90	31.75	31.53	41.79	42.46	43.30	0.47	0.47	0.46
14	32.54	32.39	32.17	37.63	38.24	39.02	0.46	0.46	0.45
15	33.01	32.85	32.61	32.70	33.28	34.04	0.45	0.45	0.45
16	33.42	33.25	32.98	27.95	28.49	29.22	0.45	0.45	0.44
17	32.92	32.72	32.42	27.73	28.32	29.09	0.45	0.45	0.44
18	32.11	31.90	31.59	28.71	29.37	30.16	0.45	0.45	0.44
19	31.19	30.97	30.68	30.01	30.67	31.41	0.45	0.45	0.45
20	30.04	29.82	29.55	32.35	33.03	33.76	0.45	0.46	0.45
21	28.95	28.72	28.46	34.77	35.50	36.27	0.45	0.46	0.45
22	27.83	27.60	27.33	37.62	38.40	39.21	0.46	0.46	0.45
23	27.36	27.13	26.88	39.39	40.17	40.98	0.46	0.46	0.46
24	26.37	26.14	25.89	46.74	47.60	48.43	0.46	0.46	0.46

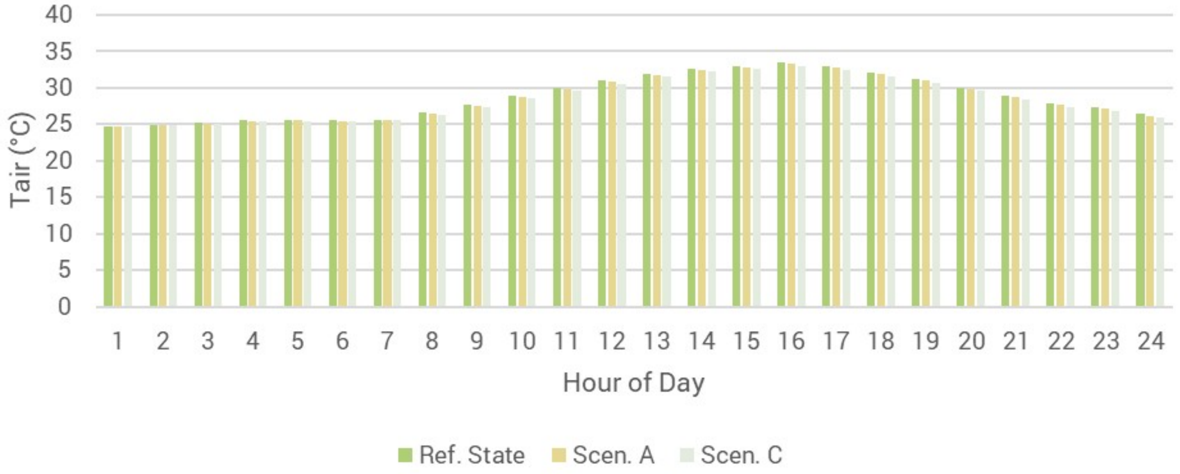


Figure 1.4-3 Hourly boundary conditions for Baseline and Scenario A, Air Temperature (°C)

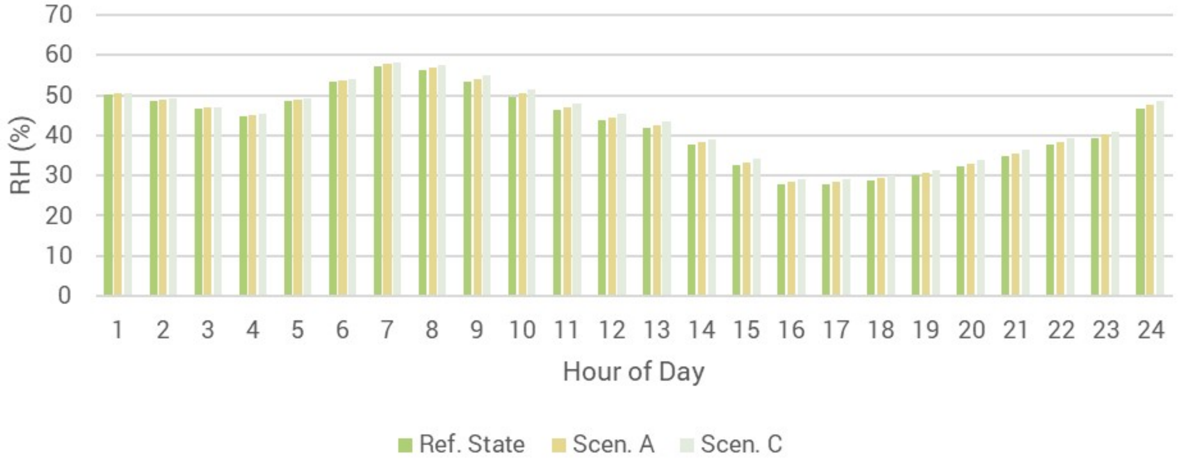


Figure 1.4-4 Hourly boundary conditions for Baseline and Scenario A, Relative Humidity (%)

1.5 RESULTS OF DESIGN SCENARIOS

1.5.1 VGS effect on microclimatic conditions

To assess the microclimatic impact of facade greening in the study area, ENVI-met simulations were performed for four configurations: the Baseline Scenario, Scenario A (Living Wall applied on selected blind facades), Scenario B (Hydroponic Wall), and Scenario C (intensive Living Wall deployment on main-street facades and internal courtyards). The study focuses on near-surface air temperature (Tair) at 1.5 m height (pedestrian level) for the hottest day, evaluated at 12:00 and 18:00, capturing both peak daytime conditions and the early evening period when accumulated heat in the urban fabric can still drive thermal stress. By comparing the spatially averaged values and the full distributions of air temperature among these three configurations, the analysis aims to quantify the cooling potential of the green wall applications and to explore whether different green wall technologies and greening densities alter ambient air temperature within the urban canyons.

Regarding the spatial thermal contribution of the reference state, higher temperatures are observed in the southern part of the area and lower ones in the northwest. The coldest areas are those in the interior of the building blocks which are mostly shaded during the day, receiving significantly less direct solar radiation, compared to the rest of the area (Figure 1.5-2, Figure 1.5-5). Relative to the Reference State, Scenario A produces a small but consistent cooling effect (Figure 1.5-3, Figure 1.5-6). At 12:00 the average Tair decreases from 31.38 °C to 31.32 °C (Δ=-0.06 °C), while at 18:00 it decreases from 32.24 °C to 32.16 °C (Δ=-0.08 °C). Changes in the domain minimum and maximum temperatures remain limited (≤0.04 °C in magnitude) However, the deviations in specific spots on the area reach up to -0.24 °C at 12:00 and -0.52 °C at 18:00, indicating higher localized benefits near grids with increased planted surfaces. Scenario B yields virtually identical values to Scenario A, confirming that, under the examined conditions, differences between green-wall system types have negligible impact on domain-average Tair.

In contrast, Scenario C—representing a substantial increase in facade greening—shows a more pronounced effect (Figure 1.5-4, Figure 1.5-7). The average Tair decreases by -0.32 °C at 12:00 and by -0.42 °C at 18:00, with corresponding reductions in maximum avg air temperature of -0.06 °C at noon and -0.19 °C in the afternoon. The cooling benefits are more pronounced locally, in specific grids with the Tair drop reaching up to at −0.95 °C 12:00 and −1.20 °C at 18:00. These results are also found in similar studies. The study of Tseliou et al. (9) in a typical urban neighborhood of Athens, suggested that a maximum reduction in the average Tair reached 0.7 °C. Similarly, the study of Daemei et al. (10), in the urban area of Tehran, observed a cooling of 0.39-0.75 °C in summer, with the maximum values near the planted surfaces. Finally, higher late afternoon benefits in all cases suggest that greening results in more prominent cooling by limiting heat-storage in the buildings' envelope and maintaining latent cooling, compared to 12:00 where the benefits mostly reflect the peak in plant evapotranspiration at that hour (Figure 1.5-8 - Figure 1.5-11). All results are presented in Table 1.5-1, while their graphical representation is provided in **Σφάλμα! Το αρχείο προέλευσης της αναφοράς δεν βρέθηκε.**.

Table 1.5-1 Air temperature at 1.5 m height (pedestrian level) for the hottest day during midday (12:00) and afternoon (18:00)

Scenario	Time	Average Tair (°C)	Min Tair °C	Max Tair °C
Reference State	12:00	31.38	29.16	32.20
Scenario A	12:00	31.32 (-0.06)	29.15	32.19
Scenario B	12:00	31.32 (-0.06)	29.15	32.19
Scenario C	12:00	31.06 (-0.32)	29.11	32.14
Reference State	18:00	32.24	30.62	32.78

Scenario A	18:00	32.16 (-0.08)	30.60	32.74
Scenario B	18:00	32.15 (-0.09)	30.60	32.74
Scenario C	18:00	31.82 (-0.42)	30.52	32.59

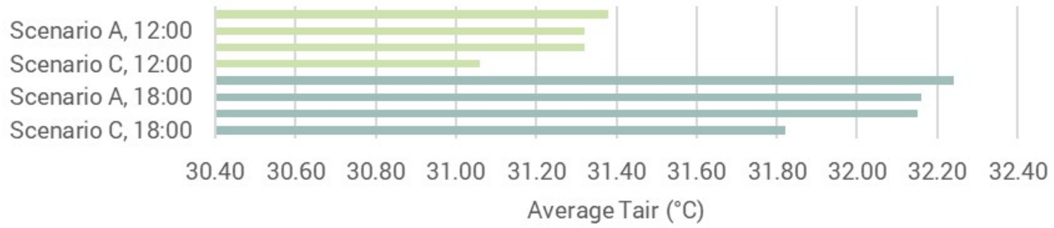


Figure 1.5-1 Air temperature at 1.5 m height (pedestrian level) for the hottest day during midday (12:00) and afternoon (18:00)

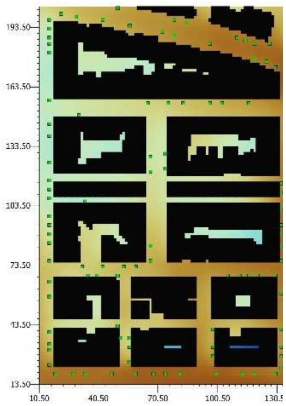


Figure 1.5-2 Reference State, Summer, 12:00 PM

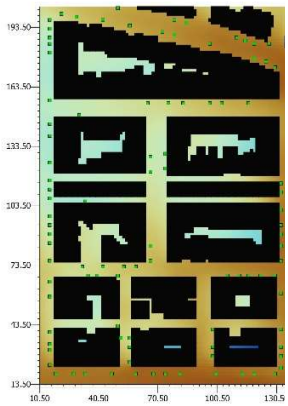


Figure 1.5-3 Scenario A, Summer, 12:00 PM

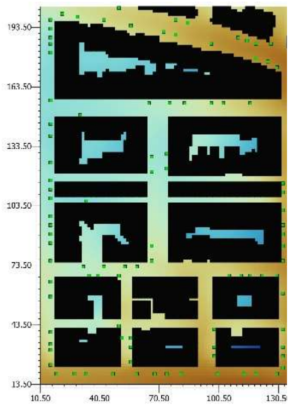
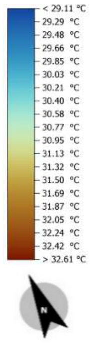


Figure 1.5-4 Scenario C, Summer, 12:00 PM



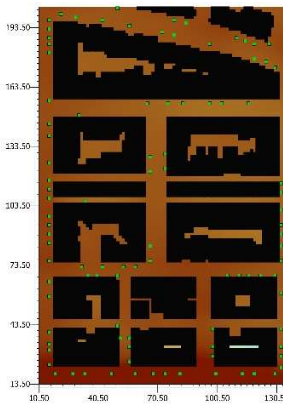


Figure 1.5-5 Reference State, Summer, 18:00 PM

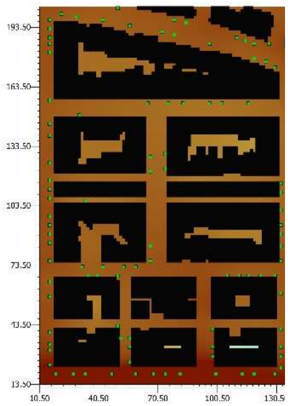


Figure 1.5-6 Scenario A, Summer, 18:00 PM

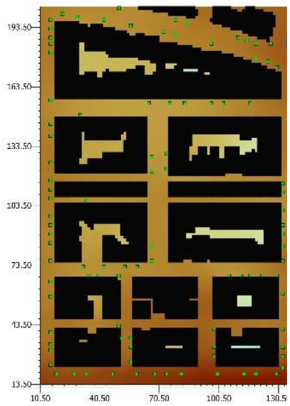


Figure 1.5-7 Scenario C, Summer, 12:00 PM

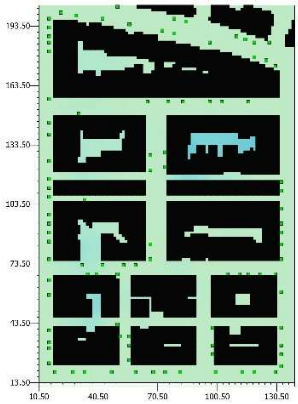


Figure 1.5-8 Comparison of Scenario A to Reference State, 12:00 PM

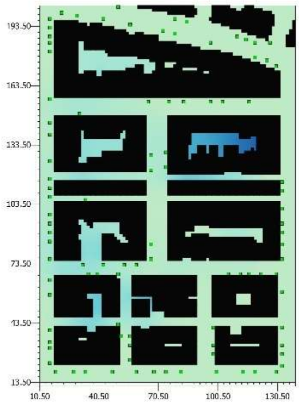
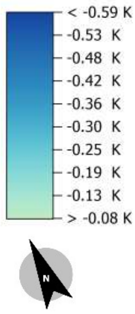


Figure 1.5-9 Comparison of Scenario A to Reference State, 18:00 PM



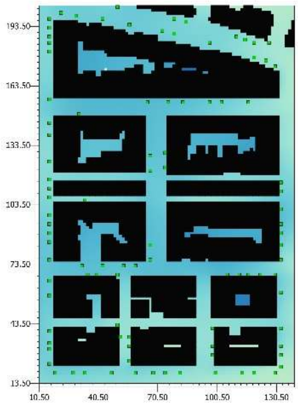


Figure 1.5-10 Comparison of Scenario C to Reference State, 12:00 PM

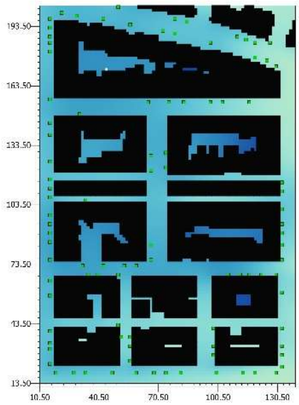
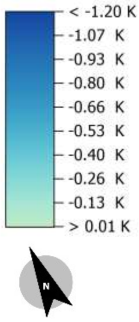


Figure 1.5-11 Comparison of Scenario C to Reference State, 18:00 PM



1.6 EFFECT OF VGS ON THE BUILDING'S ENERGY PERFORMANCE

At whole-building level, total site energy over the 24-hour period decreases from 493.07 kWh in the reference case to 473.41 kWh in Scenario A (a reduction of 4.0%), and further to 451.23 kWh in Scenario C (a reduction of 8.5%). Expressed per floor area, the daily site energy drops from 0.92 kWh/m² to 0.88 kWh/m² in Scenario A and 0.84 kWh/m² in Scenario C. These results indicate that increasing the extent of facade greening leads to progressively larger reductions in daily energy use during an extreme cooling day.

The effect is more pronounced when focusing on cooling demand. The DistrictCooling:Facility meter shows a reduction from 423.84 kWh in the reference case to 404.18 kWh in Scenario A (−4.6%), and to 381.99 kWh in Scenario C (−9.9%). The peak district cooling load also decreases from 25.33 kW in the reference case to 24.19 kW in Scenario A (−4.5%) and 23.61 kW in Scenario C (−6.8%). This attenuation of the peak load is particularly relevant for system sizing and for mitigating stress on the cooling equipment during heat-wave conditions. A summary of the key indicators for the extreme summer day is presented in Table 1.6-1.

Table 1.6-1 Building energy performance on extreme summer day (4 August)

Indicator	Unit	Baseline	Scenario A	Scenario C
Total Site Energy	kWh	493.07	473.41 (−4.0%)*	451.23 (−8.5%)*
Site Energy per Total Building Area	kWh/m²	0.92	0.88 (−4.3%)*	0.84 (−8.7%)*
District Cooling Energy	kWh	423.84	404.18 (−4.6%)*	381.99 (−9.9%)*
Peak Cooling Load	kW	25.33	24.19 (−4.5%)*	23.61 (−6.8%)*
Zone 02 Sensible Cooling Energy	kWh	493.07	473.41 (−4.0%)*	451.23 (−8.5%)*

**Δ(change) of each scenario compared to baseline state, %*

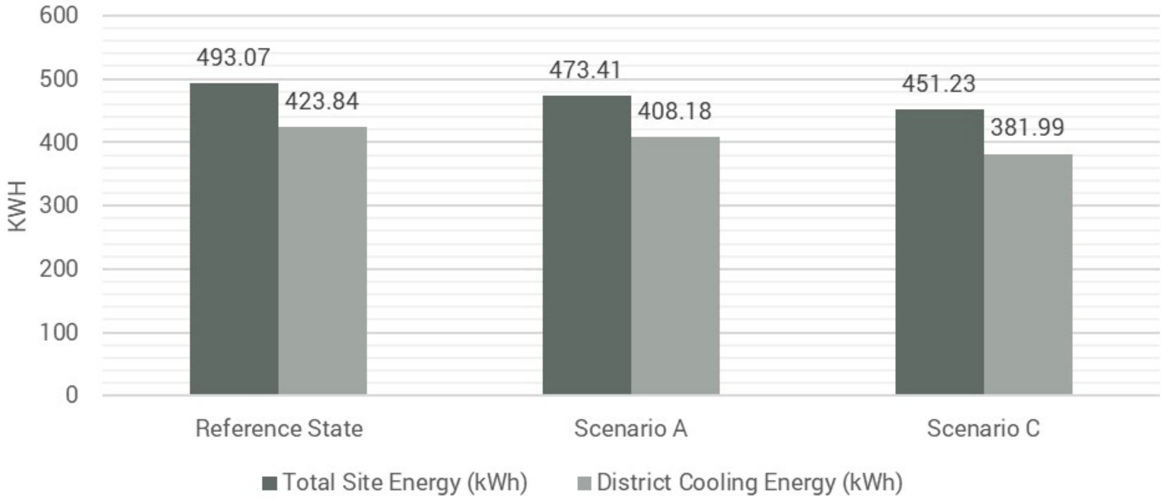


Figure 1.6-1 Total site energy (kWh) and cooling demand (kWh) for Baseline state, Scenario A and Scenario C

At zone level, the results show that the higher floors exhibit higher energy demand for cooling, mainly due to the fact that upper levels have greater exposure to external conditions and receive increased solar radiation. An exception appears in the last zone, which corresponds to a small, enclosed space combined with the stairhead/staircase termination. Due to its limited area and different geometry, it does not follow the same upward increase observed in the main occupied zones.

On the other hand, the impact of the green wall system is most pronounced at ground level, and its influence gradually weakens with height. This stronger effect on the ground floor can be attributed to the fact that the green wall interacts more directly with the immediate microclimate at street level: it can provide more effective shading and evapotranspirative cooling where the facade is closer to warmer near-ground air, reflected radiation from surrounding surfaces, and local heat accumulation. As we move upward, the surrounding microclimatic benefits become less dominant and the facade is increasingly governed by broader atmospheric conditions and direct solar exposure, so the relative contribution of the green wall diminishes from floor to floor.

When comparing the greening configurations, Scenario A yields a moderate reduction in cooling demand across all main zones, whereas Scenario C, which combines extensive district-scale facade greening with full facade coverage of the case-study building, amplifies these benefits and approximately doubles the cooling-energy reductions observed in Scenario A. The cooling energy demand per thermal zone for baseline state and scenario A are included in Table 1.6-2 and Figure 1.6-2.

Table 1.6-2 Cooling Energy Demand per Thermal Zone (Scenario A vs Baseline)

Zone	Baseline Scenario (kWh/day)	Scenario A (kWh/day)	Scenario C (kWh/day)
ZONE00	70.10	64.49 (−8.0%)*	57.77 (−17.6%)*
ZONE01	75.72	71.19 (−6.0%)*	66.26 (−12.5%)*
ZONE02	82.44	78.14 (−5.2%)*	73.95 (−10.3%)*
ZONE03	110.85	106.92 (−3.5%)*	102.60 (−7.4%)*
ZONE04	43.25	41.53 (−4.0%)*	39.45 (−8.8%)*

**Δ(change) of each scenario compared to baseline state, %*

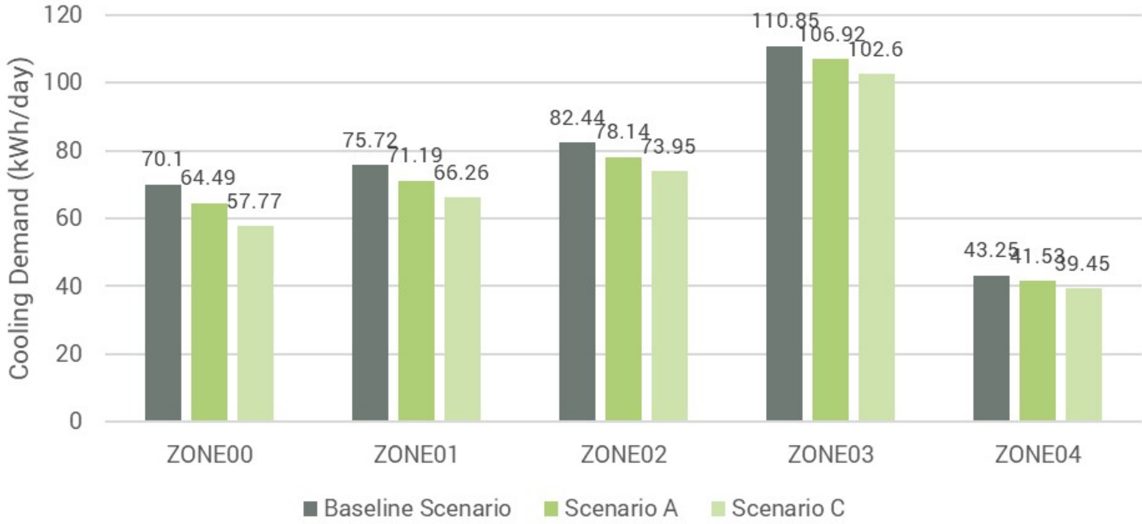


Figure 1.6-2 Cooling Energy Demand (kWh/day) per Thermal Zone (Scenario A vs Baseline)

1.7 CONCLUSIONS ON DIFFERENT DESIGN SCENARIOS OF RENOVATIONS

The proposed approach designed and assessed facade greening at two scales by coupling ENVI-met (district microclimate) with EnergyPlus (building energy performance) for an extreme summer day. The microclimate analysis compared Reference state (baseline scenario), Scenario A (moderate deployment of a Living Wall on selected blind facades/cores), Scenario B (hydroponic system), and Scenario C (intensive deployment of the same Living Wall configuration as Scenario A, applied on substantially more surfaces across the district). The building energy analysis evaluated the reference building under three envelope configurations: Baseline (REF), Scenario A (single east-facing blind wall retrofitted with the green wall system), and Scenario C (district microclimate from Scenario C and full facade coverage of the case-study building with the green wall system). All EnergyPlus scenarios use identical internal gains and thermostat setpoints, so differences are driven by microclimate and envelope changes.

A key methodological decision was to adopt the Living Wall system as the primary greening solution for the building-level coupling. This choice ensured consistency between the district-scale Scenario A and Scenario C (both Living Wall), and it was also supported by the ENVI-met results showing that Scenario A and Scenario B produced nearly identical air-temperature outcomes at district scale; therefore, Living Wall was treated as a representative and realistic retrofit option for subsequent energy assessment.

At the district scale, facade greening produced small but systematic reductions in pedestrian-level air temperature (Tair at 1.5 m). Under moderate deployment (Scenario A), the domain-average Tair reduction was −0.06 °C at 12:00 and −0.08 °C at 18:00 relative to the Reference State, while Scenario B showed essentially the same behavior. Under intensive application (Scenario C), the cooling effect became clearer but remained moderate at the district-average level, reaching −0.32 °C at 12:00 and −0.42 °C at 18:00. Maximum air temperature also decreased more noticeably in Scenario C, particularly in the afternoon (ΔMax ≈ −0.19 °C at 18:00). These results confirm that, in a compact urban fabric with active mixing and ventilation, vertical greening tends to deliver localized improvements rather than large area-wide reductions in mean air temperature; stronger effects are expected close to vegetated facades and within semi-enclosed courtyards.

At the building scale, the coupled ENVI-met/EnergyPlus workflow showed that even limited facade retrofitting can yield a robust reduction in cooling-related energy demand on a peak summer day. Compared to the baseline case, Scenario A reduced Total Site Energy from 493.07 kWh to 473.41 kWh (−4.0%) and reduced District Cooling Energy from 423.84 kWh to 404.18 kWh (−4.6%). The peak district cooling load decreased from 25.33 kW to 24.19 kW (−4.5%), indicating a consistent attenuation of both daily cooling demand and peak system requirements. At zone level, the directly affected zone (ZONE02) showed a −5.2% reduction in cooling energy transfer (82.44 → 78.14 kWh). In Scenario C, where facade greening was intensified at district scale and the case-study building was fully covered by the green wall construction, the energy benefits increased substantially: Total Site Energy dropped to 451.23 kWh (−8.5%) and District Cooling Energy dropped to 381.99 kWh (−9.9%), while the peak cooling load decreased to 23.61 kW (−6.8%). Zone-level cooling reductions approximately doubled compared to Scenario A (e.g., ZONE02: −10.3%, 82.44 → 73.95 kWh).

Overall, the results support the dual role of green walls observed in the literature: district-average air temperature reductions are typically modest, yet facade greening can still translate into measurable building-level cooling-energy savings, especially when it improves envelope thermal performance and reduces facade heat gains. The magnitude of the simulated savings—approximately 4–5% for a single treated facade and approximately 8–10% under intensive application for this extreme day—is consistent with reported performance ranges for realistic building-scale vertical greenery applications, while much larger values (e.g., >20–30%) are usually linked to idealized cases such as test cells, free-floating conditions, or full optimized coverage across orientations and very weak baseline envelopes. Finally, the outcomes should be interpreted as design-day performance rather than annual savings. The present modelling approach represents the green wall in EnergyPlus using an equivalent material layer (thermal effect), while ENVI-met captures the microclimate response; future work could extend this framework through (i) annual simulations, (ii) explicit assessment of outdoor thermal comfort indices (e.g., MRT/PET/UTCI) in ENVI-met, and (iii) sensitivity analyses on irrigation levels, foliage density (LAI/LAD), facade orientation, and baseline envelope quality, in order to identify where vertical greening offers the highest combined microclimate and energy benefits.

This first part considers the real design guideline options at urban environment of existing buildings by coupling their morphology, materials, surfaces, density, real case districts and buildings, forestry options, energy consumption and thermal comfort following an engineering quantified approach.

In the following chapters, different structural engineering aspects, considering the upgrade of reinforced concrete members and buildings (taking into account the materials and steel reinforcement detailing and brick infills of vulnerable ones), innovative green retrofits, the support of greenery and planters, compatible green envelopes etc, are thoroughly presented. Simple, vertical forest renovation-related design guidelines are proposed while respecting the real-case scenarios of chapter 1 for vertical forest renovations and the experimental and analytical developments in workpackages 1, 2, 3 and 4 and in available international literature.

2 GENERAL DESIGN GUIDELINES FOR GREENERY OF BUILDINGS

2.1 DEFINITIONS

It is important to summarize the different vegetation types on buildings, their characteristics and their benefits.

Vertical Forests

A vertical forest is a type of high-rise building—residential or commercial—that integrates trees, shrubs, and plants directly into its design. Vegetation is typically placed on balconies, roofs or/and facades, creating the effect of a green forest along the structure's exterior. In general, all different kinds of vegetation or greenery (internal or external) may be included within the framework of a constructed Vertical Forest either as integral part of a new building (or other structure), or as integral renovation scheme of an existing building (or other structure). The latter case is the focus of this report.

Such buildings can host hundreds or even thousands of plants across multiple floors, supporting a wide range of species. This vegetation attracts birds and insects, boosting urban biodiversity. At the same time, vertical forests help reduce the urban heat island effect, improve air quality by absorbing CO_2 and pollutants, and provide natural insulation, lowering energy use.

The most well-known example is the Bosco Verticale in Milan, Italy, designed by Stefano Boeri. It consists of two towers planted with about 20,000 plants, including 800 trees (480 medium to large, 300 smaller), 15,000 perennials or ground covers, and 5,000 shrubs (Boeri Studio, 2024).

Figure 2.1-1 Bosco Verticale / Boeri Studio. ArchDaily

Green roofs

Green roofs can be categorized into three main types based on their intended function, structural characteristics, and construction approach. These factors strongly influence both the choice of plant species and the overall appearance of the vegetation. The main categories include intensive, simple intensive, and extensive green roofs. Each type supports diverse plant communities with gradual transitions and variations depending on site conditions and environmental dynamics. Drawing on practical experience and vegetation research, these roof types can be distinguished according to several defining criteria. (FLL Landscape Development and Landscaping Research Society e.V.)

Figure 2.1-2 Green roofs

Balconies

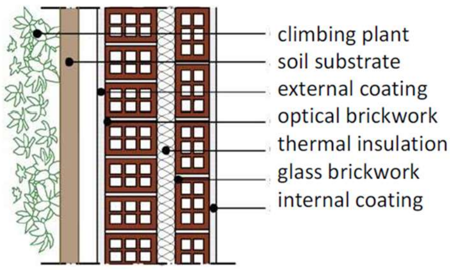
Balconies can provide the main areas for planting trees, shrubs, and smaller plants. They create small green oases that improve air quality, offer shade, and help control temperature. They also attract birds and insects, adding biodiversity to the urban environment. For residents, these planted balconies offer direct contact with nature, create visual beauty, and enhance comfort and wellbeing, turning the building into a living, breathing ecosystem. They can be vegetated with a diverse range of plant species, including small trees, shrubs, climbing plants, perennials, and ground covers, selected according to the balcony's orientation, sunlight exposure, wind conditions, and structural capacity.

Living Walls

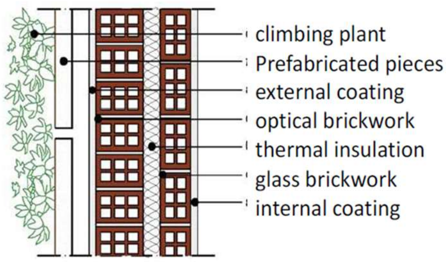
A living wall, also called a green wall, is a vertical structure covered with vegetation. Unlike vertical forests, these systems do not include trees but instead support smaller plants such as grasses, flowers, and shrubs directly on the wall's surface. They are usually installed with specialized systems that include a growing medium (soil or substrate) and an irrigation system. Living walls can be placed both indoors and outdoors, making them a flexible option for urban greening.

These walls provide several benefits: they help filter pollutants, reduce CO_2, improve urban air quality, and offer natural cooling and sound insulation. One of the most notable examples is the CaixaForum in Madrid, Spain, which features a vertical green wall designed by botanist Patrick Blanc.

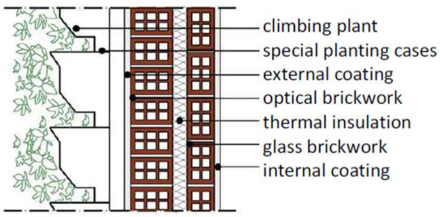
Figure 2.1-3 CaixaForum in Madrid, Spain, Patrick Blanc



B1 (Continuous Living wall system)



B2B (Modular Living wall system -prefabricated planter boxes)



B2G (Modular Living wall system - flexible cases)

Figure 2.1-4 Schematic representation of green façade systems (Theodoridou, 2018)

Green façades

Green façades are the simplest form of vertical greening. They rely on climbing or hanging plants that either grow upward from the ground or cascade downward from planters fixed to the building. Because of their relatively low complexity, they are often used to retrofit existing buildings (Dunnett & Kingsbury, 2008).

Figure 2.1-5 Pilot system installed in the courtyard of the laboratory. (Boano et al., 2019)

Green façades are commonly categorized into two main types: direct and indirect.

Direct Green Façades

In direct systems, plants attach themselves directly to the building wall using adhesive roots or tendrils. This eliminates the need for additional support structures, making them a cost-effective and environmentally friendly option (Manso & Castro, 2015). Perimeter flowerpots, where planters are arranged along a façade to form a "green curtain," also fall under this category. While these systems are simple and affordable, they typically limit the choice of plant species, grow slowly, and may lead to uneven coverage. Over time, they can also cause wear on the façade surface.

Indirect Green Façades

Indirect systems create a "double skin" by using lightweight support structures such as wire meshes, cable systems, or modular trellises (Manso & Castro, 2015; Perez et al., 2011). These allow more flexibility in plant choice and growth direction, provide opportunities for irrigation integration, and are generally easier to maintain. However, they involve higher installation costs and greater material use, increasing their environmental footprint.

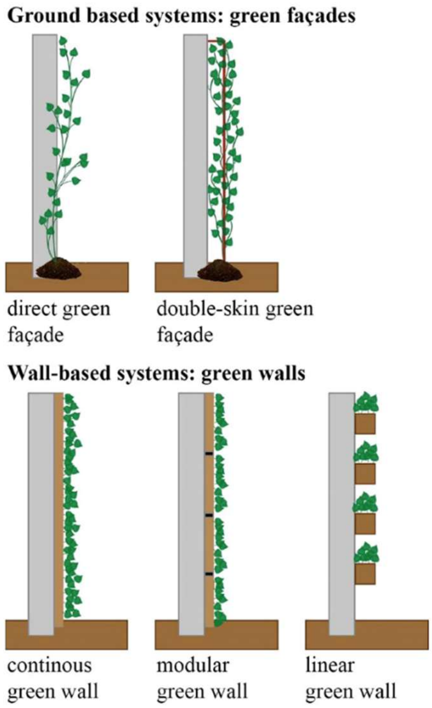


Figure 2.1-6 Green façades-ground-based greening methods. Direct (left) and indirect (right) green façade (Medl et al., 2017)

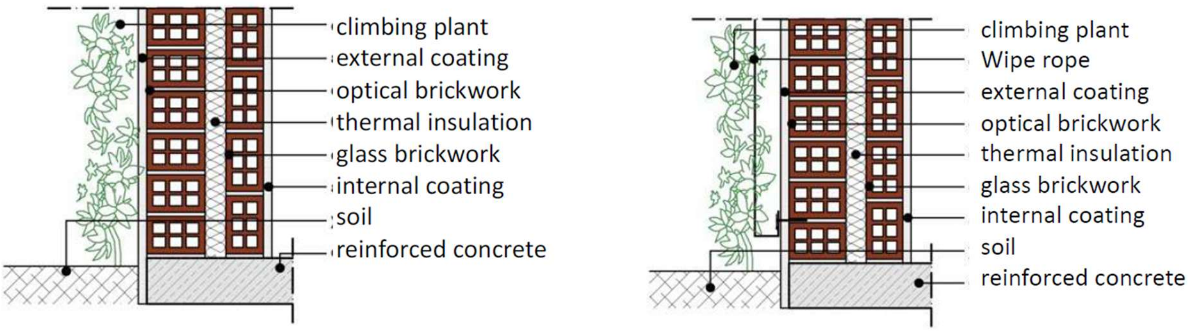


Figure 2.1-7 Schematic representation of green façade systems (Theodoridou, 2018). Direct (left) and indirect (right) green façade.

Green Walls Gardening Systems

Green walls are generally divided into two types: extensive and intensive.

Extensive walls are lightweight systems with thin planting layers (under 15 cm). They are meant for small, hardy plants that can survive with little water and soil. These walls help clean the air, cool cities, and support biodiversity.

Intensive walls have deeper soil (over 15 cm) and can support a wider range of plants, including shrubs and even small trees. They are heavier and need stronger structures as well as more maintenance.

Figure 2.1-8 Characteristic images from extensive green wall gardening. Direct greening system (a), indirect greening system (b), indirect greening system combined with planter boxed (c). (Perini et al., 2013).

Figure 2.1-9 Intensive green wall gardening (Bosco Verticale, Milan).

2.2 DESIGN CONSIDERATIONS FOR VERTICAL FOREST

When designing green walls in Mediterranean climates, a few key factors must be considered:

a) Irrigation

Because summers are very dry, efficient watering is essential. Drip irrigation is often preferred since it delivers water directly to plant roots and reduces evaporation.

b) Microclimate

The wall's orientation affects plant growth. South-facing walls receive more sun and heat, suiting sun-loving species but requiring extra irrigation. North-facing walls provide shade, making them better for shade-tolerant plants.

c) Soil and Substrate

A light, well-draining soil mix that holds some moisture and contains organic matter works best for plant health in this region.

2.2.1 Commonly Recommended Plant Types

Succulents & Cacti: Drought-resistant species like Agave, Echeveria, and Cacti, suited to extensive walls.

Herbs: Mediterranean herbs such as thyme, rosemary, and sage, useful in both wall types and offering culinary value.

Flowering Perennials: Plants like lavender and salvia, which add color, attract pollinators, and enhance biodiversity in intensive systems.

Dwarf Shrubs: Provide structure and greenery year-round, including species like boxwood or dwarf citrus.

Native Plants: Local species such as rockrose and wildflowers, which are well adapted to the climate and support local wildlife.

2.2.2 Plant Selection for Green Walls

Extensive Gardening

Mediterranean plants have developed special traits that help them survive in tough conditions, including long dry summers and poor soils. Many are xerophytes, which are plants that minimize water loss. For example, lavender (Lavandula angustifolia) and rosemary (Rosmarinus officinalis) have small, waxy leaves that reduce evaporation. Similarly, succulents like Sedum species store water in their leaves, making them ideal for extensive green walls.

Another group, halophytes, can tolerate salty soils, which makes them useful for urban areas where soil salinity may be high. A good example is saltbush (Atriplex halimus), which thrives even under saline conditions.

Although native Mediterranean plants are naturally drought-resistant, they still need some irrigation during the establishment phase, especially in extensive systems where the shallow soil dries out quickly.

Intensive Gardening

Mediterranean species, already adapted to heat, drought, and nutrient-poor soils, are especially suitable for intensive gardening.

These systems can host climbers, but when the substrate is deep enough, they can also support sclerophyllous shrubs and small trees. These plants have thick, leathery leaves that reduce water loss and help them stay green throughout the year. Examples include holm oak (Quercus ilex) and mastic tree (Pistacia lentiscus), both of which thrive in dry conditions while providing year-round greenery and visual appeal.

2.2.2.1 Drought-Tolerant Perennials for Mediterranean Green Walls

When designing green walls in Mediterranean climates, plant choices should not only survive drought but also support biodiversity and improve resilience. A balanced mix of herbs, succulents, shrubs, and climbers can provide year-round beauty while also helping to insulate and cool buildings, lowering energy use.

Because summers are hot and dry while winters are mild and wet, selecting hardy perennials is especially important. Some of the best options include:

Herbaceous Perennials: Plants like lavender (Lavandula), lavender cotton (Santolina chamaecyparissus), and Mediterranean spurge (Euphorbia characias) thrive in poor, dry soils. Lavender is attractive to pollinators and very drought-tolerant once established.

Succulents: Species such as Sedum are ideal for green walls thanks to their water-storing leaves. They need little maintenance and add texture, ranging from mat-forming types to upright forms.

Woody Shrubs: Rockrose (Cistus) and Spanish broom (Spartium junceum) are excellent drought-resistant choices. Rockrose provides colorful summer flowers, while Spanish broom produces fragrant yellow blooms and adds height.

Climbers: Vines like bougainvillea and ivy (Hedera helix) give vertical coverage with minimal water needs. Bougainvillea, with its bright bracts, is especially well-suited to hot, dry Mediterranean summers.

This plant mix ensures green walls remain visually appealing, sustainable, and climate-resilient throughout the year.

2.3 ROLE OF PROFESSIONALS

The successful construction of a vertical forest building requires close collaboration of structural engineers, builders and vegetation specialists, as their roles address complementary yet interdependent aspects of the project.

2.3.1 Architect and Vegetation Specialists:

- Select appropriate plant species suitable for urban microclimates and structural systems.
- Define soil composition and substrate depth tailored to plant needs.
- Design irrigation, drainage, and nutrient-delivery systems.
- Establish maintenance strategies to ensure healthy, long-term plant growth.

2.3.2 Structural Engineer:

- Assess the load-bearing capacity of the existing building.
- Design for additional permanent and variable loads, from soil, planters, and vegetation.
- Consider wind actions, seismic effects, and dynamic responses introduced by vegetation.
- Design appropriate retrofitting or strengthening schemes where required
- Desing anchoring systems for planters and living walls

From a structural engineering perspective, the classification and design of a building as a vertical forest requires the consideration of additional permanent and variable loads arising from vegetation, soil substrates, irrigation systems, and related infrastructure. These loads are primarily concentrated on the roof and distributed along the façades, thereby influencing both the global and local structural response. For existing buildings, a comprehensive structural assessment is required to determine the adequacy of the current load-bearing system. Should deficiencies be identified, appropriate strengthening or retrofitting measures must be designed and implemented to ensure the structure can safely accommodate the modified load demands and functional requirements associated with the vertical forest concept.

2.3.3 Builder:

- Apply design specifications as practical construction solutions on site
- Execute structural retrofitting, installation of planters, living walls and anchoring systems.
- Ensure construction quality, safety compliance and adherence to schedule and budget.

3 GUIDELINES FOR CONSTRUCTION AND VF RENOVATION STEPS

As part of this study, a renovated vertical forest (VF) structure was designed, retrofitted, and experimentally tested. The full procedure and testing methodology are presented in Annex.

3.1 DESIGN OF THE VF RENOVATION SCHEME

For the design of a vertical forest, engineers and greenery specialists play a crucial role in evaluating the building and identifying suitable greening solutions. Their expertise ensures that plants species, soil systems and irrigation are adapted to the specific structural, climatic and functional conditions of the structure. Based on this assessment, a suitable Vertical Forest design is developed that balances ecological performance with long-term sustainability, making the best use of the available space and resources. In addition, technical details are defined for the installation, anchoring, and maintenance of all key components - such as planters, instruments, and other elements that make up the Vertical Forest system.

Some of the key design characteristics are presented below:

Type of building: existing or new construction

In existing structures, design flexibility is often limited by structural capacity, available space, load-bearing restrictions, and existing architectural features. Before implementation, a detailed assessment of the building's structural capacity must be carried out to verify its ability to support the additional loads, -a detailed procedure is presented in the next Section. Where necessary, appropriate structural modifications and strengthening measures should be applied as part of the renovation process. These constraints must be carefully evaluated to determine the feasibility of integrating vegetation systems, anchoring mechanisms, and irrigation infrastructure. In contrast, new buildings allow for integrated planning from the outset, enabling structural and spatial provisions specifically designed to support the Vertical Forest concept.

Forms of vegetation for each part of VF

When designing vegetation, the options range from using cultivated plants for intensive green roofs to allowing wild plants to grow in extensive roofs that mimic natural habitats. Because there are so many possibilities, plant types are usually grouped according to the main species present. Different parts of the VF building may have different vegetation depending on site conditions like sunlight, shade, or soil depth. In addition to climate and building orientation, the selection and design of vegetation forms should also consider the available structural capacity, available space, and cost considerations to ensure feasibility and long-term performance. The target vegetation for each part should be clearly specified in the project documents, including how it will be maintained and any adjustments needed for site conditions.

For detailed presentation of the different forms of vegetation See 2.1 & 2.2

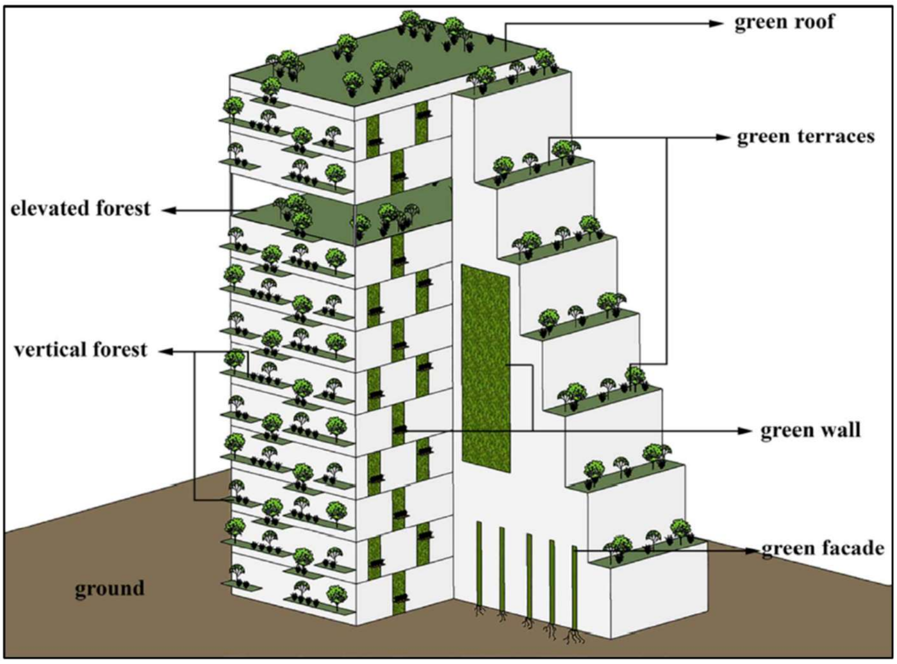


Figure 3.1-1 Classification of building greenery systems (Wang et al., 2020)

<u>Construction and effective greening</u>

The type of system used affects the structural and construction requirements for greening. All layers and materials in the roof must be suitable and effective to support healthy plant growth and ensure the system works properly.

Although Greece does not currently have specific national standards for the installation of green roofs, walls, or façades, and there is limited detailed guidance within existing building codes, a few internationally recognized guidelines are often referenced. These include the German FLL guideline, ASTM International standards, and recommendations from the Singapore Centre for Urban Greenery and Ecology (CUGE).

<u>Drainage</u>

Drainage planning should follow the standards DIN EN 12056-3 and DIN 1986-100. For green roofs, it is important to ensure that both planted and unplanted areas can drain properly. Any additional water, such as runoff from facades or other roofs, must be planned separately. Drainage systems should include roof outlets, internal pipes, door-area gullies, gutters, downspouts and emergency overflow channels. Regular maintenance following DIN 1986-30 is essential, and excess water should be directed to seepage or retention systems per FLL guidelines.

<u>Irrigation</u>

The roof should have at least one water connection, which must be protected against freezing either through technical measures or regular maintenance. The number and size of supply lines, as well as the required water pressure, depends on factors such as the site conditions, structural design, roof size and layout, and the type of vegetation. All planning must follow the requirements of DIN EN 1717.

Soil substrate

Green roof substrates are usually made from a mix of inorganic (mineral) and organic materials. Common components include scoria, pumice, ash, sand, coir, pine bark, porous foams, and even recycled materials such as crushed bricks or roof tiles. Organic matter is generally kept low (around 20% or less) because it breaks down over time, may compress, and can become water-repellent when fry, making it harder to re-wet.

The properties of the substrate- its composition, depth, and total volume determine what types of plants can grow successfully on the roof. A "good" substrate should:

- Have a known saturated weight (saturated bulk density) to be included in the roof's structural load calculations.
- Drain well to prevent waterlogging during heavy rain, while retaining enough moisture for plant growth during dry periods.
- Be stable over time, usually achieved by a higher proportion of mineral material and a smaller proportion of organic matter.

Regular garden soil is generally avoided on green roofs, as its properties are less predictable. It can degrade faster, and fine particles may clog drainage layers, causing water to accumulate.

A soil substitute that supports plant roots while supplying water, air, and nutrients. It can range from standard potting mixes for containers to specially engineered, mostly inorganic materials designed for green roofs.

Wind considerations

Design should follow relevant wind-loading standards to ensure structural stability and safety. In Europe, these include Eurocode 1 (EN 1991-1-4), which defines wind actions on structures, along with applicable national annexes that adapt the code to local climatic and topographical conditions. These codes specify how to determine wind pressure coefficients for different roof geometries, exposure categories, and building heights. The design should account for both uplift forces on the green roof system and suction pressures acting on edge details, flashings, and vegetation layers. Wind uplift is generally lowest at the center of the roof and highest along the edges, corners, and for pitched roofs, the peak. Taller buildings are more exposed to this risk. Minimizing loose or untethered components can significantly reduce the chance of wind-related damage to the green roof. Perimeter features such as balustrades or parapet walls can provide additional protection, and treatments like jute erosion netting or coated wire retaining systems may also help. Plant selection can further reduce wind impact: low-growing, hardy species should be placed in the most exposed areas, while taller, more delicate plants are positioned behind them. This arrangement creates a gradual transition in plant heigh that slows and disrupts wind flow over the vegetation.

The design should account for both uplift forces on the green roof system and suction pressures acting on edge details, flashings, and vegetation layers.

Seismic considerations

In seismically active areas such as Greece, the design of green roofs, walls, façades, and vegetated balconies must account for earthquake forces that can affect both structural stability and vegetation systems. Design should follow relevant codes, including Eurocode 8 (EN 1998) and national annexes, which define seismic actions and structural requirements. Measures such as secure anchoring of planters, balanced load distribution, and reinforcement of projections help ensure stability. Vegetation layers and substrates should also be designed to minimize movement or detachment during seismic events.

Anchoring

Anchoring systems are critical for the stability and safety of Vertical Forest structures, securing planters, green walls, and other vegetated components to the building. Each anchorage must be carefully designed to withstand not only static loads but also the dynamic actions that can occur during minor or major earthquakes, which may cause rocking or vibration. Poorly designed anchors increase the risk of elements shifting or detaching, creating safety hazards and potential structural damage. Long-term durability also depends on effective corrosion protection, as these components are continually exposed to moisture and environmental conditions. Regular inspections and maintenance are necessary to ensure continued performance. Detailed designs and examples of tested anchoring systems are presented in Section 3.3.

3.2 STRUCTURAL ASSESSMENT OF THE EXISTING STRUCTURE

Before installing a Vertical Forest system, it is essential to assess the structural capacity of the existing building to ensure it can safely carry the additional loads and withstand seismic actions. The safety of reinforced concrete (RC) buildings can be compromised during earthquakes due to poor material quality, weak design, or outdated construction that does not meet current seismic codes. Common issues include low-strength concrete, reinforcement corrosion, and inadequate detailing, which weaken the steel–concrete bond and lead to cracking. Structural weaknesses such as soft stories, short columns, or insufficient reinforcement further reduce seismic resistance.

Assessment is a quantitative process used to determine whether an existing structure, whether intact or damaged, can meet the required limit states for the actions under consideration (§2.1 of Eurocode 8), The outcome of this evaluation provides the basis for deciding if structural intervention is necessary and for developing any required retrofitting measures.

Data collection

For the assessment of an existing structure's load-bearing capacity, all available data should be cross-checked and, where feasible, calibrated to improve reliability. A tailored program of on-site inspections and laboratory tests must be prepared and supervised by the responsible assessment engineer, in line with the specific objectives of the study (KAN.EPE). Whenever possible, the chosen methodology should also integrate knowledge gained from the observed performance of comparable buildings during past seismic events, as outlined in Eurocode 8- part 3.

Damage should also be detected. Damage often results from low-quality materials, poor reinforcement detailing, and non-compliance with seismic standards. Issues such as concrete deterioration, steel corrosion, and inadequate structural design weaken a building's resilience. Additionally, poor soil conditions and interactions with nearby structures can intensify vulnerabilities, increasing the risk of serious damage or collapse during seismic events.

For guidance on assessing and classifying damage in existing structures, the Greek Code of Interventions (ΚΑΝ.ΕΠΕ.) provides clear directions. Relevant sections include:

- §2.1 – Assessment of existing structures: Outlines how the evaluation process should consider the presence of damage and its influence on intervention decisions.

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- §3.1–§3.4 – Recording of damage: Details the types of damage to be noted, such as cracks, detachments, local failures, and deformations, and describes procedures for documenting and classifying these damages (see §3.4 for recording practices).
- Appendices – Tables and figures: The Code's appendices (e.g., Figures S1–S2, Tables P1–P3) provide typical damage categories (light, moderate, severe) for structural elements such as columns, beams, shear walls, and infill walls, along with corresponding reduction factors used in structural assessment. These tables serve as the official reference for damage rating and classification.

Consulting these sections and appendices of KAN.ΕΠΕ. is recommended when developing inspection protocols or structural assessment reports.

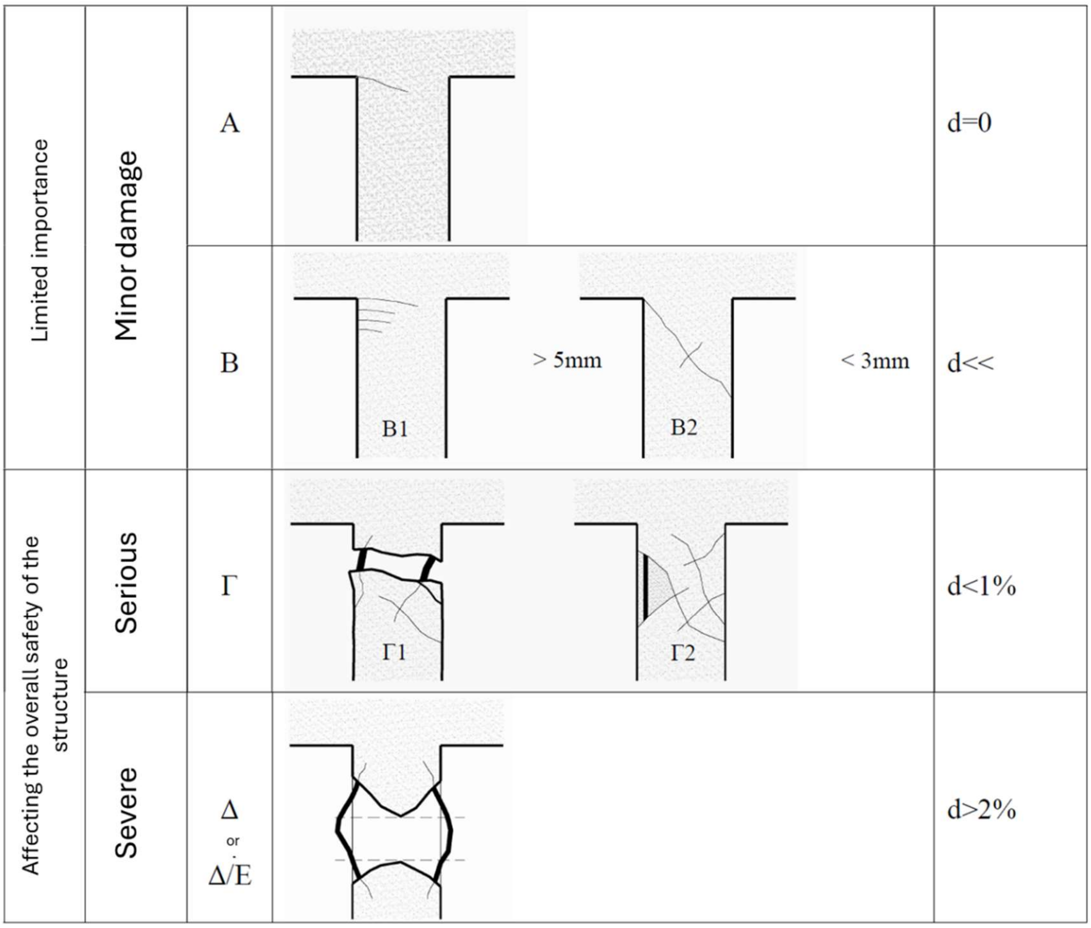

Figure 3.2-1 Typical degrees of damage to columns (and beams) (d: relative displacement of the element's ends) (KAN.EPE.)

Vanian et al. (2025) examined common reinforced concrete (RC) buildings as a reference for evaluating damage and retrofit needs in comparison with greenery-covered structures. They identified key issues such as material degradation, design deficiencies, and inadequate reinforcement details that influence structural performance and durability. Using a multiparametric assessment and expert-based risk rating, the research classifies deterioration levels and prioritizes required interventions.

The rating system is based on expert evaluations that classify structural and performance risks into three levels. Level 1 represents minor deterioration that does not require immediate action, Level 2 indicates conditions needing further investigation or monitoring, and Level 3 corresponds to severe damage requiring urgent intervention. Each parameter is scored from 1 to 3, allowing quantification of overall risk and prioritization of retrofit or maintenance actions. The scores are further grouped into low (5–8), medium (9–12), and high (13+) priority levels, supporting clear decision-making for building assessment and rehabilitation planning. The results are presented in the Table below:

Common Reinforced Concrete Buildings – Structural Performance: Causes of Damages		Damages	Levels EO1	EO2	EO3	EO4	EO5	Total
Material	Poor concrete quality	Cracking	2	2	2	3	3	12
		Reduced load-bearing capacity	2	2	2	3	3	12
		Surface spalling	2	2	2	3	3	12
		Permeability issues	2	2	2	3	3	12
	Corrosion	Reinforcement deterioration	2	2	2	3	3	12
		Loss of structural integrity	2	2	2	3	3	12
		Water leakage	2	2	2	3	3	12
Design	Non-compliance with the earthquake regulations	Structural cracking	2	2	2	3	2	11
	Short column	HRF of structural elements (columns, beams and joints), Loss of structural integrity during design EQ	2	2	2	3	2	11
	Strong beam-weak column	HRF during design EQ	2	2	2	2	2	10
	Insufficient shear capacity	HRF load-bearing capacity during design EQ	2	2	2	2	2	10
	Soft and weak story	HRF of Soft story failure, Joint failures during design EQ	2	2	2	2	2	10
	Weak attachment to the frames	HRF of elements like infill walls, ceilings and facades during design EQ	2	2	2	2	2	10
Reinforcement details	Insufficient reinforcement ratio	Reinforcement slippage	3	3	3	3	3	15
	Insufficient transverse reinforcement	Shear cracking	3	3	3	3	3	15
	Smooth stirrups	Loss of structural integrity	3	3	3	2	3	14
	Lack of crossties	Buckling of longitudinal reinforcement	3	3	3	3	3	15
	Lack of transverse reinforcement in connection region	Reduced load-bearing capacity	3	3	3	3	3	15
	90° hooks instead of 135°	Joint and connection failure	3	3	3	3	3	15
Others	Adjacent buildings effect	Collision damage, Structural instability, Cracking	2	3	2	2	2	11
	Insufficient determination of soil properties	Structural tilting, Cracks in walls and floors, Foundation failure	2	3	3	2	2	12
	Infill wall damages	Loss of lateral stability, Loss of lateral stability	3	3	2	3	2	13

HRF = High Risk of Failure/Partial or Full collapse/Falling, EQ = Earthquake, EO = Expert Opinion.

Table 3.2-1 Expert assessment of damage causes and severity in Common Reinforced Concrete Buildings (Vanian et al. 2025)

a. Analysis for building assessment

The choice of design parameters and analysis methods must comply with the relevant regulations, considering the importance factor of the building and the degree of existing damage or deterioration.

Using the information gathered in accordance with §3.2 of Eurocode 8 Part 3, a structural model shall then be developed. This model must enable the evaluation of action effects on all structural elements under the seismic load combinations specified in §4.2 of Eurocode 8 Part 3.

The seismic action effects, when combined with permanent and variable loads in accordance with the seismic load combinations specified in §4.2(4) (EC8-part 3), may be assessed through one of the following analytical approaches, presented in §4.4 Eurocode 8 Part 3:

- Linear lateral force method
- Linear modal response spectrum analysis
- Non-linear static (pushover) analysis
- Non-linear dynamic time-history analysis
- q-factor methodology

3.2.1 Design of Anchoring & rocking of VF elements

Proper anchoring of planters and vertical living wall elements is essential in Vertical Forest applications to ensure structural stability and protect the vegetation system. The choice of anchoring method depends on the type and size of the planter or wall module, as well as the characteristics and capacity of the supporting structure. In the design process, it is important to consider the seismicity of the region and the expected earthquake magnitude, as these directly influence the required anchorage strength and performance. The corrosion resistance of anchoring components must also be evaluated to ensure long-term durability in outdoor and moisture-prone environments. Furthermore, the desired structural behavior, whether a more ductile or stiffer response, and the acceptable level of damage or rocking effects during seismic events—should be clearly defined to guide the selection and detailing of the anchoring system.

Tested anchorage approaches (see Rousakis et al. 2025) include steel rods, fully or partially post-tensioned basalt ropes, and reinforcement using resin or polyurethane. These methods can be used to attach planters to the top slab and living wall elements to support, to prevent movement and ensure long-term stability minimizing rocking effects. The appropriate anchoring system should be selected based on structural conditions, planter dimensions, and safety considerations, following proper installation and tensioning practices. Moreover, for each case, the substrate's capacity to support the anchorage must be carefully assessed.

The following anchoring schemes were tested under seismic loading in the constructed VF structure, for planters and living walls, with results indicating which methods performed most effectively.

Planter Anchoring on the Top Slab:

Scheme 1: Drill through the slab. Insert a steel rod passing through the slab and planter. Secure with nuts at both the bottom of the slab and the top of the planter to simulate anchorage of the tree rooting system and planter.

Scheme 2: Drill through the slab. Insert two double basalt ropes as tendons. Fully post-tension one rope, while partially tensioning the second rope to serve as a safety measure.

Scheme 3: Two basalt ropes pass through the slab. One rope is fully post-tensioned, and the second is partially tensioned.

Scheme 4: No basalt anchors have been used. The planter is just simply supported on two opposite PM pads with dimensions 400mm x 40mm x 5mm.

Scheme 5: Two basalt ropes used as tendons that have been fully post-tensioned.

The five schemes of planters with trees demonstrated high seismic resilience, with no collapse or overturning even under very severe excitations. Anchoring methods (basalt ropes, steel rods, or with PM pads) generally withstood large drifts and accelerations, though ropes loosened, fractured, or prestressing devices displaced at higher levels – all easily repairable.

Scheme 1 (steel rod anchoring): Best overall performance. Only slight loosening of the rod was observed, causing minor bottom micro-displacements across all excitations.

Scheme 2 (single basalt rope anchoring): Performed well up to moderate excitations, but at higher levels ropes loosened, fractured, and prestressing devices displaced.

Scheme 3 (single basalt rope anchoring): Similar to *Scheme* 2, but with more frequent rope fractures and prestressing issues at severe excitations.

Scheme 4 (PM pads): Stable at low excitations, but under severe loads showed extreme rocking, pad displacements, and planter shifting (up to ±4cm), though without overturning.

Scheme 5 (double basalt rope anchoring, post-tensioned, no pads): Excellent performance overall, showing only slight rocking and minor displacements at high excitations. Rope fractures occurred at extreme levels but were easily repaired.

Best Practices for extreme successive earthquakes and high risk cases: Scheme 1 (most stable, minimal damage) and Scheme 5 (excellent stability, easily repairable).

Good Practice for moderate earthquakes and low risk cases: Scheme 4 (most rocking and displacement at high excitations).

Anchoring of the living wall mechanism

Out of plane – vertical to the loading direction (4 different cases):

1. Common approach with one steel screw (bolt) connector on the top slab.

2. Top attachment of the steel construction with two Basalt ropes, anchored through the slab depth. Initially, suitable through holes were drilled, pre-tensioning was applied to the ropes with a special metal structure from the upper part of the slab and the holes were filled with epoxy resin (Sikadur®-52 Injection LP). After the resin developed its strength, the tensioning device was removed.

3. Top attachment of the steel construction with two Basalt ropes, anchored through the slab depth. Initially, suitable through holes were drilled and then pre-tensioning was applied to the cords with a special metal structure from the upper part of the plate. The tensioning device will remain in place throughout the series of testing and will function as an active anchoring device.

4. Top attachment of the steel construction with one Basalt rope, anchored through the slab depth. The application stages are similar to case 3.

In-plane (4 different cases):

1. Top attachment of the steel construction with one Basalt ropes, anchored through the slab depth. Initially, a suitable through hole was drilled and then a tension was applied to the rope with a special metal structure from the upper part of the slab and the hole was filled with polyurethane resin (Polyurethane PM). After the polyurethane has developed its strength, the tensioning device was removed.

2. Top attachment of the steel construction with one Basalt ropes, anchored through the slab depth. Initially, a suitable through hole was drilled and then a pre-tension was applied to the rope with a special metal structure from the upper part of the slab and it was filled with epoxy resin (Sikadur®-52 Injection LP). After the resin has developed its strength, the tensioning device was removed.

3. Top attachment of the steel construction with two Basalt ropes, anchored through the slab depth. The application steps are the same as in case 1.

4. Top attachment of the steel construction with two Basalt ropes, anchored through the slab depth. The application steps are the same as in case 2.

All eight constructions had top polyurethane PM pads of dimension 40mm x 40mm x 5 mm (one or two pieces, based on the gap of the steel construction from the slab.

The eight vertical living walls (LW) (Rousakis et al. 2025) showed strong seismic resilience, with no collapses under very severe seismic excitations. Attachments with basalt ropes and PU pads resisted large drifts and accelerations. Loosening of ropes or rods occurred at higher levels but was always repairable.

LW4-3L (r2-ep.res.-pr.-1pad): Best performance. Maintained full capacity

LW1-4L (r1-pol.(PM)-2pads): Good overall, though basalt rope loosening and eventual PU pad detachment occurred at higher excitations, allowing micromovements under frequent wind loads.

LW3-2L (r1-pol.(PM)-2pads): Similar to LW1-4L, with rope loosening and PU pad detachment art high excitations, but still no collapse.

LW4-3R (st.): Slight steel rod loosening at the top, permitting micromovements under frequent wind, but no structural failure.

LW2-1L (r2-pr.-1pad) & LW3-2R (r1-ep.res.-pr.-1pad): Performed well, with only slight rope loosening, allowing micromovements under severe wind loads.

LW2-1R (r1-pr.-1pad): Showed rope loosening under medium intensity wind loads (less robust than other but still safe)

LW1-4R (r1-ep.res.-pr.-1pad): slight rope loosening, allowing micromovements under severe wind loads.

LW4-3L & LW2-1L/R (comparison): Performed better than LW4-3R at very high drifts.

Best Practice for successive extreme earthquakes: LW4-3L, fully resistant with no loosening at all.

Strong performers for successive extreme earthquakes: LW2-1L, LW3-2R, LW1-4R (only minor loosening), LW4-3R (still robust under high drifts).

Good performers for moderate earthquakes: LW1-2R (loosening under medium winds)

3.3 IMPLEMENTATION OF ADDITIONAL LOADS AND RELATED INFRASTRUCTURE IN THE ANALYSIS

3.3.1 Load assumptions

The structure, including all layers at maximum water capacity and the actual weight of the grown vegetation should be considered as part of the permanent load. This includes the fully grown weight of plants as well as the saturated weight of the substrate and vegetation. Additional loads of water that accumulates during ponding events must also be included.

Point loads from larger elements, such as trees, shrubs, pergolas, water basins and edging features, should be calculated separately and taken into account, considering EAK 2000, §3.7. Trees contribute a significant portion of the total load, not only through their weight but also due to the wind forces they transmit to the structure.

3.3.2 Seismic and Wind actions

Seismic actions should be assessed according to Eurocode 8 (EN 1998-1: and the National Annex). The analysis must consider the seismicity of the site, the importance factor based on the building's use, and the behavior factor (q), which reflects how the structure dissipates energy during an earthquake. For Vertical Forest and vegetated façade systems, the extra weight and movement of planters, soil, and vegetation must also be included, as they can affect the building's seismic response. Factors such as soil type, damping, and the building's natural period help define the design response and ensure both the structure and the vegetation system remain safe during seismic events.

Wind should be considered as a critical design factor, especially regarding its impact on roof structures and tall vegetation, where exposure can generate significant forces and dynamic effects. Wind speeds are generally higher at greater heights and can be intensified around building edges or by downdrafts from tall structures. Understanding the expected wind loads on a green roof, wall or façade is essential to ensure that the system is designed to safely resist these forces.

Key aspects to consider include:

- Basic Wind Velocity: Determining the fundamental wind speed for the specific location
- Roof category: Assessing the roughness of the surrounding terrain to understand wind behavior.
- Dynamic effects: evaluating the dynamic response of structures to wind forces.

Eurocode 1 Part 1-4 (EN 1991-1-4), Action on Structures – Wind Actions gives specifications on the evaluation and incorporation of these actions into the design.

3.3.3 Analysis

The analysis shall account for the renovated configuration of the vertical forest, incorporating all modifications introduced by the VF intervention, including changes in mass distribution, structural stiffness, and potential geometric or structural irregularities.

3.3.4 Limit State Design (ULS, SLS)

The structure shall be verified against both the Ultimate Limit State (ULS) and the Serviceability Limit State (SLS) to ensure safety, functionality, and long-term performance under the applied actions.

3.4 DESIGN OF RETROFITTING

Based on the results of the structural assessment and the type and extent of any damage, decisions must be made regarding necessary interventions/retrofitting. The choice of retrofitting type and method should rely on the information gathered during the assessment. Possible retrofitting includes repairing, strengthening, or replacing existing elements.

The retrofitting and strengthening scheme shall be developed to achieve both economic efficiency and environmental sustainability, prioritizing the use of lightweight, durable, and eco-friendly materials that minimize the overall environmental impact. Strengthening in strategic areas may achieve the design outcome while minimizing costs.

Key points to consider include:

- All identified damage should be properly repaired
- For buildings with high irregularities in stiffness or strength, efforts should be made to improve structural regularity both in plan and elevation
- Strengthening should achieve the required resistance while following guidance in Eurocode 8 (EN 1998-1 and EN 1998-3).
- Local ductility should be increased if needed, but the overall ductility of the structure should not be reduced.

Additional guidance on choosing the right retrofitting method based on the type and extent of damage, and on selecting suitable materials and techniques can be found in EC8 part 3- §5 Decisions for structural intervention, §Design of Structural Intervention. In Annexes A, B and C specific information for the assessment of Reinforced Concrete, Steel and Composite and Masonry structures accordingly.

Moreover, when designing renovated Vertical Forest (VF) buildings, several parameters beyond conventional structural considerations must be carefully assessed. Potential moisture and root penetration damage to concrete elements should be addressed. Maintenance access, irrigation systems, and occupant safety also require review to ensure safe and functional operation after retrofit. Integrating these factors ensures that strengthening interventions restore or enhance structural performance while maintaining greenery effectiveness and long-term resilience. The empirical rating tables (A2 & A3) (Vanian et al. 2025) provide guidance on these critical factors, highlighting potential risks and their severity for structural, greenery, and human-related aspects.

Greenery-Covered Buildings – Structural Performance		Levels					Total
Causes of Damages	Damages	EO1	EO2	EO3	EO4	EO5	
Root penetration (growth/action)	Wall and foundation integrity	2	2	2	2	3	11
	Potential instability issues	2	2	2	2	3	11
	Cracks	2	2	2	2	3	11
	Potential damage to technical features (e.g., pipelines)	2	2	2	2	3	11
Plants direct attachment/green layer removal	Wall and foundation integrity	2	2	2	2	2	10
	Lifted blocks	2	2	2	2	2	10
	Cracks	2	2	2	2	2	10
	Scarring	2	2	2	2	2	10
	Plaster removal	2	3	2	2	2	11
	Local wetness	2	3	2	2	2	11
High level of moisture (due to evapotranspiration)	Mold development	3	3	3	3	3	15
	Indoor and outdoor dampness	2	3	2	3	3	13
	Material covers damages	3	3	3	3	3	15
	Slow drying	3	3	3	3	3	15
High level of moisture (due to watering/irrigation systems)	Water leaks	3	3	3	3	3	15
	Water pooling	3	3	3	3	3	15
	Dripping water	3	3	3	3	3	15
	Indoor and outdoor dampness	3	3	3	3	3	15
	Mold development	3	3	3	3	3	15
	Corrosion	3	3	3	3	3	15
	Streaking	3	3	3	3	3	15
	Material covers damages	3	2	3	3	3	14
Soil moisture changes	Wall and foundation integrity	2	2	2	1	2	9
	Potential instability issues	2	2	2	1	2	9
	Subsidence	2	2	2	1	2	9
Soil microbial flora and organic acids	Concrete erosion	2	3	2	2	2	11
Overgrown vegetation	Overtaking space	2	2	2	2	2	10
	Blocking windows	2	2	2	2	2	10
	Cascading branches	2	2	2	2	2	10
	Technical features obstruction (e.g., drip grooves, pipes)	2	2	3	3	2	12

Table 3.4-1 Expert assessment of damage causes and severity in Greenery-Covered Buildings (Structural Performance) (Vanian et al. 2025)

Greenery-Covered Buildings – Structural Performance		Levels					Total
Causes of Damages	Damages	EO1	EO2	EO3	EO4	EO5	
Additional weight and stresses (plants/planting media)	Potential instability issues (e.g., reinforced concrete planting balcony)	1	2	3	2	2	10
Fire	Structural integrity	3	3	3	3	3	15
	Burned materials	3	3	3	3	3	15
	Collapse	3	3	3	3	3	15
Wind	Structural integrity	2	3	2	3	3	13
	Cracks	2	1	2	3	3	11
	Collapse	3	3	2	3	3	14
	Blown out	2	2	2	3	3	12
	Debris	3	2	2	3	3	13
Earthquake	Structural integrity	3	3	3	3	3	15
	Cracks	3	3	3	3	3	15
	Collapse	3	3	3	3	3	15
	Spalling	3	3	3	3	3	15
	Instability	3	3	3	3	3	15

EO = Expert Opinion.

Table 3.4-2 Cont. of Table 3.4-1

Greenery-Covered Buildings		Levels					Total
Greenery Performance							
Causes of Damages	Damages	EO1	EO2	EO3	EO4	EO5	
High level of moisture (due to evapotranspiration)	Pests	3	3	3	3	3	15
	Degradation of planting media	3	3	3	3	3	15
Low level of moisture (due to watering/irrigation systems)	Plant stress	3	3	3	3	3	15
	Dry vegetation	3	3	3	3	3	15
	Dead plants	3	3	3	3	3	15
	Wilting	3	3	3	3	3	15
	Gaps	3	3	3	3	3	15
	Degradation of planting media	3	3	3	3	3	15

Table 3.4-3 Expert assessment of damage causes and severity in Greenery-Covered Buildings (Greenery performance) (Vanian et al. 2025)

Greenery-Covered Buildings		Levels					Total
Greenery Performance							
Causes of Damages	Damages	EO1	EO2	EO3	EO4	EO5	
Improper maintenance	Overgrown vegetation	3	3	3	3	3	15
	Dead biomass	3	3	3	3	3	15
	Bio debris	2	3	3	3	3	14
	Gaps	2	3	3	3	3	14
	Degradation of planting media	3	3	3	3	3	15
	Loss	3	3	3	3	3	15
	Compaction	3	3	3	3	3	15
Inadequate space	Distorted vegetation growth	2	2	3	2	2	11
Environmental stressors (harsh sunlight, strong wind)	Plant stress	3	3	3	3	3	15
	Dehydration	2	3	3	3	3	14
Fire	Burnt vegetation	3	3	3	3	3	15
Wind	Uprooting	3	3	3	3	3	15
	Mechanical stress	3	3	3	3	3	15
	Dehydration	3	3	3	3	3	15
	Reduced plant growth rate	3	2	3	3	3	14
	Wilting	3	3	3	3	3	15
	Bended trees	3	3	3	3	3	15
	Falling bio debris	3	2	3	2	2	12
Earthquake	Planter anchorage and instability	3	3	3	3	3	15
	Tree pot anchorage and instability	3	3	3	3	3	15

EO = Expert Opinion.

Table 3.4-4 Cont. of Table 3.4-3

3.5 APPLICATION OF RETROFITTING

Before any strengthening work, the structure must be properly prepared to ensure effective retrofitting. This includes cleaning the surfaces, using primer, rounding corners and introducing seismic joints where needed. These preparation steps are essential to achieve proper bonding, durability and overall performance of the strengthening system.

Furthermore, the application of retrofitting must follow the specifications provided by the relevant regulations used (EC8-Part 3, KANEPE, CNR DT-200 etc.) and the instructions of the material manufacturers.

A detailed description of the approach used will be provided in the Annex, illustrated with an example of the tested vertical forest structure.

3.6 APPLICATION OF VF SCHEME

Protection against falling

When planning and installing vertical forest systems, the safety of workers and installers must be a top priority. Health and safety measures should be included from the early planning and tendering stages. Special care is needed to prevent falls during construction, but also maintenance and servicing activities. Suitable safety measures may include barriers, rope anchorage points, permanent lifts with fall protection and controlled access points.

4 MONITORING SYSTEM FOR THE RENOVATED VF STRUCTURE

A structural health monitoring system is proposed to be developed for the VF structure, using PZTs. Real-time monitoring of vertical forest (VF) concrete structures can be achieved using piezoelectric transducers (PZTs). These sensors enable early detection of seismic damage by integrating into structural health monitoring (SHM) systems.

The method relies on the Electro-Mechanical Impedance (EMI) approach, where PZT patches can act both as actuators—inducing vibrations in the structure—and as sensors—measuring changes in electrical impedance caused by structural response. This dual function makes them highly effective for identifying local damage, even in complex reinforced concrete elements. The EMI-based sensing approach has proven to be an effective tool for continuous damage monitoring in both newly built and in-service structures. A key benefit of this method is its high sensitivity to localized damage, even in structures with complex geometries (Na et al., 2018; Sam-Daliri Na et al., 2018, 2021) and in composite materials (Voutetaki et al., 2022; Naoum et al., 2023).

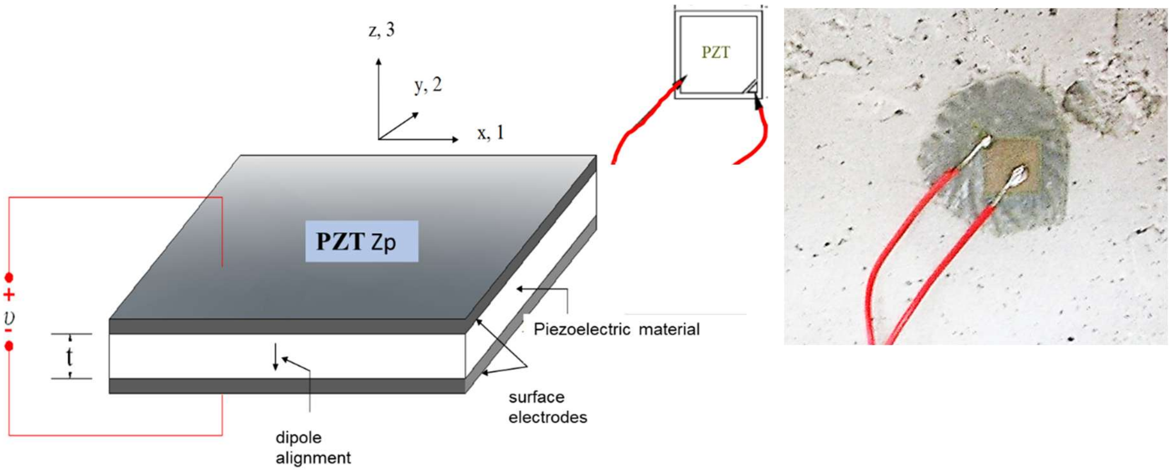

Figure 3.6-1 PZT connected using wires

PZT-based SHM has been successfully applied in beams, frames, and joints under various loading conditions, demonstrating high sensitivity to damage progression. By embedding "smart aggregates" during construction, sensors can be placed in critical regions such as beams, columns, and slabs, ensuring continuous tracking of structural behavior and improving safety in vulnerable buildings.

PZT patches can be installed at multiple points to monitor the structural condition of the renovated 3D VF model. The application of the PZTs is also used to assess retrofit effectiveness and the impact of the vertical forest elements on the RC structure. The PZT measurements can confirm that the SHM system can identify variations in structural condition at multiple points following.

A schematic view of the linkage between the custom device, the embedded PZT sensing actuators, and the host structure is presented in Figure 4-1.

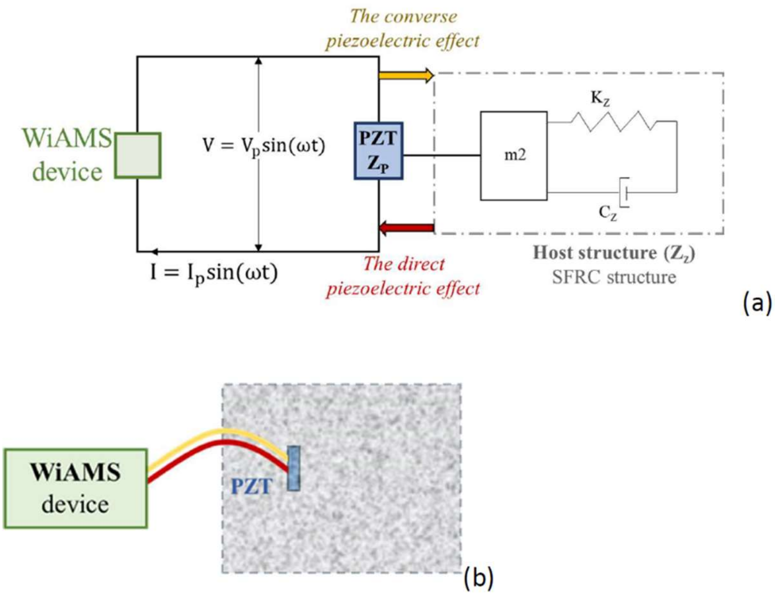

Figure 3.6-2 (a) Schematic of the electrical circuit in one-dimensional electromechanical impedance PZT-structure coupling system and (b) connection between the custom-made device the embedded PZT and the host structure, circuit

The PZT sensors can be bonded with the concrete surface with the following materials:

Surface Epoxy-Bonded PZT Patches

Epoxy-Inclined PZT Patches in Grooved Notches

Cement Paste-Coated PZTs

Quantitative assessment of damage

In the proposed monitoring framework, the damage assessment will rely on using the Root Mean Square Deviation (RMSD) indicator, a metric widely recognized for its robustness and effectiveness in Structural Health Monitoring (SHM). RMSD quantifies changes in electromechanical impedance (EMI) responses by converting differences between reference (undamaged) and damaged states into a single numerical measure.

$$\mathrm{RMSD} = \sqrt{\frac{\Sigma_1^{\mathrm{M}}\left(\left|V_p(f_r)_D\right| - \left|V_p(f_r)_0\right|\right)^2}{\Sigma_1^{\mathrm{M}}\left(\left|V_p(f_r)_0\right|\right)^2}},$$

In this expression, $Vp_{(fr)0}$ corresponds to the voltage response of the PZT transducer in the undamaged reference state,, while $Vp_{(fr)D}$ denotes the voltage response under a damaged condition. The parameter M refers to the total number of frequency sampling points within the analyzed range, and r represents the index of each discrete frequency step.

To complement these indices, a data quality threshold is proposed to evaluate the reliability of each PZT patch. The Upper Control Limit (UCL) can be used as a quantitative boundary for acceptable baseline measurements. Any index value exceeding this threshold may be considered indicative of potential abnormal behavior or damage within the sensing region of the patch.

The procedure typically involves collecting a set of consecutive measurements from each sensor while the structure is in its pristine (undamaged) state. These baseline measurements are then used to compute the UCL, expressed in the equation below, where μ is the mean of the baseline data and σ is the corresponding standard deviation.

$$\mathrm{UCL} = \mu + 3\sigma$$

5 DAMAGE RISK MANAGEMENT

Greenery-covered buildings, while offering many environmental and social benefits, are also exposed to specific risks that can lead to both reversible and irreversible damage. These damages can affect the vegetation itself as well as the structural elements of the building, particularly if proper maintenance and design considerations are lacking.

Structural Concerns

The main structural challenges include wall and foundation integrity, excess moisture, mold growth, and concrete erosion. Plant roots, especially from climbing species or trees planted too close to buildings, can exploit cracks and weaknesses in façades and foundations, leading to fissures or instability. While modern foundations are often resilient to root intrusion, older or poorly maintained structures are more vulnerable. Roots may also obstruct underground services, such as drainage systems.

Concrete balconies used for planting areas in vertical greenery systems are subject to additional stresses, bearing the weight of soil, vegetation, and irrigation water. Over time, microbial activity and root growth can accelerate concrete deterioration, highlighting the need for ongoing safety checks.

Moisture and Mold

High levels of irrigation, combined with natural evapotranspiration, increase humidity around plant-covered walls. Poorly managed watering systems or climbing plants that obstruct drainage can lead to water infiltration, dampness, and mold development inside the building. In some cases, surfaces remain constantly moist, preventing evaporation and causing plaster damage or accelerated material decay.

Additional Risks

The weight of vegetation, particularly in large-scale vertical forests, poses another design consideration. Without sufficient structural support, façades may suffer from cracking or detachment. Maintenance also plays a critical role: neglected greenery can exacerbate these problems, while well-maintained systems can mitigate risks and even protect exterior surfaces from UV radiation, rain, and temperature fluctuations.

In summary, damages to greenery-covered buildings arise from the interaction of vegetation with building materials, inadequate drainage, increased humidity, and additional structural loads. Effective design, robust construction, and consistent maintenance are essential to prevent these risks and ensure long-term safety and durability.

Vegetation Degradation in Greenery-Covered Buildings

Beyond the structural risks to buildings, the vegetation itself is also prone to deterioration. Plants in elevated systems require consistent irrigation; poor watering practices or unsuitable irrigation design can lead to stress, wilting, and eventual plant loss, creating biodebris. Limited soil volume and root space further restrict healthy growth, often resulting in distorted or weakened vegetation, particularly in trees that need sufficient space for roots and branches to expand.

Environmental stressors such as pollution, strong sunlight, and high wind exposure further compromise plant vitality. Vegetation on high-rise balconies is especially vulnerable, as greater elevation increases exposure to fluctuations in temperature, radiation, and wind. While trees on balconies can alter wind flow around the building, strong or frequent winds may cause mechanical damage, increase transpiration losses, and dry out plant tissues and soil.

Tree stability in these conditions is another challenge. Soil within planting containers may weaken during heavy rain, making uprooting more likely when combined with strong winds. Without proper structural and horticultural management, these factors reduce plant longevity and compromise the effectiveness of greenery systems.

Planting Media Damages

Damage to planting media primarily involves loss of substrate, compaction, and failures in irrigation systems. Poor selection of planting materials, inadequate maintenance, and material aging can lead to significant degradation of the growing medium. Similarly, the performance of irrigation systems can be compromised by improper flushing frequency, low-quality water, or unsuitable water sources, resulting in dry vegetation, plant mortality, and gaps in plant coverage.

Fire Risk in Vegetation-Covered Buildings

Incorporating abundant organic materials such as vegetation onto building façades introduces an inherent fire risk. This necessitates strict compliance with building codes, installation of fire suppression systems, and proper vegetation management. Poor maintenance or inadequate irrigation can lead to plant desiccation, increasing susceptibility to ignition and accelerating vertical fire spread. Low moisture levels heighten the risk of flashover and raise both thermal hazards and smoke toxicity. Overgrown vegetation can form fuel ladders, enabling fires to spread to higher floors and potentially between adjacent structures.

Experiments testing different plant species at varying moisture levels show that healthy vegetation has limited heat release upon ignition, but the heat release rate rises sharply as moisture content drops. A full-scale fire test on a high-rise green façade showed no fire crossing storey boundaries; climbing plants above the fire level remained unaffected. This was aided by 1.60 m horizontal concrete projections at ceiling levels, which acted as fire barriers. Plant boxes filled with climbing vegetation were installed at each level, helping to contain fire spread.

Factors such as plant moisture content, density, and wind conditions strongly influence fire behaviour. Beyond plants, other materials used in green façade systems — including insulation, waterproofing membranes, protection boards, root barriers, and drainage layers — can also affect fire safety if not properly maintained. The use of combustible materials such as plastics, rubber, or wood for structural stabilization further increases fire risk. Moreover, the gap between the green façade and the building can create a chimney effect, enabling fire to spread upward more rapidly.

In the event of a fire, vegetation-covered façades may obstruct evacuation routes and hinder firefighter access. The vertical orientation of green systems can facilitate fast upward fire propagation if not carefully designed and maintained. Therefore, selecting appropriate plant species, using fire-resistant materials, and ensuring regular irrigation and maintenance are critical for reducing fire risk.

Prevention Measures per Risk

Humidity and Structural Integrity

To prevent moisture damage and structural issues, use Portland cement in mortars rather than lime, especially for retrofits. Consider vegetation weight and additional water load when designing structures. Lightweight materials such as recycled plastics reduce load, while selecting non-invasive root species and installing root barriers protects walls from root penetration. Pre-existing damp issues should be resolved before planting, as vegetation slows wall drying. Well-built, crack-free walls with proper ventilation are best suited for greening systems.

Building Retrofitting

Retrofitting for green roofs requires adjusting roof edges to accommodate additional layers, with care taken for historic structures. Structural modifications must minimize impact on existing loads. For façades, careful drilling and non-invasive anchorage ensure stability. Proper sizing of drainage and downspouts, as well as accessible maintenance points, are essential for durability.

Fire Safety

Fire risk must be managed through vegetation selection, irrigation, and maintenance. Avoid excessive dry biomass, trim vegetation regularly, and maintain moisture levels. Use plant species with low flammability and ensure compliance with fire safety regulations. Incorporate fire suppression systems and safe evacuation routes.

Maintenance

Design greenery systems for easy access, replanting, and care. Choose hardy species suited to the microclimate, requiring minimal irrigation and maintenance. Proper planning of irrigation and fertilization reduces upkeep costs and plant stress.

Safety

Prevent falls by positioning vegetation away from edges or installing protection systems. Ensure safe access for maintenance crews. Fall prevention must be integrated into the design, especially for rooftop or elevated greenery.

Weather Exposure

Wind load impacts on greenery systems require design adaptations. Use windbreaks, wind-resistant species, and structural supports to prevent tree damage. Securing trees with cables or cages, as in Bosco Verticale, improves stability. Selecting species suited to wind conditions and ensuring safe anchorage reduces risks of uprooting or structural damage.

Damage measures

The selection of appropriate damage measures can be determined by evaluating specific criteria across different buildings and vegetation components. For structural components, this includes metrics such as inter-storey drift ratios, concrete and reinforcement strains, and residual deformations. For the non-structural building envelope and façade systems, measures involve cladding displacement, connector damage, glazing breakage, and loss of airtightness, as well as planter or vegetation module dislodgement. For vegetation and forestry components, key indicators include plant health and vitality, soil stability, and root integrity. Additionally, occupant satisfaction and comfort measures address indoor and outdoor environmental quality degradation, accessibility, safety concerns, and post-event habitat functionality, repairability, or removal obligations. These measures provide a comprehensive framework to define and prioritize damage prevention and mitigation strategies.

Table 5-1 (Vanian et al. 2025) focuses on human welfare and related risks in Vertical Forest and greenery-covered buildings. It identifies common causes of damage, including dead or overgrown plants, high moisture levels, poor maintenance, non-native species, fire, wind, and earthquakes. These issues can lead to a range of impacts, such as reduced aesthetics, lower comfort and utility, higher energy needs, pest problems, decreased sunlight, health risks, safety concerns, and ecological imbalances. They also result in increased repair costs and time. By rating these risks, Table 5-1 can help prioritize maintenance and safety measures, ensuring that both people and the building environment remain safe, functional, and resilient.

Greenery-Covered Buildings		Levels					Total
Human Welfare							
Causes of Damages	Damages	EO1	EO2	EO3	EO4	EO5	
Dead plants	Aesthetics	3	3	3	3	3	15
	Utility	3	3	2	3	3	14
	Energy needs (increased during summer)	3	3	2	3	3	14
Overgrown vegetation	Insects	3	3	3	3	3	15
	Aesthetics	2	2	3	3	3	13
	Energy needs (increased during winter)	2	2	3	3	3	13
	Utility	2	2	3	3	3	13
	Reduced sunlight/view	2	2	3	3	3	13
	Living space occupation	2	2	3	3	3	13
High moisture level	Health issues	3	3	3	3	3	15
	Pests	3	3	3	3	3	15
	Insects	3	3	3	3	3	15
	Mold development	3	3	3	3	3	15
Maintenance	Cost	2	2	3	2	3	12
	Time	2	2	3	2	3	12
	Potential falls	3	3	3	3	3	15
	Work at height	2	3	3	2	3	13
Non-native species	Ecological imbalances	2	2	3	2	3	12
Fire	Safety	3	3	3	3	3	15
	Evacuation obstruction	3	3	3	3	3	15
	Fire vertical propagation	3	3	3	3	3	15
	Chimney effect	3	3	3	3	3	15
Wind	Safety	3	3	3	3	3	15
	Fallen objects/bio-debris	3	3	3	3	3	15
	Turbulence	3	3	3	3	3	15
Earthquake	High repairing cost	3	3	3	3	3	15

Table 3.6-1 Expert assessment of damage causes and severity in Greenery-Covered Buildings (Human Welfare) (Vanian et al. 2025)

6 SOCIETY AWARENESS

Renovating buildings with vertical forests offers notable socio-economic and energy advantages, alongside environmental improvements.

Environmental benefits

These structures enhance air quality by integrating vegetation into façades, balconies, and terraces, which naturally filter pollutants and absorb carbon dioxide. Outdoors, vertical forests capture fine particulate matter and gaseous pollutants such as CO_2, NO_2, and VOCs, reducing pollution and improving urban air conditions. Through photosynthesis, plants sequester CO_2 while releasing oxygen, contributing to climate change mitigation. Indoors, this greening effect extends, improving air quality and promoting healthier living and working environments. The efficiency of pollutant removal depends on plant type, density, and location, with green façades proving especially effective in filtering fine particulates. Vertical forests thus provide a sustainable solution for cleaner air while supporting broader environmental and socio-economic goals.

Urban Heat Island Mitigation

Vertical greenery systems, including vertical forests, effectively mitigate the Urban Heat Island (UHI) effect by shading building surfaces and reducing heat absorption. Vegetation integrated into façades and terraces lowers surface temperatures through shading and evapotranspiration, enhancing the local microclimate. Studies show that such systems can reduce outdoor temperatures by up to 13°C and indoor temperatures by over 2°C, decreasing cooling demands and lowering CO_2 emissions. By improving thermal comfort and energy efficiency, vertical forests contribute to creating cooler, more sustainable urban environments while supporting biodiversity and reducing reliance on artificial cooling systems. Effective design and maintenance are essential to maximizing these benefits and minimizing potential drawbacks such as reduced wind flow at ground level.

Rainwater Management

Vertical green structures play a vital role in sustainable stormwater management by capturing, retaining, and gradually releasing rainwater, mimicking natural hydrological cycles. Vegetation integrated into façades and roofs absorbs rainfall through leaves, stems, and soil, reducing surface runoff and alleviating pressure on urban drainage systems. This process also filters pollutants, improving water quality before it enters waterways or aquifers. Combined with rainwater collection systems, vertical greenery supports water conservation and flood mitigation while enhancing urban aesthetics. Strategic integration of these systems with other sustainable solutions, adapted to local conditions, strengthens urban resilience by addressing stormwater challenges and contributing to long-term sustainability.

Sewage Treatment

Integrating sewage treatment with vertical green buildings offers an innovative approach to sustainable urban water management. Vegetated façades and green roofs can treat and recycle greywater, reducing potable water demand and alleviating pressure on conventional wastewater systems. Through biological filtration, plants and engineered substrates remove nutrients, organic pollutants, and pathogens, improving effluent quality. Selecting suitable plant species enhances system efficiency while minimizing water loss. These systems can reuse treated water for irrigation and other non-potable purposes, contributing to water conservation and expanding urban green space. By combining ecological benefits with wastewater management, vertical greening systems present a replicable and sustainable solution for urban sewage challenges.

Enhancement of Urban Biodiversity

Biodiversity plays a vital role in sustaining ecosystem services, supporting human health, and enriching urban life. In cities, biodiversity exists largely within green infrastructure such as parks, gardens, green corridors, and waterways, which help protect and connect habitats. However, rapid urbanization threatens biodiversity, making innovative strategies essential to preserve and enhance urban ecosystems.

Vertical greening systems — such as green walls and vertical forests — present an effective solution. These structures integrate diverse plant species into urban architecture, creating habitats for birds, insects, and other fauna while contributing to ecological connectivity. Milan's Bosco Verticale, for example, integrates over 1,600 plant species into its façade, fostering habitats and enhancing the city's ecological richness. Such vertical forests optimize space in dense urban areas, creating green corridors that support species movement and ecosystem resilience.

Beyond habitat creation, vertical greening delivers crucial ecological services: reducing the urban heat island effect, improving air quality, filtering rainwater, and providing shade to lower energy consumption. Native plantings further enhance ecological value by attracting pollinators and supporting local wildlife. By combining environmental, aesthetic, and infrastructural benefits, vertical greening emerges as a powerful tool to sustain biodiversity, promote environmental awareness, and improve urban quality of life.

Energy Efficiency

Vertical green buildings are increasingly valued for their contribution to energy efficiency and sustainable urban development. Green walls and roofs serve as natural insulation systems, reducing energy consumption for heating and cooling while mitigating the urban heat island effect and improving indoor environmental quality.

In high-rise buildings, especially in hot climates, vertical greening creates microclimates through shading and evapotranspiration, lowering building temperatures and regulating humidity. Studies have shown that green walls often provide greater annual energy savings compared to green roofs, thanks to enhanced thermal insulation and improved access to natural lighting. This results in reduced reliance on artificial cooling and lighting, thereby lowering energy use and associated emissions.

Beyond energy savings, vertical greening supports broader ecological functions such as biodiversity enhancement and stormwater management. Integrating renewable energy technologies—such as solar panels or wind turbines—into green building designs can further enhance sustainability, reducing dependence on conventional energy sources. However, challenges remain, including higher costs and maintenance needs. The use of passive and active energy-saving strategies tailored to local climate conditions can maximize the benefits of vertical greening systems.

By combining ecological performance with energy conservation, vertical green buildings represent a transformative approach to sustainable architecture. As technology advances, such systems are poised to play a pivotal role in reducing urban energy demands and supporting resilient, low-carbon cities.

Thermal Regulation

Green walls have substantial benefits regarding thermal control by reducing the surface temperatures of buildings via various mechanisms such as shading and moisture release. The succulent species, such as Sedum album and Sedum sediforme, cool the surrounding atmosphere even more efficiently because of the higher rates of evaporation. These cooling effects contribute to reducing the urban heat island effect and make the urban areas more pleasant by subsequently reducing energy use associated with cooling (e.g. Kuronuma and Watanabe 2017).

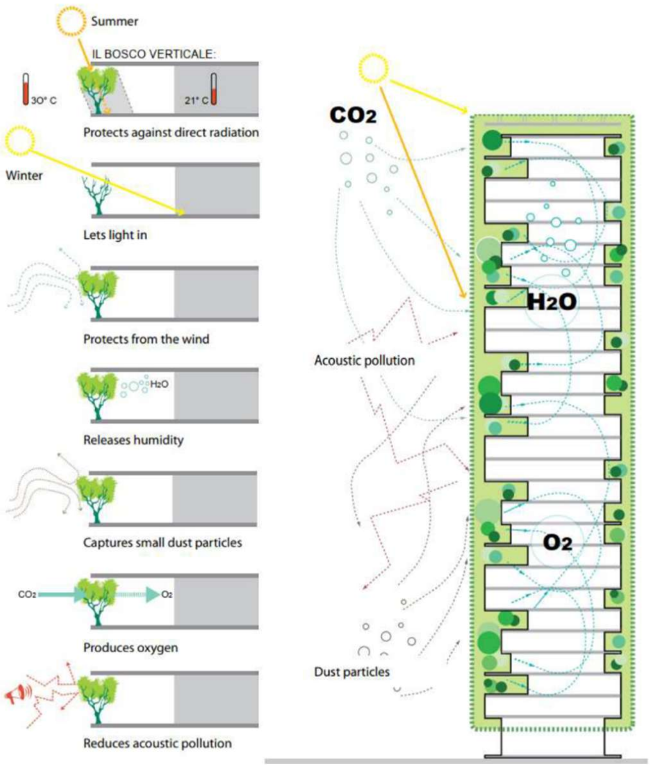

Figure 3.6-1 The life cycle concept in Bosco Verticale ©Stefano Boeri Architetti (Source Giacomo Di Ruocco)

Social Benefits

Psychological Effects and Human Happiness

With growing urbanization, open green spaces are shrinking, leading to innovations such as vertical green buildings and forests. These structures offer environmental benefits and enhance psychological well-being by reducing stress, improving mood, and fostering a sense of calm through the biophilic connection between humans and nature.

Vertical greenery also promotes social interaction, transforming unused urban areas into community spaces, especially valuable in densely populated cities. Access to natural elements has been shown to improve focus, creativity, and productivity, particularly in workplaces and schools.

However, human responses vary — poorly maintained greenery can cause apprehension, while well-designed vertical structures foster mental restoration. Gender differences also emerge, with women generally reporting stronger emotional benefits. Vertical greenery further improves perceived safety, enhancing residents' comfort and overall quality of life.

Noise Reduction

Urban areas suffer from high noise pollution, impacting health and quality of life. Vertical green buildings help reduce noise by acting as natural sound barriers. Plants and substrate layers absorb and scatter sound waves, lowering noise intensity and creating quieter, more pleasant environments.

The effectiveness of noise reduction depends on vegetation type, plant diversity, substrate thickness, and design placement. Vertical greenery can also transform soundscapes by adding natural sounds, such as rustling leaves or birdsong. When combined with well-planned, dense green spaces, vertical greening offers a powerful solution for mitigating urban noise while enhancing aesthetics and sustainability.

Economic Benefits and Importance

Protection of Building Structure:

Vertical greenery (green walls and roofs) improves building durability by providing thermal insulation, reducing temperature changes, and protecting against UV radiation and precipitation. This extends material lifespan, enhances energy efficiency, mitigates the urban heat island effect, and promotes sustainability. Challenges include higher costs and maintenance needs, requiring innovative, cost-effective solutions for wider adoption.

Branding and Marketing:

Vertical green buildings boost branding opportunities for developers and cities by showcasing environmental responsibility. Sustainability certifications (e.g., LEED, BREEAM) enhance market value and differentiate projects. Effective marketing should highlight unique ecological benefits and lifestyle enhancements. Strategic placement in prominent locations increases visibility, while educating consumers on sustainability helps drive acceptance and positions these buildings as competitive, eco-friendly developments.

7 GENERAL CONCLUSIONS

Open, customizable, advanced hybrid platform for continuous health monitoring, redesign upgrade, live demonstration, wholistic integration of design guidelines

Based on the developments of D26, D32, D41 and of this report D51, GREENERGY offers a unique open, customizable and integrable hybrid platform that may combine real time sensor records from advanced dynamic experiments (D25, D26), from advanced digital twin analyses (D32, D41) and from advanced energy-forestry-thermal comfort related analyses at building or district level etc (D51). It proves the innovative hybrid platform concept as well as real time data collection to interact with digital twin (hybrid). It provides the framework for suitable carbon neutral structure renovation with green materials and suitable green building envelopes such as vertical forest planters with trees and vertical living walls (VF). VF leads in some investigated scenarios to advanced energy savings and high quality micro-climate (D51). All these aspects may be integrated in the open advanced hybrid platform and allow for future optimization scenarios. GREENERGY contributes to increased share of green reusable and recyclable (basalt ropes etc) construction materials in building renovation (to contribute to circular economy). 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. The findings and feedback in report D62, further suggest that scientific, student, designer, construction and general public community as well as policy makers, urge for frameworks for advanced structural-environmental-quality of life for next generation buildings renovations. Advanced continuous structural health monitoring may significantly contribute in the reliable support of major decision making towards community resilience.

ANNEX: EXAMPLE OF RENOVATED VF STRUCTURE – DESIGN AND RETROFITTING PROCEDURE

An example of a renovated vertical forest (VF) structure was designed, retrofitted accordingly and experimentally tested at the DUTH laboratory. This Annex describes the renovation project, including the preparation, testing procedure, and safety measures. It highlights the benefits of VF renovations, including the addition of vertical forest elements that enhance ecological performance, improve urban environmental quality, and contribute to social well-being and urban aesthetics. Moreover, it provides a checklist before each experiment, along with safety and experiment-conducting protocols that were and must be followed.

The structural features of the as-built and renovated 3D models, including retrofits with basalt rope wrapping, PUFJ joints, and GFRPU jacketing, are presented. Monitoring systems, including draw-wire sensors, accelerometers, displacement meters, strain gauges, and PZT sensors, were used to capture both structural and greenery behavior during dynamic testing.

Vertical forests and green walls enhance buildings by improving environmental performance, air quality, carbon capture, and urban aesthetics. They are classified as extensive systems, supporting small drought-tolerant plants, or intensive systems, which host larger plants like shrubs and small trees, requiring stronger structures and more maintenance.

This project focuses on renovating vertical forest systems in Greek urban areas, proposing a framework for integrating them into existing RC buildings to support sustainability and urban livability. Retrofitting introduces challenges such as additional loads, maintenance needs, irrigation requirements, and safety concerns, especially in seismic or high-wind areas. Proper material selection, plant choice, and early design integration are essential for durability, energy efficiency, and occupant safety.

Structural and safety aspects were analyzed using Monte Carlo simulations and hazard assessments, highlighting the importance of reinforcement, monitoring, and tailored maintenance. Overall, the project develops strategies to balance structural integrity, ecological benefits, and aesthetics, making buildings safer, greener, and more resilient.

Description of the experimental procedure

The specimen was built at a 1:3 scale, representing a one-bay, single-storey reinforced concrete building with a 20 cm thick slab, four columns, four foundation beams, and four brick infill walls, with a total weight exceeding 5 tons. The structure reflects older RC design standards, featuring limited column reinforcement and low-strength brick infills with weak mortar joints.

For handling, Φ12 mm steel loops were installed at four points on the top slab near the supports, through which straps formed a lifting system. Using the laboratory's overhead crane, the specimen could be lifted, placed, and removed in parallel with the seismic table, ensuring the foundation beams touched or left the table simultaneously, avoiding undue stress. Predetermined alignment allowed Φ20 cables to pass through the foundation beams and bolt to the table (two per beam end, 16 total). Before each test, the cables were loosened and the specimen lifted slightly to prevent unwanted vibrations, then lowered and secured once the table pump stabilized. For safety, the crane remained attached without load, preventing equipment damage in case of collapse.

Instrumentation included embedded PZT sensors in the concrete elements, strain gauges on the longitudinal reinforcement of columns, 3D accelerometers on the slab, beams, and infill walls for out-of-plane motion, and draw-wire displacement meters for in-plane slab and wall movements. Dynamic testing simulated the 1978 Thessaloniki (Volvi) earthquake using the ANGO control program, which allowed gradual scaling of motion from reduced amplitudes to real earthquake levels and beyond.

This setup enabled detailed experimental evaluation of retrofitting strategies combining deficient RC and brick-infilled structures with Vertical Forest concepts, while supporting further analytical research on digital twins and structural health monitoring.

Five recording systems collected data:

- Pacific Recorder – for strain gauges and extensometers
- Roga Recorder – for accelerometers
- GW Instruments Recorder – for additional strain gauges
- Recorder for PZT Piezoelectric Sensors
- Seismic table control software (ANCO-DANCE) – for displacement and acceleration data

All recorders were synchronized with internet time and set to the same sampling frequency to ensure consistent data.

Each EQ excitation lasted about 30 seconds. An additional 10-second pause was included to capture any remaining oscillations in the specimen. The recorders then stopped, and all files were saved.

The seismic table system also received additional feedback from the sensors after each motion to confirm performance.

Strengthening and Renovation procedure

A detailed overview of the design, detailing, and instrumentation of the VF-renovated 3D structure is presented. The retrofit included lightweight basalt fiber rope reinforcement of RC columns, PUFJ seismic joints between columns and brick infill walls, and external jacketing of cracked infill walls with GFRPU.

<u>Materials and Methods used:</u>

- *Polyurethane on masonry to column joints*

- *Glass grid on wall facades*

- *Basalt rope on critical areas of column (green retrofitting)*

More specifically, the following materials are used and tested:

Polymer for PUFJ (PolyUrethane Flexible Joints) was of type Sika PM. The elastic modulus, strength and ultimate elongation of the polymer are 4 MPa, 1.4 MPa and 110%, respectively.

Polymer for FRPU (Fibre Reinforced PolyUrethane) was of type Sika PS. The elastic modulus, strength and ultimate elongation of the polymer are 16 MPa, 2.5 MPa and 40%, respectively.

GFRP (Glass Fiber Reinforced Polymer) mesh of type Sika Wrap 350G Grid, made of glass fibre reinforced polymer mesh. The mesh has a real weight 360 g/m^2, elastic modulus of 80.000 MPa, strength and ultimate elongation of the glass mesh 2.600 MPa and 4%, respectively.

<u>Preparation (of concrete substrate and joint gaps)</u>

A structural gap shall be introduced between the columns and the adjacent masonry to allow for the wrapping of the columns with basalt rope. The gap width may vary along the column height, typically ranging between 0.025 m and 0.02 m.

To prevent stress concentrations, the column corners shall be rounded prior to reinforcement. Continuous basalt rope shall then be applied around the column sections to enhance concrete confinement, while an additional layer will be provided to ensure proper self-anchorage of the wrapping system.

Any brick holes must be filled with compatible low strength materials (such as foam or mortar) to prevent PU leakage or unnecessary PUFJ consumption increase. The surfaces of concrete columns are grinded and receive primer resin. Similarly, the brick infill receives the primer. Molds should then be accurately positioned along the joint, and polyurethane (PM) must be injected to completely fill the space. Given its rapid curing characteristics, the polyurethane must be applied promptly to ensure proper placement before undesirable solidification.

Installation of fiberglass grid on masonry

Prior to grid application, the masonry must be thoroughly cleaned. A layer of primer should then be applied, followed by a base layer of PS polyurethane. The reinforcing grid is subsequently positioned onto the treated surface and fully embedded with an additional layer of PS polyurethane to ensure proper adhesion and coverage. Based on the viscosity of the PU PS with time, the resin may be easily applied with a trowel or spatula.

Additional vertical forest renovations were incorporated, featuring eight structures that simulate typical vertical living walls, including traditional bottom supports and innovative top-support detailing using PU pads and basalt ropes to reduce adverse interaction with the concrete frame. Five concrete planters with wooden sticks represent heavier tree greenery on slabs and balconies, allowing evaluation of different anchoring methods using traditional or basalt rope anchors and PU pads. These cases examine innovative green envelope solutions compared to traditional designs and the results were thoroughly described in §3.2.1.

Monitoring

Instrumentation, including draw-wire sensors, accelerometers, displacement meters, strain gauges, and PZT sensors, was employed on both the as-built and renovated structures.

The PZT sensors employed were FLAB-5-11-3LJC-F. This sensor array utilized the electromechanical impedance (EMI) technique to measure high-frequency structural responses, enabling the identification of the initiation and propagation of localized damage. The system operated with a capture resolution of 1 kHz, covering a frequency range from 10 to 250 kHz.

The bond between the PZT and each surface was accomplished by:

- PZT patch epoxy-embedded as SAs suspended by steel wire during concrete casting to maintain the designed position in columns
- Use of resin for the bond on the basalt rope's surface

On the as-built configuration, the VF concrete structure was fitted with PZTs embedded as sensing actuators. These sensors were placed inside the mold prior to casting, with each one oriented toward areas expected to experience future flexural demands. PZTs were arranged along the length of the beams and columns and installed in an array within the slab to monitor the structural response of the upper region under loading.

Figure 3.6-1 (a) PZT patch epoxy-embedded as SAs suspended by steel wire during concrete casting to maintain the designed position in a column, (b) zoom.

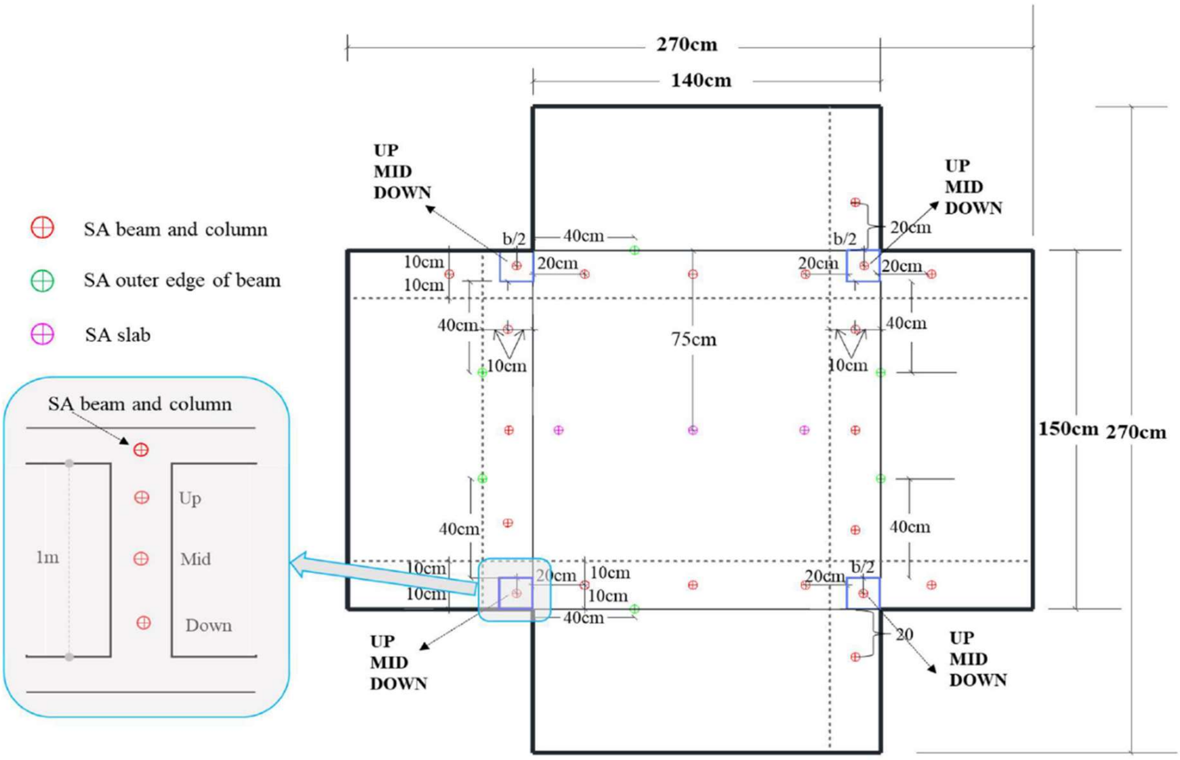

Figure 3.6-2 Designs and photos of detailing and instrumentation of constructed as-built 3d structure and position of the Sas.

For the strengthened VF-renovated 3D structure, draw-wire sensors and accelerometers captured displacements and accelerations of slabs, foundations, and infill walls, while strain gauges monitored the behavior of longitudinal reinforcement and masonry.

PZT sensors, including additional units added for the retrofits and VF installations, provided high-sensitivity detection of damage progression in concrete cores, mortar-brick joints, and the rocking behavior of planters and vertical living walls, ensuring comprehensive monitoring of structural and greenery interactions during testing.

On the renovated 3D VF structure, PZT patches were installed at multiple points to monitor its condition. Two layers of basalt rope were wrapped around the top and bottom of the column to enhance strength. During wrapping, the pre-placed PZT wiring was carefully protected, ensuring the rope was wound tightly and evenly without disrupting sensor performance. This approach strengthens the structure while keeping the PZT system fully functional. The figure shows the rope reinforcement at both ends of the column, applied in a way that shields the PZT patches and their connecting wires.

Figure 3.6-3 Application of the basalt ropes concerning the PZT patches that were already installed in the as-built structure.

The figures below show how the PZT patches were positioned and installed on selected parts of the retrofitted 3D Vertical Forest model. Their arrangement is intended to assess both the performance of the applied retrofits and the structural influence of the vertical forest elements attached to the reinforced-concrete frame.

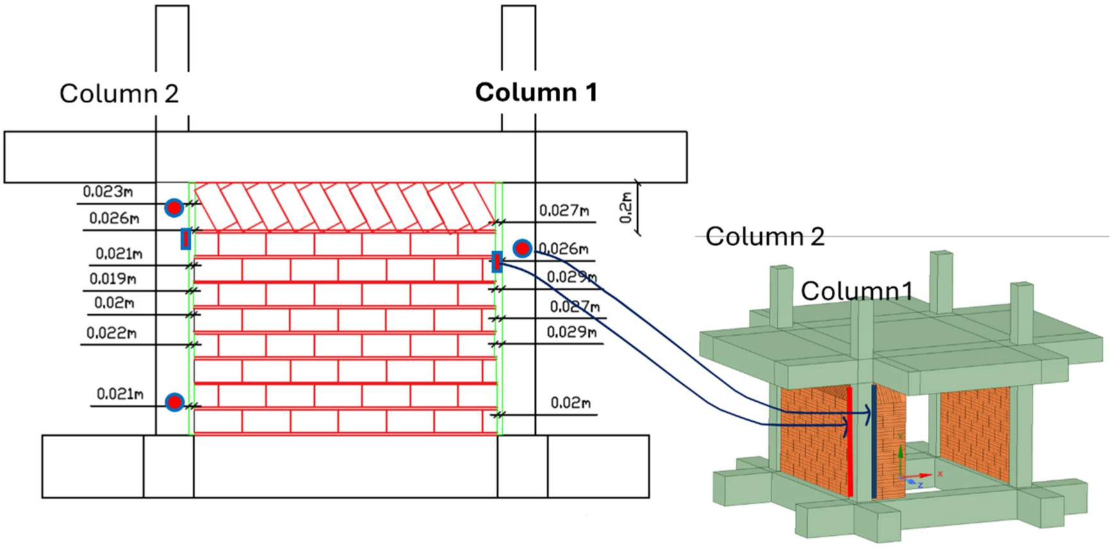

Figure 3.6-4 Location of the PZT patches installed at the surface of column.

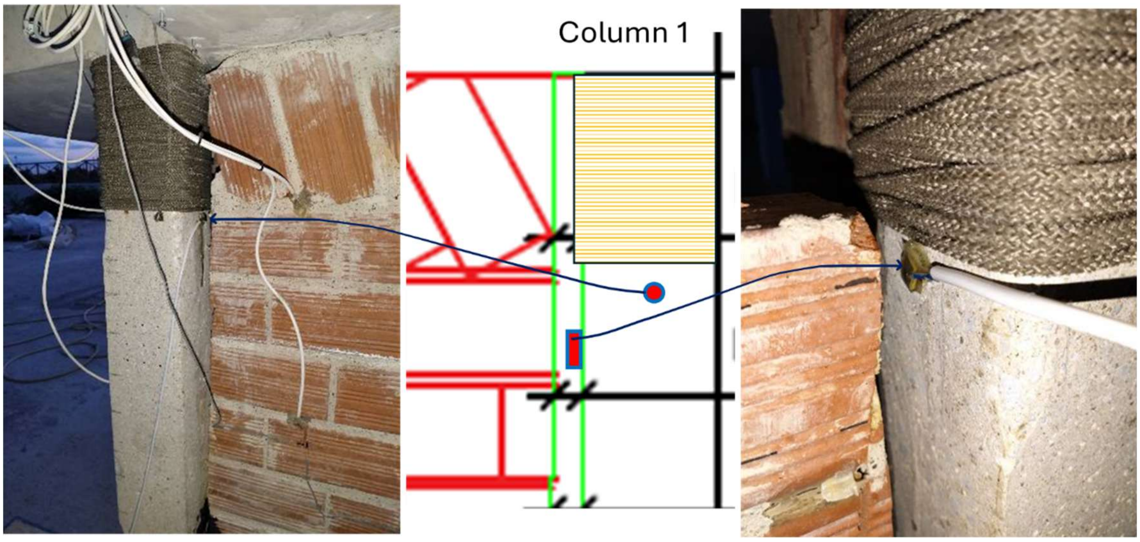

Figure 3.6-5 Details of the PZT patches installed at the surface of RC column.

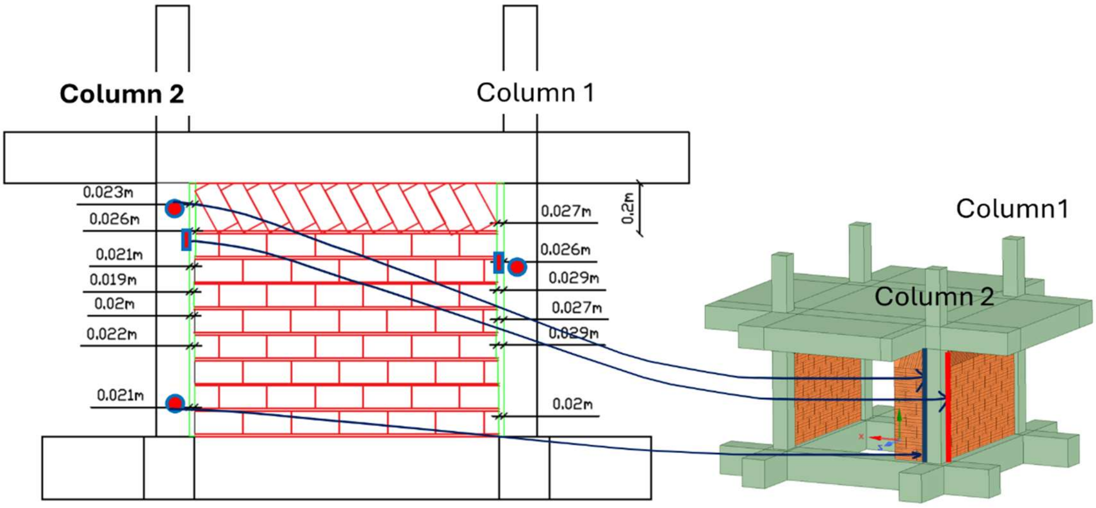

Figure 3.6-6 Location of the PZT patches installed at the surface of column.

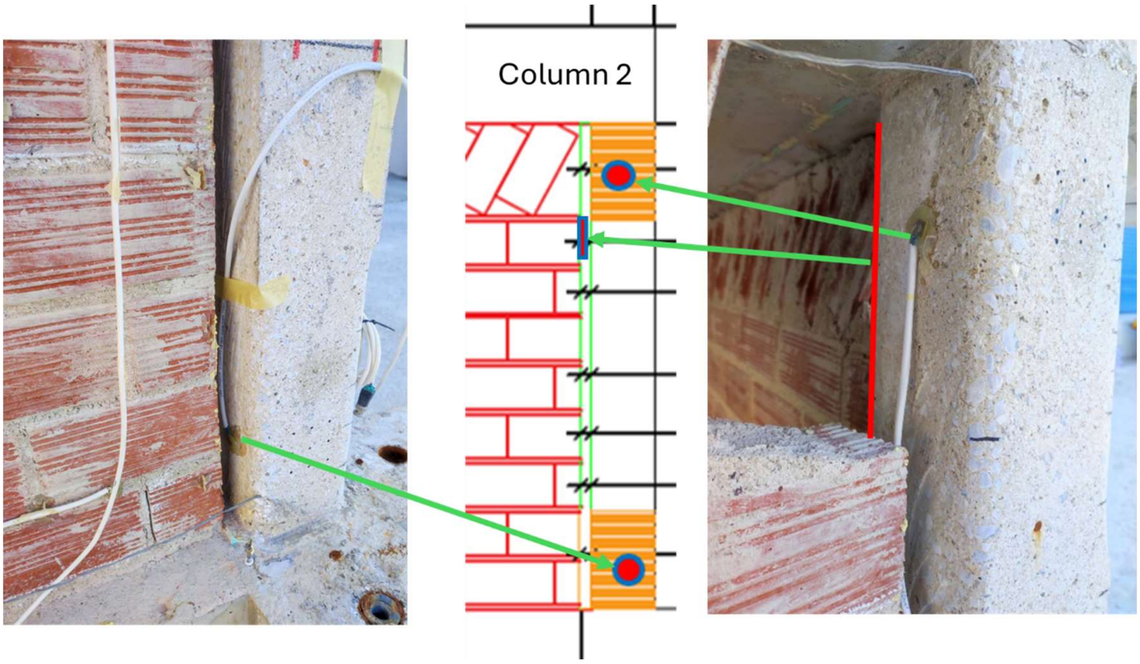

Figure 3.6-7 Details of the PZT patches installed at the surface of column 2 and at the surface of the infill inside the polyurethane.

The following figure shows the basalt rope used to strengthen the columns, along with the PZT patches fixed onto the rope with resin near the bases of Columns 3 and 4.

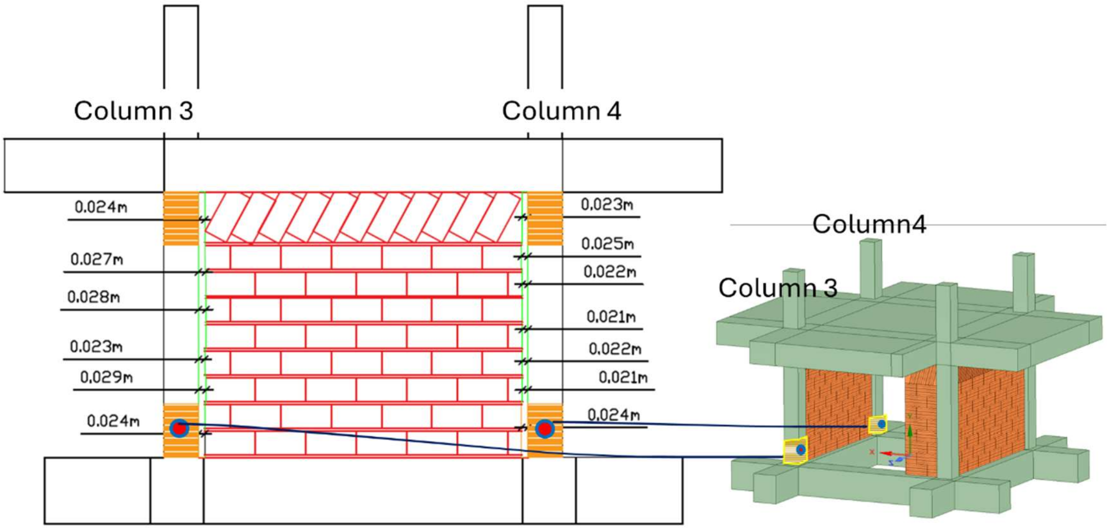

Figure 3.6-8 Location of the PZT patches installed on Basalt ropes using resin at the bottom of columns.

Figure 3.6-9 Details of the PZT patches installed on columns.

The next figure shows where the PZT patches were placed on the basalt rope used to anchor the vertical LW steel assembly within the slab. A hole was drilled to insert the rope, and a slight tension was applied using a specialized steel fixture mounted at the top of the slab.

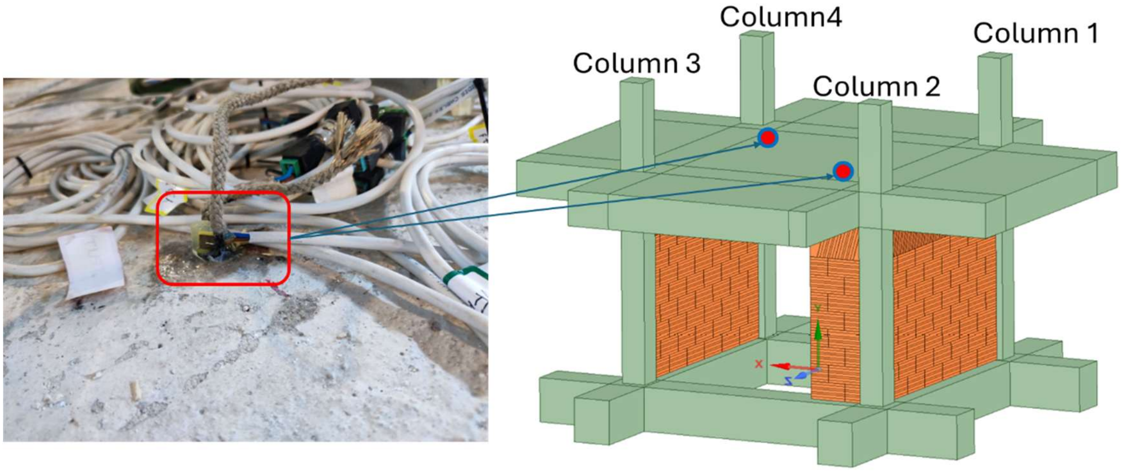

Figure 3.6-10 Location of the PZT patches installed on Basalt ropes using resin on the roof.

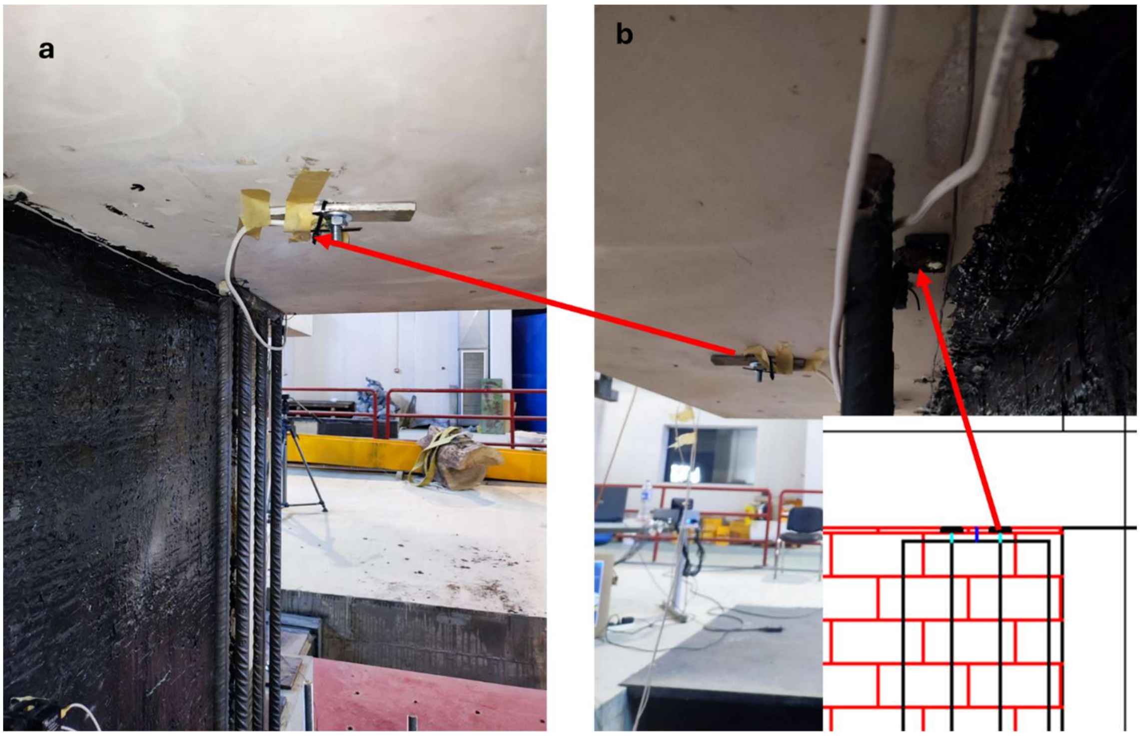

Figure 3.6-11 PZT patches installed on the anchoring of metal structures for the (a) planter and (b) Living wall structure.

Results and Conclusions

The results of seismic tests on both the as-built and VF-renovated structures were presented. In the first phase, the as-built model showed minor cracks in concrete at construction joints and some cracking or partial debonding of the infill walls, while the top slab remained intact. Steel reinforcement stayed below yield, and accelerations and displacement drifts were carefully monitored. PZT sensors captured damage effectively, with readings matching visual observations. Eleven dynamic tests at five earthquake levels provided a solid baseline for subsequent retrofitting.

During the second phase, the VF-renovated structure—including strengthened columns, partial brick infills, living walls, and planters—performed well under severe seismic excitations. Columns displayed ductile behavior, supported by basalt rope wrapping, PUFJ joints, and FRPU jacketing, which redistributed damage and protected the concrete core. Partial infill walls experienced minor cracking and local bottom brick crushing only under extreme drifts, while the FRPU jackets, basalt ropes, and PUFJ joints held firmly. Vertical living walls and planters resisted high accelerations without collapse, showing recoverable performance; minor anchor loosening did not compromise overall stability. Shear tests on masonry triplets confirmed that PS jackets and glass textiles strengthened joints and improved crack resistance.

Overall, the monitoring system—using accelerometers, displacement meters, strain gauges, and PZT sensors—confirmed that the VF renovations and retrofits effectively maintained structural integrity. The structure sustained severe seismic loading with low residual drift, improved stiffness despite added top mass, and high energy absorption. These results demonstrate that VF retrofitting can combine resilience, environmental benefits, and recoverable structural performance in existing buildings.

PROTOCOLS

The following protocols and checking lists were and must be followed.

Experiment Conducting Protocol

Each experimental cycle followed the same sequence of tasks and checks. This reduced the chance of errors, missing data, or problems during the experiment. To carry this out, specific personnel were assigned to fixed roles.

Experimental EQ excitation execution and real-time recording

- Data Acquisition System – Sensor Recorder Operator:

Responsible for supervising the proper function and performance of the sensors and most importantly starting and stopping the recording of sensors' values over time at the beginning and end of each test with the data acquisition system. The recorders had to start before the seismic table moved and stopped a few seconds after it ended. The operator also checked all sensors (extensometers, accelerometers, strain gauges, etc) to ensure they were communicating correctly and fixed any connection problems.

- Audio-Visual recording - Camera Operator:

Responsible for photos and videos. Visual documentation and visual high-speed recording of the movement of each different aruco marker or characteristic structural spot, was important for drawing conclusions about the experiment. Cameras were placed to cover all directions, and recordings had to start and stop together with the main recorders. The operator also checked all aruco marker visibility and areas of special focus. Special care should be given on the focus and zoom functions to achieve highest image quality.

- Seismic Table Operator:

In charge of the seismic table control system. The operator prepared the pumps, activated the cooling systems, and selected the correct earthquake excitation input together with the supervisor. Once everything was ready, the supervisor gave the command to start. During the test, the operator was ready to press the emergency stop if anything unexpected happened. Successive excitations might be required prior to the tests with dummy specimens to achieve the desired table excitation, taken into account the interaction of the mass and stiffness of structure with the table specifications in order to take advantage of the advanced PID closed loop control.

- Supervisor and Assistant:

Responsible for final checks before and after each experiment. They reviewed the checklist, confirmed everything was in order, took care of safety issues for the staff, the systems and the guests and proper system function and gave the command to the seismic table operator, Camera operator and data acquisition system operator to begin. They also monitored the process and could order a stop if necessary. They decide the termination of the tests and the safety of the specimen and additional shoring measures if necessary. They ensure all safe recording and save of all recordings and suitable elaborations of the results to provide meaningful conclusions and decisions for different stakeholders.

- Hybrid platform Supervisor:

Recording of sensors before and after excitations – PZT sensor recording and crucial decision making

- Supervisor:

Responsible for final checks before each recording with respect to safety measures for the WIAMS operator near the specimen as well as for undesirable sounds and vibrations or for the condition of the sensors and of the specimen itself. Estimate the time available for all WIAMS recordings to conclude.

- WIAMs operator

Safety Protocol

During all experimental tests, safety was given top priority. To minimize the risk of accidents and protect both personnel and laboratory equipment, strict rules and procedures were followed.

- Protective Equipment:

All personnel were required to wear helmets, safety shoes, protective glasses, and gloves at all times.

- Use of Equipment:

Only trained staff operated laboratory equipment. During the transport or movement of heavy components, all other personnel stayed at a safe distance.

- Seismic Table Gap Cover:

A gap exists between the moving of the fixed parts of the seismic table. Since preparation and checks took a long time and required staff to work on the specimen for extended periods, this gap was covered during preparation for safety. The cover was removed just before the experiment began and replaced immediately after.

- Lifting Belts:

The belts used for lifting the specimen were designed with a double safety factor. They were positioned so as not to interfere with the specimen's movements during testing, while still preventing equipment damage in case of collapse.

- Collapse Risk:

In the final stages of testing, the risk of specimen collapses increased. For this reason, the lifting belts and safety structures ensured that equipment would be protected, and personnel would remain safe.

- Personnel Positioning:

During every experimental cycle, all personnel (and especially guests) stood at a safe distance behind protective barriers.

Checklist Before Each Experiment:

- Confirm the correct earthquake excitation graph (multiplier) was selected
- Check cameras (brightness, distance, and that recordings were active)
- Remove protective dampers and panels around the table
- Verify specimen anchoring to the seismic table
- Check protective straps for looseness
- Confirm planters and vertical wall specimens were anchored in the correct positions
- Check all sensors were properly attached and working properly
- Ensure all personnel were in standby positions behind the safety barriers
- Ensure, emergency button is active
- Ensure all five persons of the required staff are in place

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