GREENERGY

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

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

Recorded damages to common and VF buildings and lessons learned

Deliverable D1.4 Work package 1

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF DIAGRAMS

LIST OF ACRONYMS

CO_2	Carbon Dioxide
EEA-38	European Environment Agency network, Eionet
ELSTAT	Hellenic Statistical Authority
GHGs	Greenhouse gases
GDP	Gross Domestic Product
PVC	PolyVinyl Chloride
UHI	Urban Heat Island
UN	United Nations
WHO	World Health Organisation

ΠΕΡΙΛΗΨΗ

Η ενσωμάτωση του πρασίνου στον κτιριακό σχεδιασμό έχει γίνει δημοφιλής τα τελευταία χρόνια, και για αισθητικούς, όσο και (κυρίως) για περιβαλλοντικούς λόγους και των περιβαλλοντικών πλεονεκτημάτων που προσφέρει. Ενώ παραδοσιακά λοιπόν το πράσινο στον τομέα της αρχιτεκτονικής εξυπηρετούσε κυρίως αισθητικούς σκοπούς, στη σύγχρονη εποχή, στα κίνητρα για την ενσωμάτωσή του στο κτιριακό σχεδιασμό, περιλαμβάνονται επίσης οικολογικά, ενεργειακά και οικονομικά οφέλη. Σε αυτά μεταξύ των άλλων περιλαμβάνονται η μείωση της ενεργειακής κατανάλωσης, η θετική επίδραση στο κλίμα πλησίον των κτιρίων αλλά γενικότερα στη θερμοκρασία της πόλης, η προστασία από ακραία καιρικά φαινόμενα, η προώθηση της βιοποικιλότητα. Ωστόσο, τα κτίρια που καλύπτονται από πράσινο («κάθετα δάση» αλλά και φυτεμένα δώματα), είναι πιθανό να εμφανίσουν ζημιές και αστοχίες, γεγονός που καθιστά αναγκαία την ενδελεχή μελέτη τέτοιων φαινομένων και των μειονεκτημάτων εν γένει που συνοδεύουν μια τέτοια παρέμβαση.

Τα κύρια μειονεκτήματα που εντοπίζονται σε κτίρια με «κάθετα δάση» περιλαμβάνουν τη στατική επιβάρυνση, τον κίνδυνο εμφάνισης υγρασίας, την ανεπαρκή άρδευση, τις δυσκολίες στην επισκευή και τον κίνδυνο πυρκαγιάς. Η βλάστηση στα «κάθετα δάση» είναι επίσης ευαίσθητη λόγω της διαφοροποίησης των συνθηκών ανάπτυξης σε σύγκριση με τα φυτά που αναπτύσσονται απευθείας στο έδαφος. Η στρεβλή ανάπτυξη και η καταπόνηση των φυτών είναι τα πιο συνηθισμένα προβλήματα. Εκτός αυτού, οι ένοικοι των κτιρίων ενδέχεται να βιώσουν ανεπιθύμητες καταστάστεις, οι οποίες σχετίζονται με την ασφάλεια, την χρήση δικτύων κοινής ωφέλειας, καθώς και το υψηλό κόστος συντήρησης.

Οι μηχανισμοί αστοχίας σχετίζονται κυρίως με σχεδιαστικές αστοχίες, κακές πρακτικές εγκατάστασης και ανεπαρκή συντήρηση. Τα ακατάλληλα δομικά υλικά για την υποστήριξη του πρόσθετου βάρους, η έλλειψη κατάλληλων συστημάτων στεγανοποίησης και η μη προσαρμογή των δομικών και πυροσβεστικών κανονισμών είναι μερικά παραδείγματα. Η μη τακτική επιθεώρηση και επισκευή των συστημάτων αποστράγγισης, καθώς και τα παραμελημένα και ξηρά φυτά επιτείνουν τον κίνδυνο ζημιών. Επιπλέον, η επιλογή ακατάλληλων φυτικών ειδών μπορεί να προκαλέσει ζημιά στη δομή του κτιρίου και να δημιουργήσει νέες προκλήσεις και κινδύνους.

Τα κτίρια που καλύπτονται από «κάθετα δάση» προσφέρουν πολυάριθμα οφέλη, αλλά παρουσιάζουν και συγκεκριμένες προκλήσεις που πρέπει να αντιμετωπιστούν για να διασφαλιστεί η ανθεκτικότητα και η λειτουργικότητά τους. Μια ολοκληρωμένη προσέγγιση που περιλαμβάνει προσεκτικό σχεδιασμό, σωστή εγκατάσταση και επιμελή συντήρηση είναι απαραίτητη για την πρόληψη ζημιών και τη διασφάλιση της μακροπρόθεσμης επιτυχίας αυτών των κτιρίων. Με την αντιμετώπιση των γενεσιουργών αιτίων των αστοχιών και την εφαρμογή αποτελεσματικών προληπτικών μέτρων, τα πλεονεκτήματα των κτιρίων με «κάθετα δάση» μπορούν να αξιοποιηθούν πλήρως χωρίς να διακυβεύεται η δομική σταθερότητα.

Ως εκ τούτου, το παρόν παραδοτέο επικεντρώνεται στην ανασκόπηση και ταξινόμηση των πιθανών τύπων αστοχιών και κινδύνων που συνδέονται από την ενσωμάτωση «κάθετων δασών» στα κτίρια, προσδιορίζοντας τις φυσικές ζημιές και τη διακινδύνευση που προκύπτουν τόσο σε κτίρια που περιλαμβάνουν «κάθετα δάση» όσο και σε τυπικά κτίρια λόγω ποικίλων κινδύνων (ακραία καιρικά συμβάντα, σεισμοί, τυφώνες, διάβρωση κ.λπ.).

Περαιτέρω, γίνεται μια καταγραφή διδαγμάτων που αντλήθηκαν από τη βιβλιογραφία, σχετικά με τα κύρια αίτια τυχόν ζημιών και των πιθανών μηχανισμών αστοχίας, για διάφορα στοιχεία των «κάθετων δασών»

SUMMARY

The integration of greenery into building designs has gained popularity for its environmental benefits and aesthetic appeal. While traditionally, greenery in the field of architecture has predominantly served aesthetic purposes, contemporary justification for its integration includes ecological and economic factors as well, encompassing energy conservation, enhancement of urban climate conditions, promotion of biodiversity and others. However, these greenery-covered buildings have been subjected to various types of damage and failures that necessitate a detailed examination.

The main damages identified in greenery-covered buildings include structural deterioration, water leaks and stability issues. Planted vegetation is also exposed due to the differentiation of the growth conditions compared to the vegetation grown directly on the ground. Distorted growth and plant stress are the most common problems. Besides, inhabitants may experience undesirable implications of plants and facilities, such as safety and utility issues along with high living costs.

The failure mechanisms are primarily associated with design failures, poor installation practices, and inadequate maintenance. Improper structural materials to support additional weight, lack of proper waterproofing systems and non- adaptation of structural and fire regulations are some examples. Failure to regularly inspect and repair drainage systems, as well as neglected and dry plants exacerbates the risk of damage. Additionally, the selection of inappropriate plant species can damage the building's structure and impose new challenges and risks.

Greenery-covered buildings offer numerous benefits but also present specific challenges that must be addressed to ensure their durability and functionality. A comprehensive approach involving careful design, proper installation, and diligent maintenance is essential to prevent damage and ensure the long-term success of these buildings. By addressing the identified failure mechanisms and implementing effective preventive measures, the advantages of greenery-covered buildings can be fully realized without compromising structural integrity.

Therefore, this deliverable focuses on the classification of potential and recorded vertical forest buildings damages and risks, identifying the physical damages and risks of the various common and vertical forest buildings, that are observed during hazards (past extreme events or harsh conditions like earthquakes, hurricanes, corrosion etc.). Further, a summary of some lessons learned is gathered, including the main causes of damage as well as the potential failure mechanisms for the various components of vertical forests from a structural, energy and habitant satisfaction.

1 INTRODUCTION

According to the UN, we are at a crucial moment in global urbanization, with over 55% of the world population already residing in cities, a number expected to rise to nearly 70% by 2050, accommodating an additional 3 billion people (UN-Habitat, 2022). Besides the unique opportunity for positive change through effective urban planning, rapid urbanization also poses risks, demanding a re-evaluation of institutional frameworks to address challenges like climate change and disaster risks. More specifically, cities are major contributors to greenhouse gas emissions, playing a pivotal role in both contributing to and mitigating climate change. Hence, local authorities are increasingly taking the lead in terms of designing and implementing actions tailored to citizens' needs to tackle climate change, emphasizing the importance of low-carbon and resilient urban development. Following principles like compactness and inclusiveness unlocks opportunities for sustainable urban growth. In summary, strategic urban planning is vital for navigating the complexities and opportunities of urbanization, ensuring that cities become hubs of prosperity, sustainability and resilience. Thus, urbanization will lead to approximately 6 billion urban dwellers by 2050, whilst cities will be exposed to the effects of climate change, such as high GHG emissions as well as intensified Urban Heat Island (UHI) phenomena (McCarthy et al., 2010). More specifically, cities contribute approximately 70% of the world's carbon dioxide (CO2) emissions (IEA, 2022). With societies recovering from the effects of pandemic COVID-19, there was a rapid recovery in CO_2 rates, and total energy-related CO_2 emissions increased by 1.1% in 2023 reaching a new record high of 37.4 Gt (IEA, 2024). In this context, cities, acting as a major global economic powerhouse, account for 80% of global Gross Domestic Product (GDP), presenting a critical opportunity to accelerate efforts towards ambitious climate goals. Urban building stock plays an important role on the global share of energy consumption; in the developed countries it consumes 20–40% of the total energy use, surpassing transport and industrial sector consumption (Pérez-Lombard et al., 2008).

Based on the international data, it is evident that measures must be taken in cities in order to address UHI phenomena that affect urban health and adaptation parameters in cities. Hence, distinct air temperature variations emerge between urban zones and the surrounding rural landscapes, leading to the phenomenon known as the Urban Heat Island (UHI) (Oke, 1987). The UHI is intensified, among other factors, by the gradual replacement of permeable natural surfaces with coarse mineral materials like asphalt and concrete. This change results in increased absorption and re-emission of solar radiation within the urban environment. Additionally, the reduced sky view factor contributes to trapping short and long-wavelength radiation within urban canyons, impeding natural cooling processes (Memon et al., 2008). It is important to note that the UHI is not a static phenomenon; its intensity is higher on cloudless and windless nights and varies over seasons and diurnal cycles (Klsyik & Fortuniak, 1999; (Kim & Baik, 2005).

Greek cities experienced substantial growth since World War II, though governed by a centralized urban-planning system, that led to extensive and continuous built systems, characterized by social practices diverging from established scientific and technical planning norms (Papamanolis, 2015). Thus, the organization of Greek urban spaces, mainly Athens and Thessaloniki, has been and remains non-functional, characterized by high building density, lack of coordination in central operations, limited access to the natural environment as well as urban sprawl towards the city outskirts (Maloutas, 2000).

It is characteristic that Greek cities represent some of the most concentrated urban built environments in Europe, with 61.2% of Greece's total population residing in cities. The metropolitan areas of Athens and Thessaloniki alone account for over one-third (35.9%) of the entire population according to the Hellenic Statistical Authority. Approximately 80% of the urban population inhabits the 18 largest cities, each exceeding 50,000 inhabitants, while the remaining 20% reside in another 66 cities with populations ranging from 10,000 to 50,000 inhabitants1. The compact and dense structure of Greek cities is undoubtable, whilst there is a strong relationship between Greek urban built environments and the energy efficiency of their building stock (Tsirigoti & Bikas, 2017). Hence, according to Theodoridou et al, (2012) 73% of the total population living in urban areas, mainly in the two largest Prefectures of Athens and Thessaloniki (Theodoridou et al., 2012). More specifically the population density in the Municipality of Athens rises to 19,133.41 people/km2 with an even higher concentration in Thessaloniki, reaching 20,429.20 people/km2, compared to Berlin (3,796.30 people/km2), inner London (8,902.00 people/km2), Stockholm (280.90 people/km2), and Zurich (733.50 people/km2). Therefore, Greek cities diverge in their typological features, concerning built-up density compared to Western European and North American cities, as post-war Greek urban architecture lacks a distinct 'own identity', leading to its manifestation in disorderly forms (Beriatos & Gospodini, 2006).

Greek cities have fewer green spaces per capita than other European cities; according to data from the European Environment Agency, regarding the percentage of total green infrastructure, urban green space and urban tree cover in the EEA-38 capital cities, Athens is in the second last position, before Valletta. Hence, Athens features 11% urban tree cover and 17% total green infrastructure, while the related numbers for EEA-38 cities average are 30% and 42% respectively2 (Figure 1).

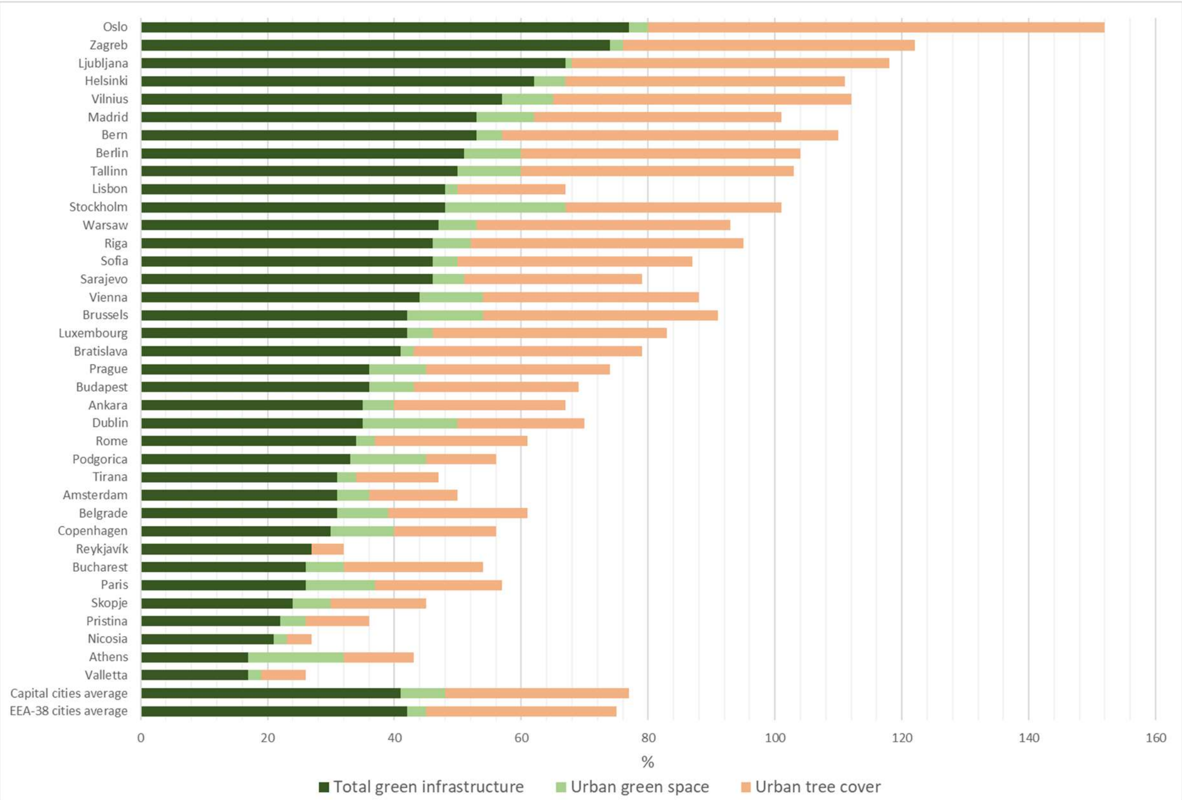

Figure 1 Percentage of total green infrastructure, urban green space, and urban tree cover in EEA-38 capital cities (excluding Liectenstein)[3].

[1] https://www.statistics.gr/
[2] https://www.eea.europa.eu/data-and-maps/daviz/percentage-of-total-green-infrastructure#tab-googlechartid_chart_11
[3] https://www.eea.europa.eu/data-and-maps/daviz/percentage-of-total-green-infrastructure#tab-googlechartid_chart_11

The above data underline the lack of accessible green spaces in Greek cities, as a significant portion of the city surfaces is covered by asphalt roads and concrete pavements (Papamanolis, 2015). More specifically, the defining feature of Greek cities is residential buildings, particularly the prevalent MF-building typology known as Polykatoikia (Greek: polys—many and katoikia—dwelling). Despite diverse influences from Italic, German, Ottoman, and French rule, as well as remnants of ancient Greece and Byzantium, Polykatoikies persist as a dominant architectural form across all Greek urban areas, regardless of climatic conditions or historical contexts. Both in Thessaloniki and Athens, roughly 80% of buildings serve purely residential purposes, with 90% of mixed-use located in Polykatoikies, predominantly featuring apartments (Theodoridou et al., 2011). It is evident that the typology of Polykatoikia serves as the central and pervasive element in Greek cities; measures to reduce UHI and improve the built-up environment of Greek urban centres will have a direct positive impact on their domestic building stock, with various benefits in terms of social aspects besides reduced residential energy consumption. This was shown in research concerning the influence of large-scale green roof implementation in Thessaloniki; the results showed that the implementation of green roofs in the residential building stock can lead to reduced heating and cooling consumptions up to 5% and 16% respectively (Theodoridou et al., 2017). Hence, methods to increase grass coverage and greenspace overall is an important tool, towards UHI minimization and urban cooling in Greek cities (Dandou et al., 2021; Georgi & Dimitriou, 2010; Tseliou et al., 2022).

As a result, significant environmental challenges arise and the demand to reconnect with nature becomes imperative (Al-Kodmany, 2023; Wang et al., 2020). Buildings are significant contributors to CO2 emissions (Al-Kodmany, 2023) worldwide as shown in Figure 2. Especially, high-rise buildings alter the air flow and combined with the use of low albedo and high thermal mass materials contribute to the urban heat island effect (Thomsit-Ireland, 2018), significantly increasing temperature within cities.

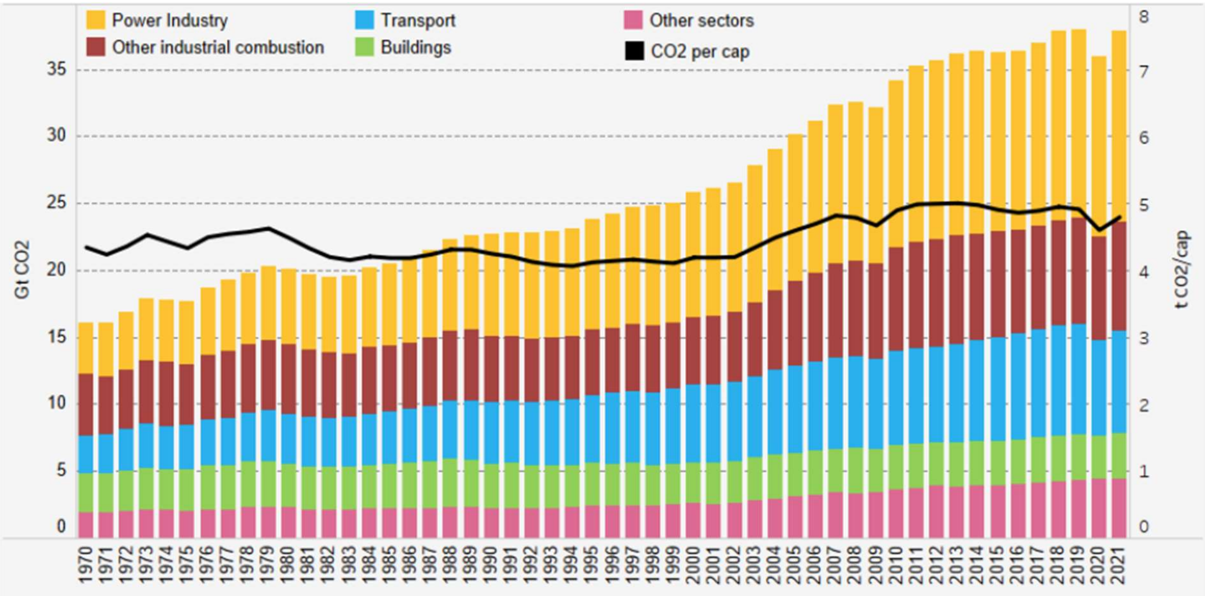

Figure 2 Global fossil CO2 (Gt) emissions by sector (left axis) and per capita (right axis), during 1970-2021 (Crippa et al., 2022).

Urban environments are characterised by poor air quality and most of them exceed the recommended concentration limits for atmospheric pollutants specified by the World Health Organisation (Thomsit-Ireland, 2018; World Health Organization, 2016). In addition, impervious materials covering the largest extent of the urban areas reduce water infiltration, leading to surface water flooding.

These concerns, have increased the demand for the inclusion of nature in urban life and encouraged cities to reassess their urban planning and environmental policies, focusing on developing greener and more sustainable living spaces. Biophilic design incorporates elements of nature into the architectural and interior design, to create spaces that generate positive emotional responses and promote the well-being of the occupants, recognising the inherent human need to connect with nature (Al-Kodmany, 2023).

1.1 BUILDING GREENERY SYSTEMS

Greenery can be introduced into buildings in many different forms; horizontally and vertically, outdoors, and indoors (Wang et al., 2019). By growing plants in pools mainly located at balconies, facades and roofs, it renders buildings to be vertical forests (Li et al., 2023). Green infrastructure may include all natural, semi-natural and artificial networks of multifunctional ecological systems within, around and between urban areas at all spatial scales (Wang et al., 2019). The two main categories include horizontal greenery and vertical greenery systems.

1.1.1 Horizontal Greenery

Horizontal Greenery includes green roofs and elevated forests and they are one of the earliest forms of green infrastructures (Figure 3, Figure 4). Green roofs, which feature a vegetated surface and substrate, can be divided into intensive and extensive green roofs based on substrate depth, roof dimensions, and intensity of use. Their relatively lightweight nature allows for installation on many roofs without the need for structural reinforcement, leading to a global increase in their adoption. Another form of horizontal greenery is elevated forests, where trees grow in sheltered horizontal open spaces, creating forests in the sky (Wang et al., 2019).

Figure 3 Green roofs[4].

1.1.1 Vertical Greenery Systems

While horizontal spaces accommodate plants, vertical spaces offer even more possibilities, allowing vegetation to be integrated into buildings' facades. A vertical greenery system refers to

[4] https://www.iko.com/blog/green-roof-maintenance/

structures that support vegetation, which can either be attached or not to a building's facade or to an interior wall. These systems are also known as vertical gardens, green walls, vertical green, and sky-rise greenery (Wang et al., 2020). Usually, in vertical greenery systems, vegetation covers partially or completely surfaces of the building (Dahanayake & Chow, 2018). A traditional vertical greenery system uses a building facade as the media for growing or supporting vegetation. The modern vertical greenery system uses separate structural systems and artificial growing mediums to support plants. Traditionally, climbing plants were used on the facades of buildings for botanical and decorative purposes. In recent years, vertical greenery systems have evolved significantly with the incorporation of new materials and structural attachments. Modern vertical greenery systems such as modular living walls and hydroponic systems are faster to construct and can be installed at higher building elevations (Dahanayake & Chow, 2018).

According to the strategies of development of vertical greenery systems, they can be categorized as green facade, green/living walls, green terraces, elevated and vertical forests (Figure 4). There are four major components in the vertical greenery systems: plants, planting media such as substrate and containers, supporting systems which can hold plants, and irrigation systems.

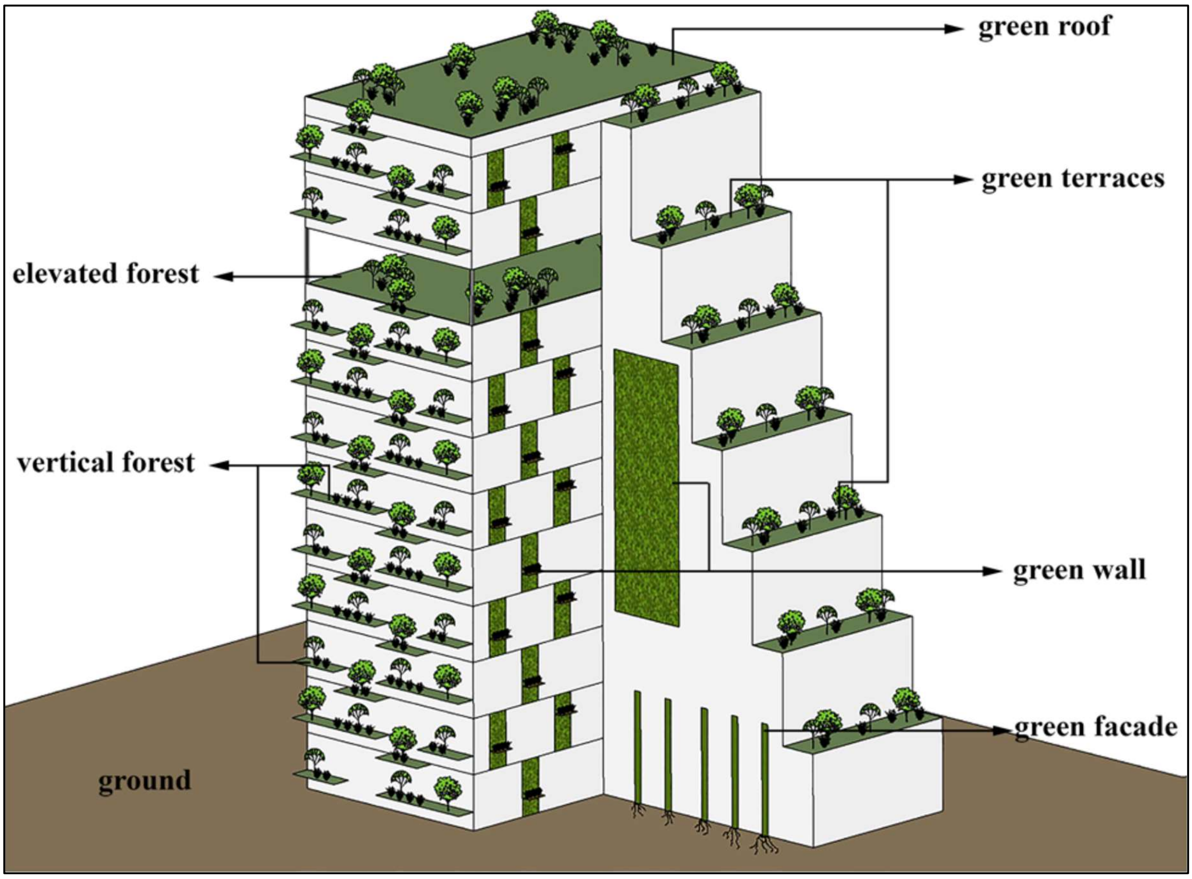

Figure 4 Classification of building greenery systems (Wang et al., 2020).

<u>Green facade</u>

Facade green walls refer to vegetation, usually climbing plants, rooted on the ground and using either the wall itself for climbing (traditional direct systems) or independent supporting systems, such as trellis, netting, lattice, wires, cables or meshes (double-skin indirect system) affixed to walls to support climbing plants, allowing them to spread and grow along the building's facade (Wang et al., 2020).

According to Giacomello et al., (2015) this form of greenery is defined as *"a system in which plants grow on a vertical surface such as a building facade in a controlled fashion and with regular maintenance. Climbing plants* grow *naturally on building facades by attaching themselves directly to vertical surfaces by means of various mechanisms. Self-clinging climbers and self-supporting woody plants can attach themselves directly to the facade surface or grow along the facade without any added support. Other plant species, including climbers with aerial roots, suckers and tendrils, twinning climbers and lax shrubs (ramblers), require additional support, such as trellises, netting or wires attached to the facade surface to promote or sustain vertical growth".*

Green living walls/ Facade-Integrated Green Walls

Facade-integrated green walls are a type of living wall system where the plants, substrate, and structural support are directly attached to the building wall. They may involve geotextile, pots, panels, boxes or *modular* nets/panels or containers where pre-cultivated vegetation of various plant species (mostly modular plants or plants with hanging-down branches) has been planted and subsequently suspended and fixed to a larger vertical structure. Living walls require more intricate constructions and imply higher installation and maintenance costs in comparison to green façades (Wang et al., 2019).

Green terraces and Rooftop Gardens

They are defined as plants growing on the horizontal terraces, which are built on different heights and levels. Buildings with vegetated terraces incorporate green spaces or gardens on elevated platforms, creating outdoor spaces for relaxation and recreation while promoting biodiversity (Al-Kodmany, 2023). Usually short, medium and tall plants are planted (Wang et al., 2019).

Vertical forest

Vertical forests are groups of trees which grow on cantilevered balconies (vegetated balconies) around the envelop of a building. High-rise buildings with vegetated balconies have greenery or plantings on their external balconies, providing occupants with a connection to nature and enhancing the aesthetics of the building. In addition, there may be buildings with vertical planters that incorporate specially designed containers or structures to accommodate plants and vegetation, often installed on the exterior of the building (Wang et al., 2020).

Vegetated Exoskeleton

The exoskeleton is an exterior support structure that can also be designed to accommodate greenery and vegetation, contributing to the viability and aesthetics of the building (Al-Kodmany, 2023).

1.1.2 Greenery-Covered Buildings

In an attempt to mitigate the negative effects of urbanization on human well-being, cities worldwide have incorporated greenery-covered buildings into urban planning. The French botanist Patrick Blanc is a pioneer in the greening of urban design and architecture. His unique mur végetal, which was patented in 1988, combines a metal frame, PVC layer, and polyamide felt with an automatic watering and fertilization system that enables a group of plants to be kept steadily against a vertical surface. A variety of native and imported plant species are usually found in these living walls, and they are positioned with care to take advantage of vertical changes in temperature and moisture content. Blanc's first plant installation was made for the Cité des Sciences et del'Industrie in Paris in 1986. Other highly regarded projects in the city, include the Fondation Cartier (1998), which was designed by the architect Jean Nouvel and the Musée du quai Branly (2006) (Figure 5). Numerous projects, including hotels, shopping malls, museums, and embassies, have used Blanc's vertical gardens (Gandy, 2010).

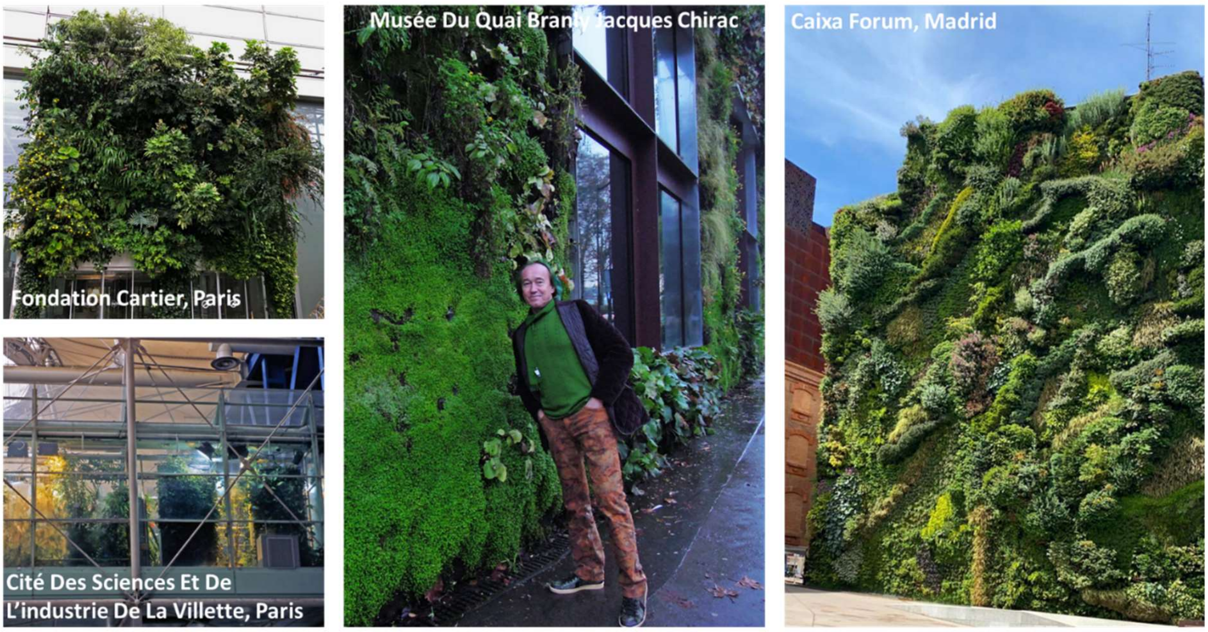

Figure 5 Mur Vegetal, Patrick Blanc[5]

Based on biophilic design, the Italian architect Stefano Boeri pioneered the concept of the "Vertical Forest", where high-rise buildings are covered with trees and plants on multiple floors, establishing a vertical ecosystem within urban environments. The fundamental principle of the vertical forests is to reintroduce nature into city centres by integrating abundant greenery into tall structures. The first example, built in Milan in the Porta Nuova area (2014), consists of two towers that are respectively 80 and 112 metres high, housing a total of 800 trees providing an amount of vegetation equivalent to 30,000 m^2 of woodland and undergrowth, concentrated on 3,000 m^2 of urban surface (Figure 6)[6].

Some of the most famous buildings are also ACROS Fukuoka Prefectural International Hall (Fukuoka, Japan) built in 1995, One Central Park (Sydney, Australia) built in 2013, the "1000 Trees" (Shanghai, China) built in 2019 and others. All these buildings contain one or more of the aforementioned green elements such as, vertical forests and vegetated balconies, green roofs and green facades (Figure 6).

[5] https://www.verticalgardenpatrickblanc.com/
[6] https://www.stefanoboeriarchitetti.net/en/project/vertical-forest/

Figure 6 Greenery- covered buildings worldwide.

In Greece, there is also an increasing interest for such buildings. Some of them are shown in Figure 7 and Figure 8 including green elements such as green roofs, vertical gardens, and green facades. For example, on the facade of the Department of Urban Environment building in Thessaloniki, 804 pots containing four types of plants suited to the local climate have been installed over a 50 m^2 surface. The building's roof is equipped with infrastructure to collect rainwater, which is then used to irrigate the vertical garden through an irrigation and drainage system[7]. The Hellenic American Educational Foundation Preschool & Kindergarten[8] contains a green roof enhancing local biodiversity, mitigating urban heat-island effect, and enhancing rainwater management (Figure 7). At the 1st and 2nd vocational high schools in Stavroupoli, Thessaloniki green roofs of a total area of 3087 m^2 (with 25,000 plants) as well as green walls of a total area of 100 m^2 (with 3098 plants) were created (Figure 8). The intervention on the roofs of the school complex includes waterproofing of the roofs, shaping of the substrate, supply and installation of plant material and automatic irrigation system. The green wall intervention includes the installation of a vertical wall system, i.e. installation of an infrastructure with an integrated irrigation and drainage system, fixing - clasping of the plant containers and planted vegetation[9,10].

The Stavros Niarchos Foundation Cultural Centre in Kallithea, Athens (Figure 7) supports biodiversity by plant selection creating a sustainable ecosystem. It implements green roofs which integrate the buildings with the park. The planted vegetation, including endemic plants, shrubs and olive trees, offers many benefits to the residents and the environment such as thermal and noise insulation of the opera and the library and rainwater collecting. The Stavros Niarchos Park’s vegetation has a positive impact on the micro-climate and decreases the temperature in the neighbouring areas (Makowska, 2021).

[7] https://www.archetype.gr/projects/kathetos-kipos-sti-thessaloniki
[8] https://www.dcarbon.co/project/haef-preschool-kndergarten/
[9] https://pavlosmelas.gr/epalstavroupolis_ergo_fitemenodoma_2022/
[10] https://pavlosmelas.gr/εσπα-2014-2020/ολοκληρωμένη-χωρική-ανάπτυξη-οχε/prasino_doma/

Figure 7 Greenery-covered buildings in Greece.

Figure 8 The 1st and 2nd vocational high schools of Stavroupoli, Thessaloniki with green roofs and vertical gardens.

1.2 GREENERY BENEFITS

Multi-storey buildings integrated with green elements may offer advantages in environmental and ecological, social, aesthetic and economic terms, making them an attractive and sustainable solution for urban development (Al-Kodmany, 2023; Li et al., 2023). It is broadly accepted that these complex urban ecosystems (Boeri, 2015) with the appropriate configuration of plants and trees surrounding buildings, positively affect inhabitants' psychology and at the same time they can enhance microclimatic conditions around these buildings (Hoyano, 1988). Improved storm-water management, regulation of building temperatures, noise reduction, urban heat-island mitigation (Besir & Cuce, 2018), biodiversity support (Oberndorfer et al., 2007) and shading are some of the ecosystem services these buildings may provide (Wang et al., 2020).

Regarding environmental benefits, the presence of greenery-covered buildings, contributes to the air quality improvement, urban heat island mitigation and biodiversity support among others. Vegetation on buildings act as a natural filter between indoor and outdoor of living spaces, absorbing CO_2 through photosynthesis and capturing air pollutants (Wang et al., 2019). Fine particulate matter gets trapped on vegetation surface as air passes through the leaves and vegetation. By reducing CO_2 and air pollutants levels in the atmosphere these buildings can contribute to cleaner and healthier air in the surrounding urban environment, especially where air pollution levels become hazardous for human health.

Greenery can also contribute to the urban heat island mitigation. Due to this effect, temperature within cities increases in relation with temperature levels at the surrounding rural areas. Multiple greenery elements on buildings may have a cooling effect, due to evapotranspiration, thus cooling the surrounding air and reducing reflected heat from building materials. At the same time this reduces the need for air conditioning in buildings (Pan & Chu, 2016) therefore reducing heat exhaust from air-conditioning units (Thomsit-Ireland, 2018). This leads to lower energy consumption, reducing emissions from energy production, and improving air quality. Temperature regulation of buildings is provided directly because of the decrease of heating and cooling energy use and indirectly through water runoff (Silva et al., 2016). In addition, intercepting and retaining part of the rainfall, by absorbing and filtering rainwater, facilitate water drainage problems associated with maximum rainfall and adding a layer of bioprotection for old buildings (Thomsit-Ireland, 2018) and increasing the lifespan and durability of gray infrastructure by protecting them from weathering, corrosion, and erosion (Kaposztasova et al., 2024).

Retrofitting existing residential buildings with greenery systems, such as green facades, allows for the reactivation of old buildings to participate in sustainable development of the urban environment providing cooling loads, shading effect, mitigating solar and conductive heat gains and reducing building energy consumption (Mostafa Khalil, 2022).

1.3 LARGE-SCALE IMPLEMENTATION BENEFITS

Large-scale implementation of vertical green policies can significantly contribute to environmental sustainability and energy efficiency in urban areas (Čekić et al., 2020). Studies emphasize the positive impact of vertical greening on reducing local pollution emissions, improving total factor productivity, and enhancing energy efficiency in buildings (Čekić et al., 2020; Zeng et al., 2022). Implementing vertical green solutions can mitigate air pollutants, improve air quality, and reduce energy consumption through the absorption of fine dust particles and gaseous pollutants, ultimately benefiting the urban environment and public health (Perini & Roccotiello, 2018; Zeng et al., 2022). In addition, they contribute to the enhancement of the aesthetic and social value of urban spaces by creating attractive and diverse environments that foster community engagement and well-being (Kaposztasova et al., 2024).

Green infrastructure has been adapted and defined in European policies as a “strategically planned network of natural and semi-natural areas with other environmental features designed and managed to deliver a wide range of ecosystem services”. Urban green spaces, including parks, urban forests, river canals, and other water bodies, as well as green roofs and green walls, offer ecosystem services for a more focused view of urban areas that are thought to be the most anthropogenic from an ecosystem perspective. These spaces are essential for converting cities into more sustainable and adaptable systems.(Gantar et al., 2022).

The growing recognition of the environmental benefits of greenery has led cities to oppose the construction of glass skyscrapers due to their environmental impact. For example, former New York City Mayor Bill de Blasio (2014-2021) proposed legislation to ban glass skyscrapers in order to reduce the city's greenhouse gas emissions by 30%. De Blasio argued that glass towers are "incredibly inefficient" because they lose significant energy through glass, making them a major source of greenhouse gas emissions. In contrast, Toronto, Canada, is promoting the use of timber construction, specifically cross-laminated timber, which is very strong, for the construction of high-rise buildings. Utrecht, in the Netherlands, requires all buildings to incorporate green or solar roofs. In Singapore, the government subsidizes up to half the cost of incorporating greenery into buildings, resulting in most new construction being rich in vegetation. In addition, many European cities are seeing an increase in vertical greenery, such as living walls, terraces with vegetation and green roofs (Al-Kodmany, 2023).

2 PHYSICAL DAMAGES AND RISKS

Damages refer to the physical changes of an asset (Scott et al., 2013). Buildings, both common and greenery-covered, are subjected to many hazards which threaten their integrity, especially when regulations are overlooked. Natural disasters such as earthquakes, tornados and fire can cause serious damages to buildings and many times they are irreversible. Regarding greenery-covered buildings, besides benefits that may offer, incorporating plants and trees imposes challenges and concerns, particularly regarding the structure and utility of the buildings as well as plants health. Green integration into buildings necessitates supplementary structural guidelines to ensure they can support the additional weight of the plants and the extra weight of supporting equipment such as irrigation systems and planters. Additional costs for construction, maintenance and watering have to be taken into serious consideration when constructing or retrofitting such buildings. If these factors are devalued, they can lead to construction failures and damages to the buildings as well as plant degradation, compromising security and resilience, and ultimately affecting the well-being of the inhabitants.

2.1 DAMAGES TO COMMON BUILDINGS

The structural integrity of buildings is of great importance. Natural disasters, such as earthquakes may cause severe damages and building collapses exposing civilians to danger (Figure 9). Vulnerabilities in RC buildings are often related to poor quality of materials, poor design of the bearing structure of the building and of the detailing of the steel reinforcement. Last but not least, the non-compliance with the earthquake regulations, is a key factor that may lead to irreversible and severe consequences.

Figure 9 Pancake collapse (left) and soft story collapse (right), (Binici et al., 2023).

Material defects may involve poor quality of concrete, or poor maintenance leading to concrete carbonation and local concrete strength degradation due to cycles of corrosive environments (chlorides) followed by internally caused expansion due to internal steel corrosion. Steel bar and stirrup reinforcement corrosion itself reduces the effective area and diameter of the reinforcement locally (pitting) or over broader surfaces (Triantafyllou et al. 2017, Triantafyllou et al. 2019) and the bond of steel to concrete causing extensive concrete cracking (Figure 10). Abovementioned effects often lead to severe building damages and are revealed or exacerbated during strong earthquakes. Further, poor steel reinforcement detailing with sparse or of low yield stress or smooth stirrups and transverse steel reinforcements in general, column sections without crossties, or column-beam joints without transverse reinforcement or the common old practice of transverse reinforcement anchorage with hooks at 90 degrees instead of 135 degrees, as well as inadequate longitudinal steel bar lap splices at regions of structural joints in columns and premature bar buckling under compression, largely contribute to local disintegration of column concrete core and may lead to partial or full building collapses (İnce, 2024, Karabinis and Rousakis, 2010, Anagnostou and Rousakis 2022, Rousakis 2016).

Figure 10 Damages due to inadequate concrete material performance and corrosion of steel reinforcement (İnce, 2024).

Morphological based vulnerabilities and absence of capacity based or performance based design during the original conceptualization of the building can significantly lower the performance of RC structures during severe earthquakes and violate the desirable damage accumulation and collapse mechanism (Karabinis and Rousakis, 2010). Discontinuity of the RC bearing frames, weak column-strong beam cases, formation of soft and weak story collapse mechanism, formation of short column due to detrimental wall infill-column interaction (Figure 11) and in general low shear strength of the columns (Karabinis and Rousakis, 2010) constitute main reasons of buildings' partial or full collapse. Severe damage can be caused by other factors such as neighbouring buildings (Figure 12), which were not considered during the design phase (İnce, 2024). Moreover, insufficient soil information, neglecting soil examination, and disregarding soil liquefaction risks can lead to building damage (Binici et al., 2023). In Table 1, the main causes of building damages are listed.

Table 1 Categories of causes of damage to common buildings (İnce, 2024).

Material	Poor concrete quality Corrosion
Design	Short column Strong beam-weak column Insufficient shear capacity Soft and weak story Discontinuous frames Stair damages
Reinforcement details	Insufficient reinforcement ratio Insufficient transverse reinforcement Lack of crossties Lack of transverse reinforcement in connection region 90º hooks instead of 135º
Others	Adjacent buildings effect Insufficient determination of soil properties Infill wall damages

Figure 11 Damages due to short column effect (İnce, 2024).

Figure 12 Damages due to adjacent building's collapse (İnce, 2024).

These can affect many reinforced concrete buildings leading to significant structural damage, including cracks, spalling, and the collapse of walls and floors. Heavy infill wall damage may be observed in many buildings, rendering occupancy impossible. Roof damages are also common, with some buildings experiencing complete collapse. Foundation damage in some buildings, can lead to long-term structural instability (Binici et al., 2023).

2.2 DAMAGES TO GREENERY-COVERED BUILDINGS

Damages to greenery-covered buildings pertain to the reversible and irreversible wear and tear they undergo and can be induced by different sources. The presence of different plant species itself may cause physical damage to buildings envelope, especially when there is no provision for proper maintenance. On the other hand, vegetation on buildings may experience stress and degradation, as it is exposed at different conditions compared to ground-level vegetation. Other factors, including extreme events and harsh conditions can pose hazards and risks making greenery-covered buildings vulnerable to deterioration exposing at the same time inhabitants to risks. Below is a list of damages to both structural and greenery elements, considering various potential sources.

2.2.1 Structural damages

The primary concerns regarding the integration of trees and plants into buildings include wall integrity and structural stability which may be affected by the additional weight, mould development due to the increased moisture levels associated with irrigation systems and evapotranspiration, and concrete erosion which may be induced by root growth and action.

Wall and foundation integrity

The integrity of walls can be compromised by the presence of plants or trees and structural wear and tear may occur, especially to aged and poorly maintained buildings. Self-climbing plants, such as ivy *(Hedera helix*), which form green facades attached to the wall directly can root into weakened historic walls or inadequately maintained buildings. These plants can lift blocks of stone off walls by growing beneath them (Thomsit-Ireland, 2018). Additionally, sidings, tiles or loosely fitting cladding are at risk, as these plants can grow underneath the surfaces and lift them. The external wall plaster must have sufficient strength to support the weight of the plants, along with any rain or snow loading, otherwise they could pull or crack the external plaster. Furthermore, depending on the plant removal methods employed, they can leave 'scarring' on surfaces including those that are painted, or made of wood or masonry (Figure 13). These marks are visible after green layer is removed and is created due to the etching effect of the slightly sap of the root cells (Thomsit-Ireland, 2018).

Figure 13 Root structure remains on the wall after green layer removal (a), and ivy scars on wood, painted wall and masonry (b) (Mir M.A, 2011; Thomsit-Ireland, 2018).

Furthermore, tree roots can directly damage buildings and structures, though the foundations of most modern buildings are typically designed to withstand such activity (Satriani et al., 2010). Over time, tree and plant roots may become unmanageable and result in structural and external fissures in buildings. As they grow, tree roots can exert a considerable amount of power to absorb nutrients and moisture from the earth. Tree roots can take advantage of any cracks in the walls or facades or flaws in a building's foundation to worsen the damage. Cracks and possible instability may result from the roots pushing on the building's framework as they spread and grow. This typically happens when trees are given insufficient space; as they grow, their roots begin to extend and move beneath structures. (Figure 14) (Al-Kodmany, 2023; Lantini, 2021).

Trees can also indirectly cause structural damage to historical buildings and monuments, especially in the case of shrinkable soil types, such as certain clays, which expand and contract in response to soil moisture changes. In winter, shrinkable soil becomes wetter and increases in volume, while in summer, the opposite occurs. During the dry season, tree roots near buildings and monuments can extend towards the foundations, drawn by the higher moisture content compared to the surrounding soil. This reduction in soil moisture increases matric suction to remove interstitial water, resulting in a decrease in soil volume. This phenomenon occurs only where the roots penetrate, causing differential subsidence in the soil and leading to damage in the overlying masonry structures (Lantini, 2021).

Figure 14 : Tree roots growing under foundations (Lantini, 2021).

Underground services, especially drainage systems, are often obstructed or damaged by root growth. This deterioration typically occurs in older infrastructure, which was constructed using materials prone to decay over time. Roots are attracted to the moisture around pipes, which tend to maintain a lower temperature compared to the adjacent soil causing them to grow near the pipelines (Figure 15).

Figure 15 Roots growing around a pipe (Lantini, 2021).

Usually, as long as the original cladding is in good condition, roots will not threaten the integrity of walls, foundation and other structural characteristics (Mir M.A, 2011; Ottelé, 2011). The pressure that roots are capable of exerting is relatively weak and is further diminished by urban soil compaction (Lantini, 2021). Moreover, modern building foundations are designed to withstand root-inducted movement and plant covered surfaces can protect the building's exterior from UV radiation, rain and temperature differentials, reducing thermal tensions. However, where deterioration has already occurred, plants can indeed accelerate the process of damage. In fact, woody species are expected to cause much more damage than the herbaceous plants because of secondary growth in their roots and stems resulting in appreciable dimensional changes.

Another issue that greenery covered buildings face is concrete erosion and the additional weight that must be supported. In vertical greenery systems, such as vertical forests, the reinforced concrete planting balcony is widely used often being adjacent to the living balcony. This balcony is typically divided into an inner part for living and an outer part for planting. The reinforced concrete planting balcony supports not only the weight of the soil and plants but also the stresses caused by root growth. Additionally, the microbial flora and organic acids in the soil can erode the concrete. Consequently, the reinforced concrete planting balcony is susceptible to damage over time, and its safety must be carefully monitored (Li et al., 2023).

Humidity and mould development

Due to evapotranspiration plants release water vapour into the surrounding air, especially during summer, increasing humidity (Ottelé, 2011) and making walls vulnerable to damp. In addition, plants require systematic watering and irrigation, but excessive watering may lead to water pooling, leaks, and potential damage to the building structure and its components due to dampness (Figure 16).

Figure 16 Water leakage and degradation of substrate of the vertical placed panel (Ottelé, 2011)

Another issue that increases moisture levels is that self-climbing plants, if not properly maintained, can obstruct technical features designed to prevent water ingress such as drip grooves (Figure 17). This allows water to collect in the groove and not fall away from the structure, but rather run off into structural material. However, if the building is structurally robust without cracks or damp, and Portland cement is used in the mortar instead of lime, these issues can be addressed (Thomsit-Ireland, 2018).

Figure 17 Ivy growing in and around gutter (Thomsit-Ireland, 2018).

Vertical green facades and especially green living walls emerge moisture-related problems, as water drips around the edges of windows that cause streaking and possible corrosion of the wind envelope (Figure 18). In addition, it can cause mould development at the indoor space that is connected to those surfaces (Ottelé, 2011; Thomsit-Ireland, 2018).

Figure 18 Water leakage problems causing stripes and possible corrosion (Ottelé, 2011).

Humidity issues are also related to the direct attachment of the plants with the walls. Self-climbing plants may function as a precipitation protector, however if the whole surface of the wall is not covered by plants, the wall may become locally wet. In addition, vertical greenery prevents evaporation in case of moisture resulting from ground water. Thus, the moisture cannot dry rapidly, causing mould (Figure 19) and damages to the material covers (Figure 20). Another point is that deciduous climbers cannot completely protect walls from rain or snow during winter (Mir M.A, 2011).

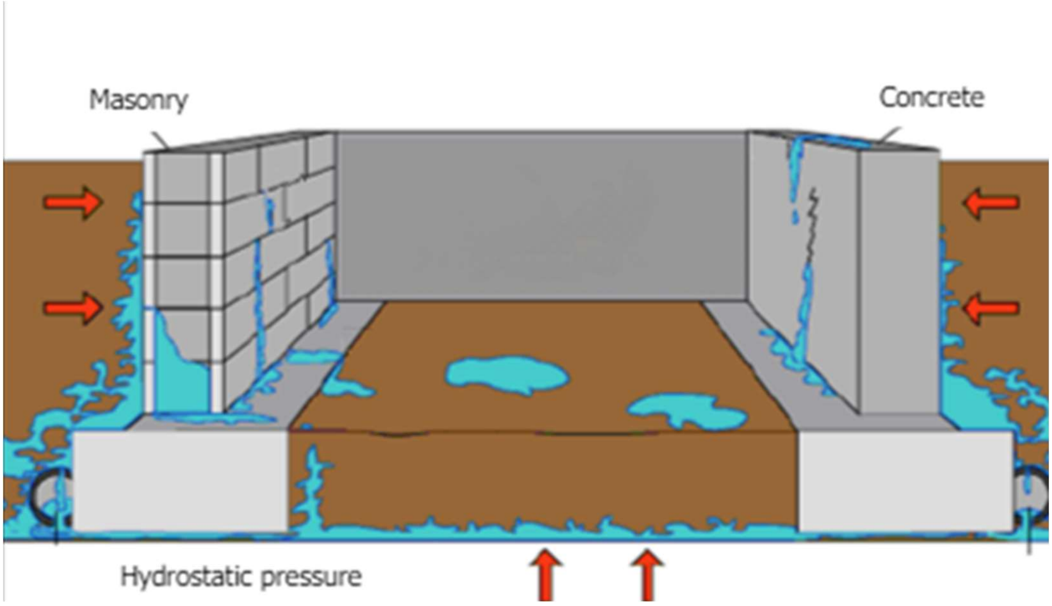

Figure 19 Open contact between foundation and the facade, where the wall would not be able to evaporate capillary moisture rapidly with the presence of vertical green (Mir M.A, 2011).

Figure 20 Damaged wall with cracks and plaster removal due to high moisture levels at a planted balcony in Thessaloniki (Photograph by authors).

2.2.1.1 Building retrofitting

Any modification of existing buildings to include green elements requires a thorough revision of structural performance of the building under additional load caused by the greenery and associated equipment. Especially when the retrofitting concerns older or historical buildings, information about their structural details is scarce (Sofi et al., 2014) and there is uncertainty about the construction techniques that were used. Hence, the integration of greenery, usually green roofs and/or green and living walls, into pre-existing buildings requires careful planning taking into account various factors that are not always considered such as (Santi et al., 2020):

- The existing structure of the building can support the increased loads.
- There is sufficient space to accommodate the increased thickness of roofs and facades.
- The new envelope is likely to meet the expected performance standards.
- Construction elements that may obstruct the implementation of the system should be removed or mitigated.
- Integrating the irrigation system for the greenery into the pre-existing building is feasible.
- Plant species should be carefully chosen to integrate with the surrounding context.

The problems concerning the installation of green and living walls on a building's facades are related to the type of facade, even with the ventilated cladding, which is fixed to the building structure. The geometry and inclination of structure and coating, alignments and holes for windows and doors, interface of doors and windows with the interior and façade are the primary issues. Furthermore, the system and type of connection and internal-external coordination, the acoustic and thermal bridges, the collection and disposal of rainwater, the assembly and disassembly of the flexible interface with other subsystems, plants, installations, and elements, the cleaning of facades and glazing, and the upkeep of the cladding and windows should all be taken into consideration (Santi et al., 2020).

The increased loads that a green roof adds to the building have been investigated in terms of earthquake occurrence in various studies (Bianchini et al., 2016; Contreras & Nunez, 2020; Elhout, 2022). Prior to the implementation of green roofs, analysis must be carried out to determine the capacity of the structural elements to resist the increase in gravitational loads due to the extra weight coming from the green roof. According to Bianchini et al., (2016), they do not affect the seismic performance of reinforced concrete frames. However, for different geometries and green roof load ranges must carry out extensive analysis must be carried out, as it is difficult to determine whether a green roof will pose or not a risk to the frame structure that has a top story which can develop significant nonlinear behaviour during the design ground motion. Other studies (Contreras & Nunez, 2020) concluded that the tested construction (bus stop) would not suffer damage due to the green roof. Elhout (2022) indicated that the effect of green roofs on the roof drift ratio and the maximum story drift ratio is mainly decreased by increasing the number of the story, whereas it is not significantly affected by the type of green roof frames (extensive and intensive). Also, the fundamental periods of green roof frames were higher than those in the frame without the green roof and increased with increasing the frame height, because of the mass of the structures that are greater than that without a green roof.

2.2.2 Greenery damages

Except for structural damages on buildings, elevated vegetation faces degradation as well. Plants require systematic watering and irrigation in order to stay healthy; insufficient watering and inappropriate irrigation systems can cause plant stress and wilting, leading to dead plants and bio-debris. Restricted growing space can also result in distorted vegetation especially regarding trees, which need adequate space both for roots and for stems and branches growth. In Figure 21 and Figure 22, different types of distorted tree growth are depicted.

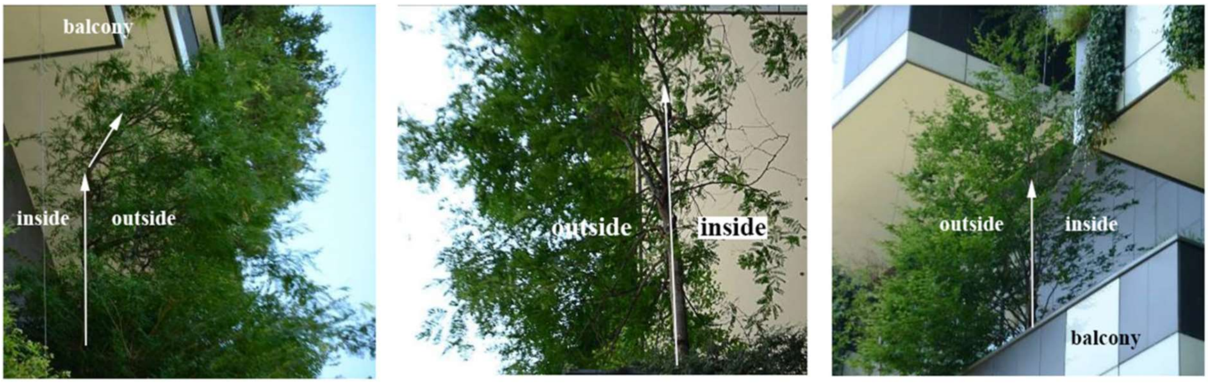

Figure 21 Distorted growth of trees regarding stem and branches and dense foliage, Bosco Verticale (Wang et al., 2020).

Figure 22 Distorted growth of trees and bio-debris at a planted balcony in Thessaloniki (Photograph by authors).

Giacomello et al., (2015), pointed out that any environmental stressor, determined by urban pollution or exposure to harsh sunlight and high wind generated negative effects on selected trees. Indeed, the higher the vegetation is planted the more it is exposed to variations in factors such as temperature, solar radiation and wind, impacting its health and demands.

High-rise buildings are exposed to intense winds (Al-Kodmany, 2023). From the perspective of wind engineering, trees planted on balconies of high-rise buildings change their external shapes and subsequently reduce local wind pressure and global wind loads on the building (Wang et al., 2019). However, wind effect affects the greenery systems depending on the intensity, orientation, and frequency. Strong winds may induce mechanical stress on vegetation, resulting in physical damage, dehydration, and uprooting. Additionally, wind deteriorates transpiration rates, reducing moisture from plant tissues and soil (Manouchehri et al., 2024) resulting in reduced plant growth and wilting. Considering the stability of trees, the soil strength during rainfall diminishes around trees planted for example in a concrete pot within a vertical forest. Consequently, uprooting due to strong winds is very possible (Figure 23, Figure 24) (Wang et al., 2019).

Figure 23 Green wall damage after heavy rain and windy conditions and restoration (Tan, 2020).

Figure 24 Bended tree on balcony under strong wind load, Bosco Verticale (Giacomello et al., 2015).

In contrast, in Figure 25, a damaged building is depicted after a typhoon occurred in China. It is observed that the building's facade has been severely damaged however the green wall was not affected.

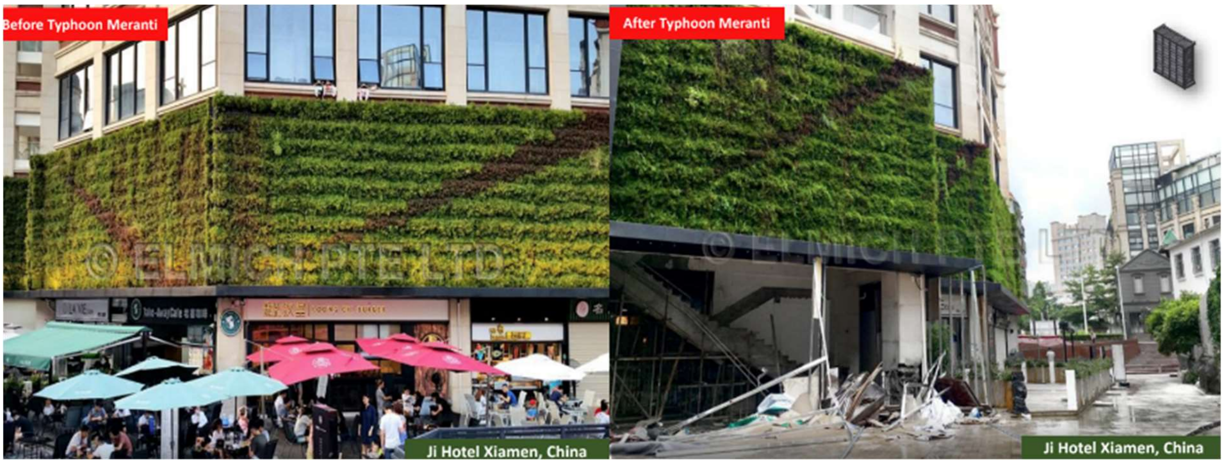

Figure 25 Damaged building before (left) and after Typhoon (right), in China, where greenery remained undamaged (Tan, 2020).

2.2.2.1 Planting media damages

The main damages regarding planting media concern loss and media compaction and malfunctions of the irrigation systems. Wrong material selection, inadequate maintenance and material aging process may lead to serious degradation (Figure 26). Similarly, irrigation systems' function may be affected by improper frequency of flushing, water source and quality of water, leading to dry vegetation, dead plants and gaps in the continuity of vegetation (Figure 27) (Tan, 2020).

Figure 26 Loss and compaction of media after 5 years (up) and 10 years (down) respectively (Tan, 2020).

Figure 27 Irrigation choked problem leading to dry vegetation, dead plants and gaps in the continuity of vegetation (Tan, 2020).

2.2.2.2 The risk of fire

Integrating abundant organic materials on building façades in the form of vegetation can introduce the risk of fire (Karunaratne & Chow, 2022) requiring strict building regulations, fire suppression systems and appropriate conservation (Al-Kodmany, 2023). Inadequate maintenance and improper irrigation systems can lead to desiccation of vegetation, resulting in a significant fire hazard. The dry vegetation is highly susceptible to ignition, which can escalate the fire's vertical propagation. A low moisture content significantly increases the risk of flashover, and also the thermal risk and smoke toxicity hazards. Neglected vegetation may eventually grow excessively, forming a fuel ladder that facilitates fire spread to upper floors. Additionally, this can contribute to the transmission of fire between structures.

Experiment[11] testing different plant samples of selected species with different moisture contents, has shown that the transient heat release rate of healthy vegetation is not significant upon ignition; however, it escalates as the moisture content diminishes (Figure 28). During a full-scale fire test to analyze the fire spread over the green façade of a high-rise building, No fire extended across the storey boundary, and the climbing plants on the two stories above the fire level did not catch fire (Figure 29). This high-rise building's 1.60 m horizontal concrete projections at ceiling level stop fire from spreading from storey to storey. Each story of these projections has a plant box filled with climbing plants. Moisture content, plant density and wind have a significant impact on the expansion of the fire and should be taken into account (Engel & Werther, 2024).

[11] https://www.sfpe.org/publications/fpemagazine/fpeextra/fpeextra2018/fpeextraissue31

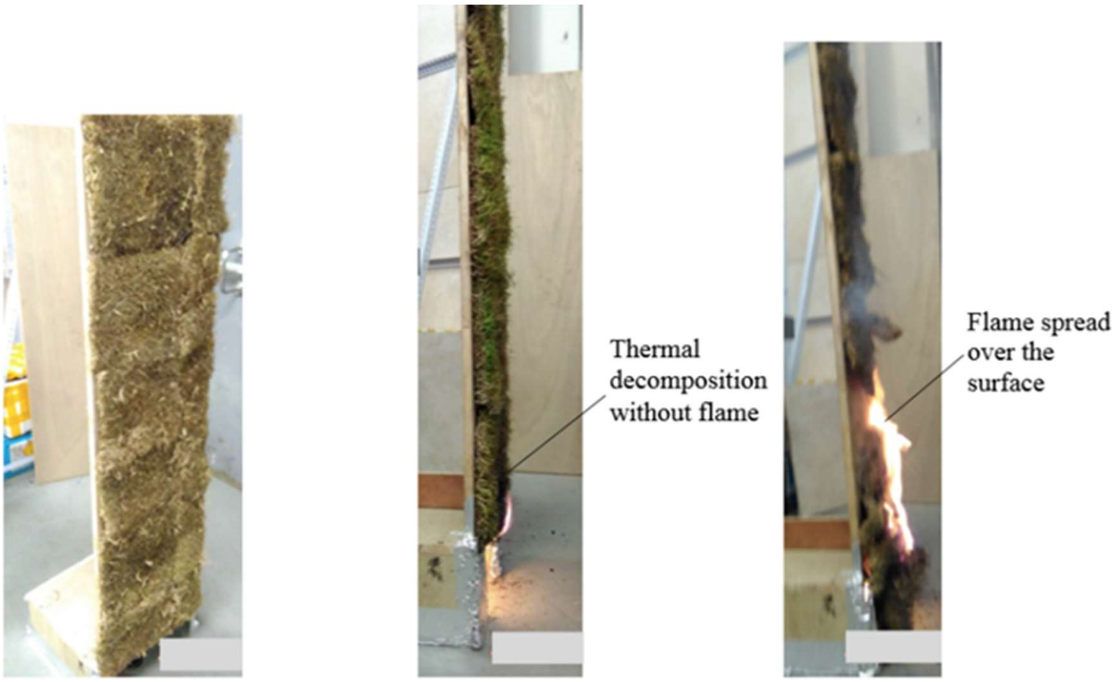

Figure 28 Experiment for the transient heat release rate of healthy and dry vegetation[7].

Figure 29 Full-scale fire test on a green façade (Engel & Werther, 2024).

Besides growing vegetation, other materials are used in green systems synthesis (insulation, waterproofing membrane, protection boards, root barrier, drainage layer) which, without systematic maintenance, have negative fire safety implications. The utilization of plastic, rubber, or wood materials for the stabilization of vertical vegetation, elevates the combustible content within the building. Conversely, the distance between green facade and the building facade induces a chimney effect, facilitating the upward spread of fire (Yildiz & Beyhan, 2023).

A burning vertical green system may obstruct the evacuation of the building and the entry of firefighters during a fire emergency (Dahanayake & Chow, 2018). The potential of damage by fire may increase as long as vertical greenery systems are not properly settled, due to its vertical orientation which facilitates fast propagation of fire upwards (Karunaratne & Chow, 2022). Hence, the careful selection of plant species and materials as well as proper maintenance and irrigation practices are essential (Dahanayake & Chow, 2018).

2.2.3 Aesthetic and other utility issues

Other issues may arise regarding aesthetics and the living conditions for the residents as well as utility problems. Dead plants, unattractive bare areas of green facades and plants growing uncontrollably are some of the most common problems (Figure 30, Figure 31) (Ottelé, 2011). In addition, health issues can arise due to potential mould development, pest breeding and insects. Ecological imbalance may also occur by the introduction of non-native species, which must be managed through careful selection and maintenance of the vegetation.

The systematic maintenance of greenery by experts as well as the potential building repair entail additional costs, for example in case of earthquake damages (Welsh-Huggins & Liel, 2017), are also burdened on residents. These tasks also involve the risk of falling as they have to be carried out at height and along roof edges (Tan, 2020). In some cases, the presence of vegetation may expose residents to danger as in a case of fire or the risk of falling objects and bio-debris (Tan, 2020).

Figure 30 Dead plants at a building's green façade in Spain (Ottelé, 2011).

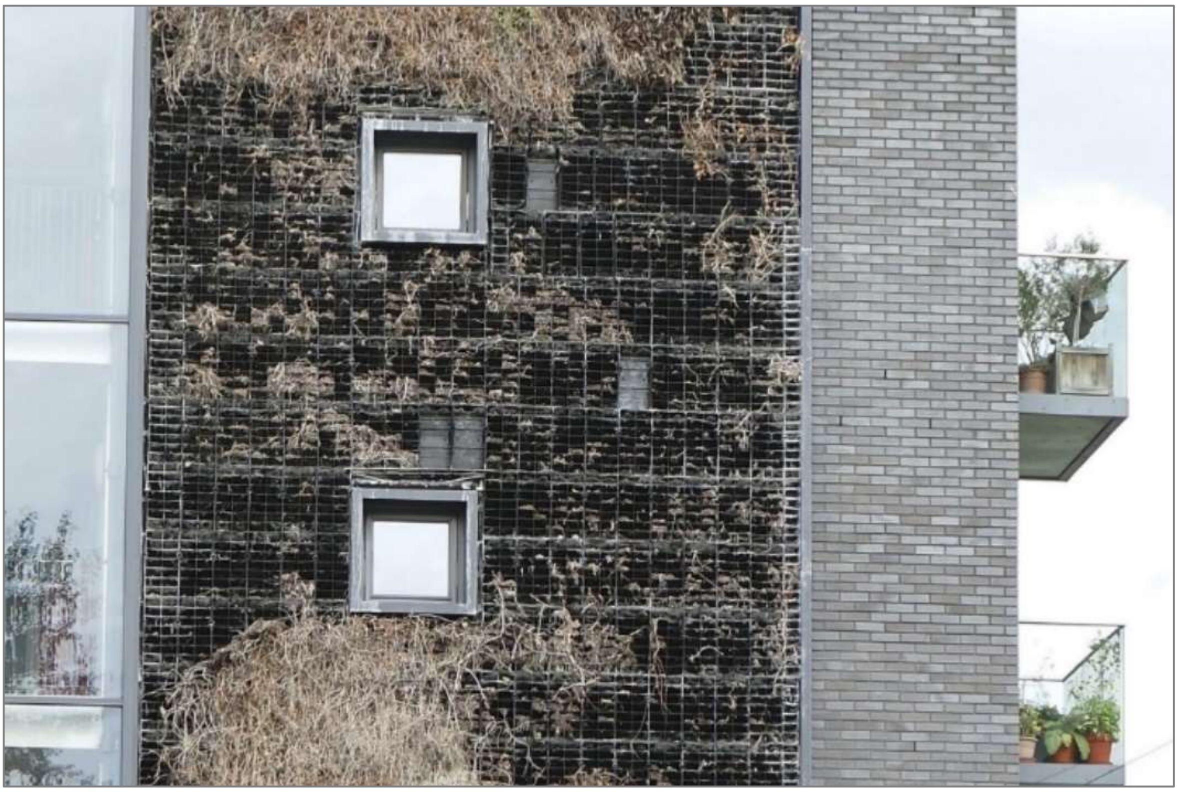

Figure 31 Dead green wall on a Pocket Living housing scheme in west London[12]

Regarding utility, greenery may occupy living space or obstruct view and sunlight. The physical characteristics of plants such as density of foliage, leaf size, and distribution have a significant impact on the quality and quantity of daylight into buildings. Besides plant species selection, sun positions such as altitude and azimuth angles in different times and dates of the year also influence daylight and should be taken under consideration for vertical greening system integration in buildings (Figure 32) (Satumane & Suk, 2018). Regarding energy savings, additional trees and vegetation on buildings despite blocking solar radiation thus decreasing energy needs in summer, during winter they decrease solar radiation, leading to increased energy needs (Giacomello et al., 2015)

Figure 32 High dynamic range photographs of light distribution patterns (Satumane & Suk, 2018).

2.3 CLASSIFICATION OF DAMAGES TO BUILDINGS

The following Tables (Table 2, Table 3, Table 4) present a classification scheme of damages on buildings, greenery and consequences for residents' well-being. This scheme categorizes different types of damage, highlighting the various impacts on structural and green elements and on human welfare as well. By systematically identifying and classifying these damages, this report aims to provide a comprehensive understanding of the interactions between buildings, greenery and human, facilitating the adoption of measures for mitigating adverse effects.

Table 2 Classification of damages on greenery-covered buildings.

Cause of damage	Structural damages
Root penetration *(growth/action)*	• wall and foundation integrity - *potential instability issues* - *cracks* - *potential damage to technical features (e.g. pipelines)*
Plants direct attachment/green layer removal	• wall and foundation integrity - *lifted blocks* - *cracks* - *scarring* - *plaster removal* • local wetness
High level of moisture *(due to evapotranspiration)*	• mould development • indoor & outdoor dampness

[12] https://www.architectsjournal.co.uk/news/growing-pains-why-some-green-walls-die

	• material covers damages • slow drying
High level of moisture *(due to watering/ irrigation systems)*	• water leaks • water pooling •dripping water • indoor & outdoor dampness • mould development • corrosion • streaking • material covers damages
Soil moisture changes	• wall and foundation integrity - *potential instability issues* - *subsidence*
Soil microbial flora & organic acids	• concrete erosion
Overgrown vegetation	• overtaking space • blocking windows • cascading branches • technical features obstruction *(e.g. drip grooves, pipes)*
Additional weight and stresses *(plants/planting media)*	• potential instability issues *(e.g. reinforced concrete planting balcony)*
Fire	• structural integrity - *burned materials* - *collapse*
Wind	• structural integrity - *cracks* - *collapse* - *blown out* - *debris*
Earthquake	• structural integrity - *Cracks* - *Collapse* - *Spalling* - *instability*

Table 3 Classification of damages on greenery integrated on buildings.

Cause of damage	Greenery damages
High level of moisture *(due to evapotranspiration)*	• pests • degradation of planting media
Low level of moisture *(due to watering/ irrigation systems)*	• plant stress - *dry vegetation* - *dead plants* • wilting • gaps • degradation of planting media
Improper maintenance	• overgrown vegetation • dead biomass • bio-debris • gaps • degradation of planting media - *loss* - *compaction*
Inadequate space	• distorted vegetation growth
Environmental stressors *(harsh sunlight, strong wind)*	• plant stress • dehydration
Fire	• burnt vegetation
Wind	• uprooting • mechanical stress • dehydration • reduced plant growth rate • wilting • bended trees • falling bio-debris
Earthquake	• planter anchorage and instability • tree pot anchorage and instability

Table 4 Classification of negative impacts on human welfare.

Cause of damage	Human well-being and other issues
Dead plants	• aesthetics • utility •energy needs *(increased during summer)*
Overgrown vegetation	• insects • aesthetics •energy needs *(increased during winter)* • utility - *reduced sunlight/view* - *living space occupation*
High moisture level	• health issues - *pests* - *insects* - *mould development*
Maintenance	• cost • time • potential falls - *work at height*
Non-native species	• ecological imbalances
Fire	• safety - *evacuation obstruction* - fire vertical propagation - chimney effect
Wind	• safety - *fallen objects/bio-debris* - *turbulence*
Earthquake	• high repairing cost

3 LESSONS LEARNED

Introduction of greenery elements onto buildings has gained popularity in an attempt to bring humans closer to nature and benefit from integrated vegetation into urban ecosystems. Greenery systems, both vertical and horizontal, can contribute to urban heat island mitigation along with air and sound pollution. They are also capable of providing passive energy benefits in the form of shadow and insulation through the vegetation layer and the substrate, and evaporative cooling through evapotranspiration (Karunaratne & Chow, 2023). However, greenery-covered buildings, have shown potential vulnerabilities that can lead to damages especially if there is no proper maintenance of the vegetation and the appropriate facilities to support it.

Damage to buildings can stem from various sources, including natural disasters like earthquakes, which can lead to structural and non-structural component damage, necessitating repair actions based on specific damage states and associated costs (Welsh-Huggins & Liel, 2017). Additionally, poor fire risk management can result in damage to property and surrounding structures, emphasizing the importance of mitigating fire risks during design and construction (Daryl Harris, 2020). Furthermore, the growth of plants with invasive root systems against building structures can exacerbate vulnerabilities, causing cracks and instability, highlighting the need for careful planning and selection of non-invasive plant species and root barriers to prevent damage (Al-Kodmany, 2023). Contrary to misconceptions, green facades do not inherently damage walls, but deteriorating structures can be accelerated by plant growth, especially in the presence of cracks or porous mortar joints, necessitating caution with certain plant species to avoid damage (Ottelé, 2011).

3.1 CASE STUDIES OF DAMAGED GREENERY- COVERED BUILDINGS

Since the greenery-covered building concept is relatively new, the number of damaged buildings recorded is limited or their damages are minor. However, there are some typical examples that can provide knowledge and failures to avoid. Below some case studies of damaged greenery-covered buildings are presented.

The common perception is that greenery systems on buildings are not a fire threat if they are properly maintained and keep green and alive (Dahanayake & Chow, 2018). However, there are some examples of such incidents. A fire incident was reported in Frankfurt, Germany, in a residential building. The fire spread throughout the wall, along the climbing plants, up to the neighbouring property. Another incident reported fire in a semi-enclosed beer garden in August 2012 in Sydney, Australia, where ferns in vertical greenery system caught fire from a candle. The vegetation in this fire incident was hand-watered, without a proper irrigation system. Furthermore, some synthetic plants were also integrated into this green wall (Dahanayake & Chow, 2018; Kotzen et al., 2023).

Another fire incident occurred at a Block of Flats in Ealing, London on 5 August 2018 (Figure 33). During the fire the living wall of the building and decking on the 7th floor of the residential building were destroyed. The external fire entered the building damaging parts of the 7th and 8th floor corridors. Dry vegetation was burning fiercely and crossing over from one part of the living wall across a door onto the 7th floor roof and a window on the 8th floor. The speed of fire propagation was remarkably fast. The cause of the fire was most likely a discarded cigarette or match (Kotzen et al., 2023).

Figure 33 Green wall fire in London, 2018 (Kotzen et al., 2023).

On 6 June 2018 a large living wall caught fire at the Mandarin Oriental Hotel Hyde Park (Figure 34). According to The London Fire Brigade the fire was started by an arc welding byproduct that got onto the felt lining of the planting façade.. The hotel's refurbishment included the installation of green living walls on five of the inner courtyard's façade.. The fire is believed to have spread across the vertical facade for plants and vegetation as well as into multiple floors of the hotel. A few parts of the hotel levels, the external planting façade, the roof and the plant machinery on the roof were severely damaged. Both inside and outside the building, the living wall served as a path for the fire to spread. In Figure 35 a part of Chengdu's Qiyi City Forest Garden in China is depicted. The towers were constructed in 2018 and plants were provided to reduce noise and clean up pollution. However, the plants thrived while sales were slow, and no one was pruning the greenery to keep it under control. As a result, empty balconies have cascading branches of plants overtaking space, blocking windows and in conjunction with the humid and semi-tropical climate greenery favoured the proliferation of insects.

Figure 34 Living wall fire at the Mandarin Oriental Hotel Hyde Park in London, 2018[13]

Figure 35 Balconies at Qiyi City Forest Garden residential buildings complex is overrun by plants in Chengdu, China, Sept. 15, 2020. (EPA Photo)

3.1.1 Case studies of damaged greenery- covered buildings in Thessaloniki, Greece

In the most cases in Thessaloniki, Greece the main damages are related to greenery damage due to negligent plant treatment. Damages on the buildings' envelope are also observed. For example, in Figure 36, the green façade of a company's building composed of self-climbing plants (ivy) shows gaps in vegetation cover, plaster removals and traces of moisture at the bottom of the building's pillars.

[13] https://www.ttgmedia.com/news/video-firefighters-tackle-huge-blaze-at-mandarin-oriental-hyde-park-14419

Figure 36 Green façade on a company's building in Thessaloniki with recorded damages on vegetation and building' s envelope https://maps.app.goo.gl/6ethyiDjWyXcnLJG6 (Source: Google Street View).

In Figure 37, the vertical garden that forms the face of the building of the Directorate of Urban Environment Management of the Municipality of Thessaloniki is presented. This intervention relates to the installation (2019) of a special grid on the outer shell of the building, with special recesses where removable pots (about 800) are placed and has special irrigation and drainage systems. The garden covers the external surface of the building over an area of 50 m^2 . In Figure 38, the building is shown in two different dates. it is observed that the plants have started to overgrow, hanging and covering the windows. Some dead plants haven't been removed as well, increasing the risk of fire propagation. In addition, the initial design of the garden aimed to highlight the colour changes of the plants throughout the year, however this was not maintained sufficiently, resulting in an aesthetic degradation.

Figure 37 Green façade implemented in a buidling of the Directorate of Urban Environment Management of the Municipality of Thessaloniki, https://maps.app.goo.gl/EU3bcfW1n6J63NTx5 (Source: In situ survey for the GREENERGY project-October 2024).

Figure 38 Green façade over the building of the Directorate of Urban Environment Management of the Municipality of Thessaloniki with overgrown vegetation https://maps.app.goo.gl/EU3bcfW1n6J63NTx5 (Source: Google Street View).

As can be observed in Figure 39 where details of the structure are shown, the condition of the green façade is considered satisfactory after 5 years, although some distortions in the supporting structure can be observed at the bottom of this figure.

Figure 39 Construction detail in the vertical façade applied in the building of the Directorate of Urban Environment Management of the Municipality of Thessaloniki https://maps.app.goo.gl/EU3bcfW1n6J63NTx5 (Source: In situ survey for the GREENERGY project-October 2024).

However, on closer observation (Figure 40), at various points under the pots that make up the structure, there are strong signs of corrosion due to the water used to water the plants. It is estimated that in the future this will also affect the building itself.

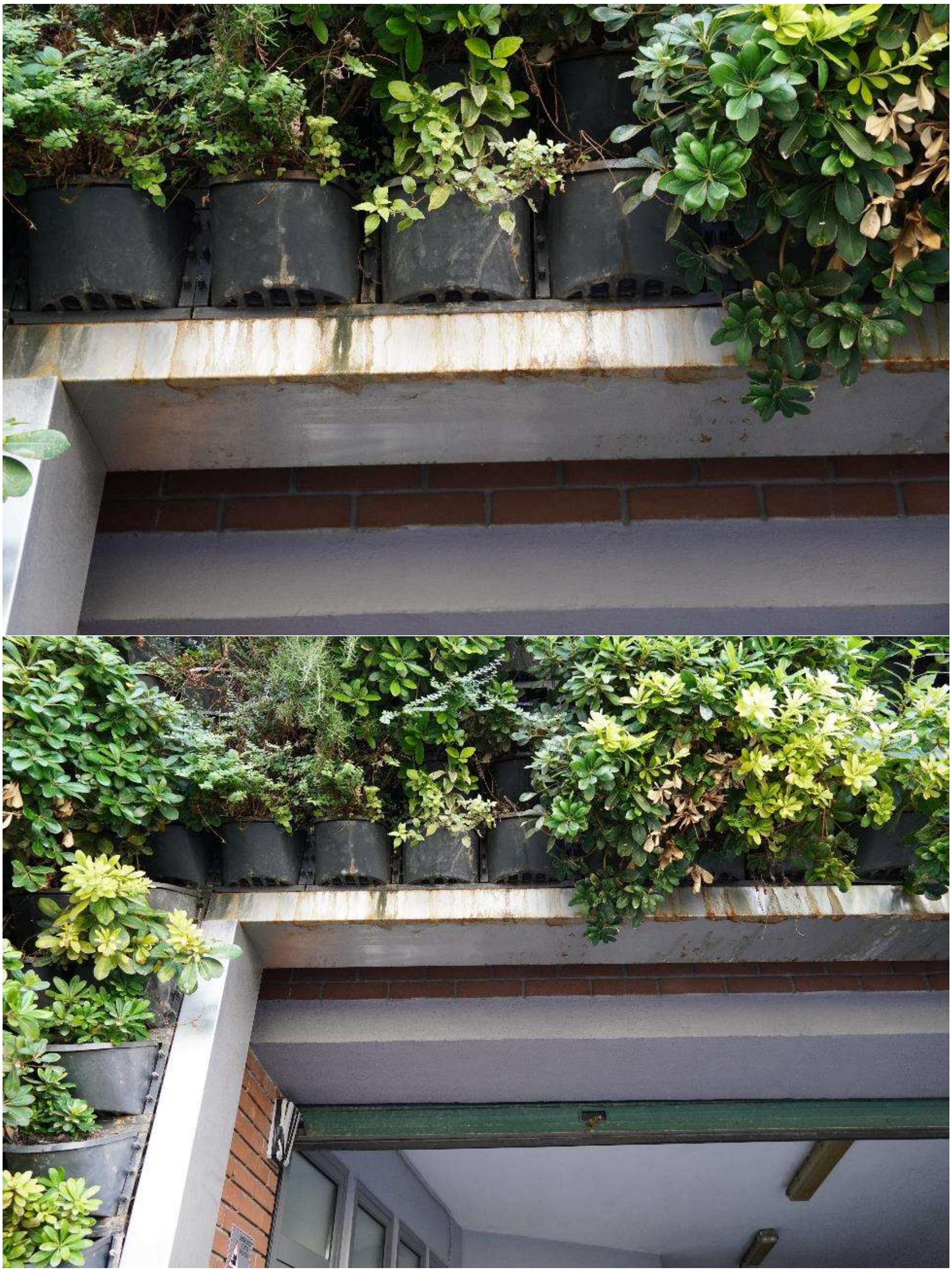

Figure 40 Corrosion phenomena of a metal infrastructure in the applied in the building of the Directorate of Urban Environment Management of the Municipality of Thessaloniki https://maps.app.goo.gl/EU3bcfW1n6J63NTx5 (Source: In situ survey for the GREENERGY project-October 2024).

Another example of green façade can be found in the 16th primary school of Thessaloniki (Figure 41) and involves the installation (2023) of a metal mesh with special stainless-steel wires which is fixed to the wall and leaves a small gap from the wall (about 3cm). The garden covers the external surface of the building in an area of 90 square meters.

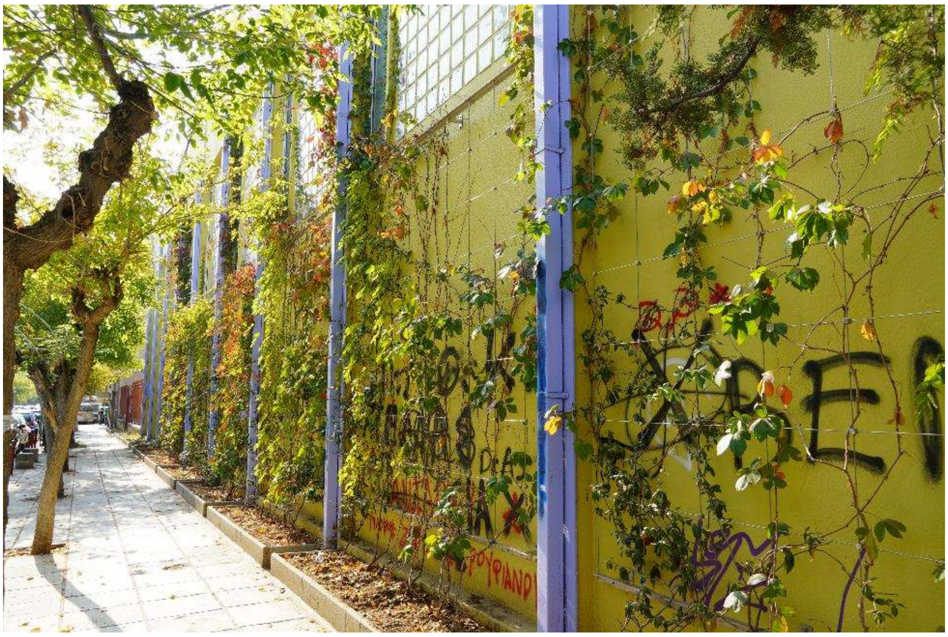

Figure 41 Green façade in the 16th primary school of Thessaloniki, https://maps.app.goo.gl/yE7XmPaVT9eYURCV9 (Source: In situ survey for the GREENERGY project-October 2024).

Figure 42 Green façade in the 16th primary school of Thessaloniki, https://maps.app.goo.gl/yE7XmPaVT9eYURCV9 (Source: In situ survey for the GREENERGY project-October 2024).

As shown in this case, in Figure 42, the structure is in good working order, although it appears that banners etc. have been placed on the metal mesh, which in general in the future are likely to result in the deterioration of the metallic material, but possibly also to the building itself.

Another case of a recently (2023) implemented green façade relates to the Community Centre of the Municipality of Thessaloniki.

Figure 43 Green façade in the the Community Centre of the Municipality of Thessaloniki, https://maps.app.goo.gl/cHY6b6JcR9s1svVD9 (Source: In situ survey for the GREENERGY project-October 2024).

This technology involves the installation of a metal mesh with special stainless steel wires which is fixed to the wall and leaves a small gap from the wall (about 3cm). The garden covers the external surface of the building in an area of 52 m^2.

Figure 44 Vandalism and construction failures in the green façade in the Community Centre of the Municipality of Thessaloniki, https://maps.app.goo.gl/cHY6b6JcR9s1svVD9 (Source: In situ survey for the GREENERGY project-October 2024).

As it can be seen in this case (Figure 44), due to the recent construction age, there is no damage to the building. However, construction failures or (likely) vandalism to the green façade infrastructure are evident.

In the case of the municipal swimming pool, located on the site of the former Courtyard Toumba (Figure 45)no damages were also observed. The green façade develop in 2023, involves the installation of a metal mesh with special stainless steel wires which is fixed to the wall and leaves a small gap from the wall (about 3cm). The garden covers the external surface of the building in an area of 12 square meters.

Figure 45 Green façade in the municipal swimming pool of Toumpa https://maps.app.goo.gl/CBUG6hePugKjR5qV6 (Source: In situ survey for the GREENERGY project-October 2024).

Another case of a public building (Environmental Education Center in Eleftherio-Kordelio, Thessaloniki,) with green roofs and planted species in balconies, leading to the formation of green façades is depicted on Figure 46. As it can be seen the vegetation on the roofs is extremely dry due to insufficient watering and improper irrigation system, whereas balconies are damaged mainly due to moisture leading to plaster removal and moisture streaks.

Figure 46 Green roofs and green covered façades of the Environmental Education Center in Eleftherio-Kordelio, Thessaloniki, with dry vegetation and damages on the building's envelope (https://maps.app.goo.gl/hntTBYYeyCa9Ab4LA) (Source: Google Street View).

In Figure 47 two building's façades are covered with self- climbing plants. On the front façade only the roots and the woody stem of the ivy is observed, meaning that the self-climbing plant is insufficiently watered. In addition, the plant has occupied the gutter system. On the other side of the building, the plant growth is dense, covering the entire facade and obstructing some windows as well. In both cases designation was not neatly arranged to provide a green facade with all benefits a vertical greenery system could provide. In Figure 48, a building is also depicted where the self-climbing plant, ivy as well, on its fades is dry and without leaves on.

Figure 47 Self-climbing plants over the façades of "Christos Tsakiris" - Center of Culture (Municipality of Pavlos Melas) in Thessaloniki. The plants are either overgrown or dry (https://maps.app.goo.gl/i9F1b2LkiGBTipyi9) (Source: Google Street View).

Figure 48 Dry ivy on façades of a private property in Thessaloniki https://maps.app.goo.gl/8uRomSae2V9wqKBh9 (Source: Google Street View).

In the following pictures, the green façades (installed in 2008) over the building hosting the Historical Archives of Macedonia are presented

Figure 49 Green façade in the building hosting the Historical Archives of Macedonia https://maps.app.goo.gl/SWY5F674hJ12NqnJ9 (Source: In situ survey for the GREENERGY project-October 2024).

As it was noticed, cracked in the building walls (Figure 50) and excessive dry matter (Figure 51) that increase fire risk were noticed

Figure 50 Wall cracks underneath the green façade in the building hosting the Historical Archives of Macedonia https://maps.app.goo.gl/SWY5F674hJ12NqnJ9 (Source: In situ survey for the GREENERGY project-October 2024).

Figure 51 Excess dry matter within the green façade in the building hosting the Historical Archives of Macedonia https://maps.app.goo.gl/SWY5F674hJ12NqnJ9 (Source: In situ survey for the GREENERGY project-October 2024).

Finally in the case of the 35th and 37th primary schools of Thessaloniki (Figure 52) we identified erosion and mould development

Figure 52 Green façade in the 35th and 37th primary schools of Thessaloniki https://maps.app.goo.gl/oZELaqJDvpm4TUyU6 (Source: In situ survey for the GREENERGY project-October 2024).

Figure 53 Erosion, cracks and mould development over the building 35th and 37th primary schools of Thessaloniki https://maps.app.goo.gl/oZELaqJDvpm4TUyU6 (Source: In situ survey for the GREENERGY project-October 2024).

3.2 FAILURE MECHANISMS

Most of the failures that result to building damage and greenery degradation are related to maintenance both considering the building itself and its green elements. Also, potential damages can occur if the initial design of the green- covered building is deficient as in the case of improper materials and plants species selection. Insufficient or excessive watering, inappropriate irrigation and drainage systems, poor plant care (e.g. pruning), inadequate soil volume and planters, plant species selection, and non-resistant construction/planting materials are some of the main factors. Non-adaptation of the fire and seismic regulations also increases the fire risk and earthquake damages, exposing buildings to danger and increasing the repairment cost and time. Residents, as the end users of such infrastructure can be directly affected in many different aspects.

As mentioned above, in the case of fire outbursts at buildings with green façades and living walls the main failures are related to the plants care. Dry vegetation and low moisture content levels significantly contribute to the fire propagation. Hand-watering and flammable materials such as plastic, also affect the fire propagation rendering the consequences more intense. In addition, till now, there is little research on the combustibility properties of plant species used in green living walls (Kotzen et al., 2023), meaning that selecting the wrong species could negatively impact fire propagation. Abandoned plants due to unoccupied houses, have also caused insect and aesthetic issues to residents as well as uncontrolled vegetation growth, covering windows and exits. Furthermore, insufficient planter sizes lead to distorted vegetation growth and fact that affects trees stability, causing falls especially during severe winds. The selection of inappropriate structural materials without considering the additional weight and moisture of the plants often lead to plaster removal and mould development and can harm walls and foundation integrity.

Besides damages mentioned above, seismic loads can cause excessive damages to buildings. Regarding greenery covered buildings, earthquake induced damages are expected but not recorded yet. However, in terms of repair costs and repair time, the demands are higher (Welsh-Huggins & Liel, 2017).

3.3 PREVENTION MEASURES PER RISK

Awareness of the failure mechanisms both during the construction and maintenance phase of a building, can contribute to the implementation of prevention measures. This approach can help avoid many of the aforementioned damages and risks or at least ensure that repairs will be carried out at the lowest possible cost and time.

3.3.1 Humidity and integrity related issues prevention

More specifically, in order to prevent wall integrity damages, Portland cement in the mortar instead of lime is preferred (Thomsit-Ireland, 2018). Especially for retrofitted buildings the weight of vegetation and additional water should be taken into account when calculating the structural load. Using lightweight recycled plastics and media will significantly reduce the overall weight. Patric Blanc also designed a very lightweight vertical greenery system with less than 29 Pa (Taher et al., 2018).

Proper selection of tree and plant species is crucial to avoid root penetration effects as well; non-invasive root systems can help mitigate the risk of these damages. Additionally, using specially designed root barriers and structural systems can help guide root growth away from critical areas of the building. The presence of climbing plants, such as ivy, is generally safe as long as the building's materials are carefully chosen and there are no pre-existing damages, such as cracks and damp (Thomsit-Ireland, 2018). If a wall is already wet, it must be allowed to dry once the sources of the water intrusion have been addressed. This needs to be completed before any vegetation is placed in front of the wall since plants slow down the pace at which water evaporates from the wall surface. Rainfall interception counteracts any rise in humidity brought on by evapotranspiration by the plant. Buildings that were dry before greening and that are well built without cracks or other flaws shouldn't experience damp problems. Additionally, cavity walls are frequently ventilated using weep vents, although the absence of cavity ventilation may indicate that a building wall is not suitable for direct greening (Thomsit-Ireland, 2018).

3.3.1.1 Technical solutions for building retrofitting

Retrofitting existing roofs to incorporate green roofs requires raising the perimeter edges to accommodate the increased thickness of the new roof layers. This is particularly challenging for historical buildings due to their original construction techniques, (e.g. delicacy of wooden roofing), and the presence of large decorative elements, including finely worked ledges and gutters, making interventions that affect the eaves, ledges, ribs become even more complex (Santi et al., 2020).

While uplifting the perimeter edges of a roof, a cant of the ribs can be provided through the mechanical connection of the structures, along the perimeter of the existing structure, to which the new roof flashings could be anchored. The roofs could also be incorporated into the existing ledges, taking into account the building legislation to prevent the risk of falling from high buildings to ensure stability and safety requirements. Furthermore, for the accumulation of rainwater and irrigation water, the correct sizing of the existing downspouts must be taken into account, which, if necessary, must be integrated with new ones by interfering with the existing structures, by creating holes to allow the connection of the covering to the downspouts installed along the perimeter of the building; in addition, in order to allow accessibility and maintenance of the drains, some control wells must be installed (Santi et al., 2020).

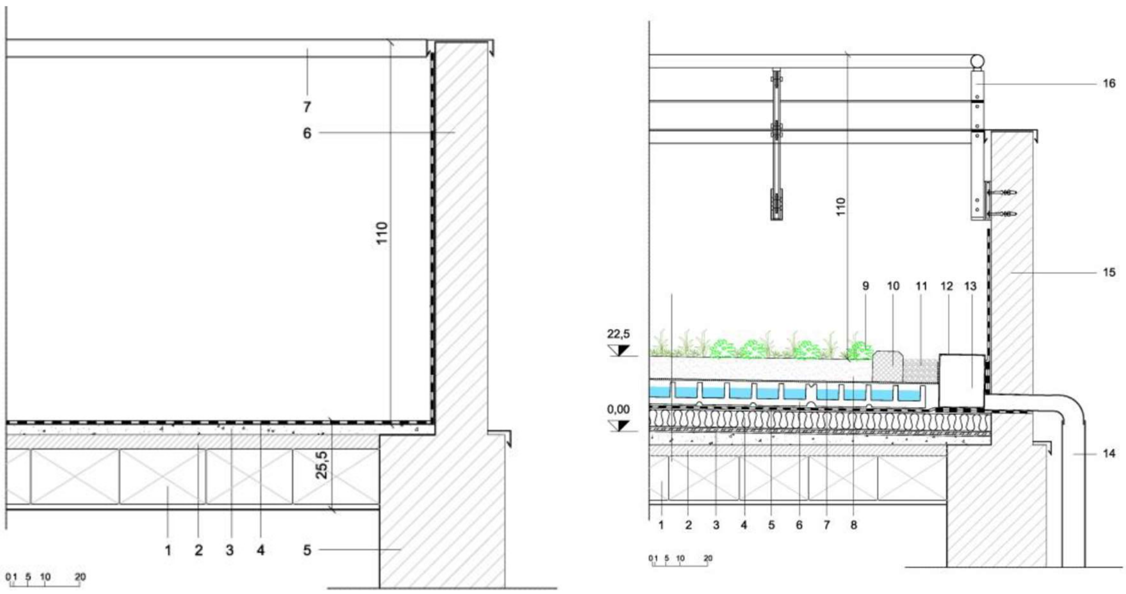

Figure 54 Flat roof (left) and flat green roof after retrofitting (Santi et al., 2020).

With regard to green façades and living walls, the necessity of drilling through the masonry, often uneven, to connect fixings and the stability problems this entails, must be carefully analysed. Of particular importance is the calculation of the dimensions of the fixings (Santi et al., 2020). Furthermore, the anchorage could be designed to be non-invasive and allow the green facade to be installed on any building and structural system (wood, concrete, steel, masonry) through a precise dry connection to the load-bearing structure (Sciuto et al., 2019).

In both cases the choice of intervention must be oriented so not to seriously affect the existing structure and maintains the present load conditions, both of the wall and of the coverage almost unchanged. As far as green roofs are concerned, light interventions are indicated, as their load is almost exclusively represented by the presence of water in the substrate and in the accumulation and drainage layer (Santi et al., 2020).

3.3.2 Fire safety

Fire safety measures to protect both occupants and the building itself have to be considered. Designers and engineers are frequently required by national building rules to come up with methods to prevent fires from spreading via external cladding or façades. To address this issue, particular measures must be implemented to control the fire risk that vegetation poses.It is crucial to comply to relevant legislation, which calls for strategies that reduce the risk of fire. The maintenance and management of the vegetation itself is one of the many aspects covered by these strategies.Controlling the amount and condition of the vegetation is an essential part of fire risk management. To lessen the chance of a fire starting and spreading, it is crucial to keep the vegetation within certain size ranges and avoid letting it dry out. Incorporating suitable evacuation and fire suppression systems is also necessary to guarantee a safe evacuation and prompt response in the event of a fire. Maintaining and handling vegetation properly is essential to preventing fires. Keeping the amount of organic matter in the soil low can assist avoid ignition and reduce the risk of fire. Frequent irrigation and trimming practices also help to lower the risk of fire outbreaks.(Al-Kodmany, 2023; Kotzen et al., 2023). If a greenery system consists of a wide range of plant species, it is important to understand fire behaviour of each plant species, since different plant species may behave differently when subjected to fire (Dahanayake & Chow, 2018). The risk of fire can be reduced by selecting plants with low peak heat release rates and low total heat release (Kotzen et al., 2023).

3.3.3 Maintenance

Vertical greenery systems need to be designed in such a way that gardening crews are able to maintain, replant, and provide overall care for the plants and should have unrestricted access to the systems. Therefore, access for maintenance and designated area for personal lift should be considered in the initial design (Tan, 2020). To reduce maintenance complexity and cost, species selection is a crucial factor; hardy plants, plants appropriate to the site's microclimate (tolerant to sun and shade) and compliant with owners' expectations should be preferred. Rate growth and weeding as well as fertigation and irrigation systems with low maintenance needs (Tan, 2020) should also be taken into account.

3.3.4 Safety

Compared to rooftop greenery, vertical greenery systems pose a greater risk of access and fall protection concerns. Trees, creeper vines, and other vegetation that hang over a building's roof pose significant safety risks. Facade cleaning crews will face significant difficulties. As a result, ledges should receive extra attention when it comes to fall prevention and protection. The height of the greenery shall not be greater than its horizontal distance from the roof edge or top of the parapet unless fall protection measures are in place for vertical plants above ground level on roofs, terraces, and other upper surfaces. Stated differently, the vegetation should be positioned away from the building's edge to minimize the distance in the event of a fall or equipment failure. Fall protection and safe access options are essential when designing a greenery system for building ledges, and as such, they must be taken into account during the design stage while organizing the installation and maintenance process. (Wang et al., 2019).

3.3.5 Weather exposure

Studies have investigated the impact of wind loads to buildings in order to determine the resilience of greenery and to prevent tree falls and uproots. Argentini et al., (2010) demonstrated small and full-scale wind tunnel experiments of a vertical forest within a boundary layer wind tunnel, analysing the impact of aerodynamic wind pressure on the hardwood trees on the balconies. It was found that the aerodynamic forces acting on the trees, exhibited significant magnitude in specific directions, while all measured points of the wind environment were acceptable with respect to quick and slow walk cases. Wang et al., 2019) studied the wind loads on different tall building's façades both with and without trees. It was concluded that the planted trees on balconies have a limited effect on the mean and extreme wind forces experienced by the windward and leeward sides of buildings. Nevertheless, the existence of trees did contribute to a reduction of mean and extreme wind forces on the sidewards façades. Additionally, the effects of trees on the extreme pressure coefficient were greater than that on the mean pressure coefficient. Having trees on buildings increased the range of wind effects at a 90° angle compared to buildings without trees. This is likely due to the extra turbulence caused by the trees on the balconies. Planted trees on buildings decreased the intensities of local wind pressure on separation and lift fluctuating forces. The presence of trees on balconies increased the values of fluctuating torsional moment.

Vertical forest designers have proposed different devices to maintain security of trees planted on balconies under strong wind. Windbreaks, wind resistant plant species, and structural reinforcements can help to mitigate the negative effects of wind stress on greenery systems (Manouchehri et al., 2024). In the case of Bosco Verticale in Milan, the stability of trees in windy conditions is ensured by fastening them to the structure with steel cables. The largest and most vulnerable trees were encased in steel safety cages and secured in place once the structure was finished. According to structural engineers, smaller and larger trees are equipped with a safety cable to mitigate the risk of toppling in case of trunk collapse. The largest trees in areas most susceptible to strong winds are enclosed in steel cages that restrict the roots and prevent uprooting during severe wind events (Al-Kodmany, 2023; Giacomello et al., 2015).

3.3.6 Environmental and socio-economic aspects

The influence of climate is of great importance regarding energy savings, and type of greenery system and materials selection. Vertical green systems in temperate Mediterranean climates outperform those in temperate oceanic regions due to higher energy savings for cooling during summer, underscoring the benefits of vertical green systems as a passive insulation technique for buildings. In colder climates, vertical green systems installations are not economically viable from an energy perspective leading to minimal heating energy savings. Consequently, the payback time for vertical green systems in terms of energy savings is quite long and the geographic location should be carefully considered (Taher et al., 2018).

In addition, the analysis of microclimate conditions of the selected location is a key factor of vertical green system type, plants species and planting media selection, contributing to the successful growth of the planned system (Čekić et al., 2020). The selection of materials has a wide range of effects on the environment. Panels, planter boxes, tubes, and support structures are examples of construction materials that are not environmentally friendly because they are all synthetic materials made from steel, aluminum, or crude oil. Living wall systems have a greater environmental impact than green façades because the production of these materials is detrimental to the environment. Conversely, using organic and ecological materials for green façades—like wire, steel, and wood—creates viability risks because of water, microbes, and the low pH of these systems (Tzortzi & Sophocleous, 2018). In addition, Ottelé (2011) demonstrated that direct green façades were more cost-effective and environmentally friendly than modular living wall solutions.. For living walls, lowering the amount of materials used, using longlasting and eco-friendly solutions, and adding drip irrigation and water-retaining planter boxes promotes both financial gains and environmental sustainability. (Senalankadhikara et al., 2024).

Regarding water consumption, the possibility of water recycling from the irrigation systems, the implementation of a catch basin to control falling water (Tzortzi & Sophocleous, 2018) and the utilization of rainwater or greywater can further contribute to water waste reduction. The irregular precipitation, drought periods, and lack of natural water storage necessitate additional irrigation (Hoffmann et al., 2023). To conserve water, Manso & Castro-Gomes, (2015) suggest using gravity-fed vertical irrigation to arrange plants with higher water requirements at the bottom and those with lesser requirements at the top. In order to irrigate bigger amounts without running the danger of runoff, Martensson et al. recommend substrates with good water retention (Mårtensson et al., 2014). Irrigation systems require routine maintenance to fix leaks, check controllers and sensors, remove debris from injectors, replace electronic components as necessary, and ensure appropriate water flow and pressure. (Ascione et al., 2020; Senalankadhikara et al., 2024).In socio-economic terms, the adoption of vertical green systems is linked to a country's GDP and motivations, with higher implementation rates in wealthier and denser cities (Taher et al., 2018).

4 CONCLUSIONS

The continuous expansion of urban fabric and the human distancing from nature along with environmental degradation and climate change, create the need for urban greening. Since open green spaces are shrinking, a relative new concept has emerged in order to exploit all the possible surfaces of urban ecosystems to make them greener. Thus, designers have introduced the idea of integrating vegetation on buildings. Green façades, living walls, green roofs and vertical forests are some of the most popular types of building greenery systems.

Building greenery systems provide various benefits regarding environmental protection and human well-being. Urban heat island mitigation, urban climate improvement, energy savings, buildings protection from wind and solar radiation, construction materials durability, biodiversity support, aesthetics and so forth (Pérez et al., 2014). On the other hand, the design of such buildings has high requirements regarding construction and maintenance cost. Additional structural materials must be used in order to support the additional weight of plants, planting media, structures that support/attach vegetation and irrigation systems. This not only increases the construction cost, but also requires additional investments in infrastructure and equipment (Al-Kodmany, 2023).

Additionally, repairing potential building damages requires consideration of the vegetation as well, which increases both the cost and time of repair. The most common damages of greenery covered buildings are related to the presence of the vegetation itself and its improper integration and/or conservation. Systematic maintenance routines should take place to prevent structural and greenery degradation. This involves, for example, ensuring adequate watering of plants while preventing any water leaks that could cause moisture problems in the buildings.

Buildings may experience various damages regarding their envelope integrity. Root growth and action, plant direct attachment, high level of moisture are the main causes of damage. These often lead to cracks, stability issues, plaster removal and mould development both indoors and outdoors. Potential water leaks from irrigation systems can create moisture issues to the buildings as well. On the other hand, vegetation may experience degradation mainly due to improper irrigation systems, difficulty of access by gardening crews and restricted space. These factors can increase plant stress, and lead to dead or dry vegetation. Both buildings and vegetation damages burden on the residents with various concerns. Additional cost, safety issues, insects, pests and aesthetic issues may arise. In addition, it has to be ensured that greenery does not compromise the quality of indoor environments by obstructing views, diminishing daylight, or causing issues related to moisture, humidity, and temperature regulation (Al-Kodmany, 2023).

Plants on buildings may have a key impact during the outburst of extreme events and harsh conditions. Extreme events, such as fires, earthquakes and strong winds may have different consequences on greenery covered buildings due to vegetation presence. Dry plants for instance can accelerate the spread of the fire, whereas strong winds, especially on high-rise buildings can uproot trees if they are not properly secured. Earthquakes, on the other hand, can cause damages that require high repair costs.

In order to take advantage of the benefits from greenery-covered buildings there are many aspects to be considered. From a structural perspective it has to be ensured that the right materials are chosen. Structural materials capable of enduring the additional challenges and demands of integrated vegetation are necessary. From basic materials such as cement and plaster to specialised constructions to support vegetation must be carefully tested. Plant species have a crucial role as well. The kind of greenery system to be chosen, the planting media to be used and the location of planting are of high importance as well. Moreover, due to vegetation's variability across time and space (shape, weight, foliage density), its benefits and drawbacks are neither immediate nor constant in time. This aspect makes it difficult to quantify its behavior, which might compromise its use in structures as engineers and architects must regulate every design variable, particularly during the design phase. (Pérez et al., 2014). From an energy perspective, these buildings can contribute to energy savings, regulating temperature. For example, during the summer months in Hong Kong, an average daily electricity savings of 16% was attained by implementing vertical greenery (Leong et al., 2021). However, weather conditions and elevation in conjunction with daylight blocking can lead to the opposite results, especially during winter.

Greenery- covered buildings must meet the housing needs and welfare of their occupants. Therefore, it is crucial to address drawbacks such as safety and health issues. Integrating green elements as early in the design process is of high importance and the high cost of initial investment and maintenance should not hinder the successful and safe construction of greenery-covered buildings (Makalesi & Ekren, 2017). Careful consideration of construction, emergency preparedness, and long-term maintenance may ensure sustainability and resilience of both common and innovative structures like the Vertical Forest buildings (Li et al., 2023). By leveraging existing knowledge, challenges can be mitigated, despite the limited understanding of the long-term performance of such structures[14].

[14] https://www.rmmagazine.com/articles/article/2009/11/01/-The-Hidden-Risks-of-Green-Buildings-

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