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LOW-CARBON & LOW-DAMAGE TECHNOLOGIES FOR IMPROVING THE RESILIENCE OF BUILDINGS

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Abstract: *The transition towards a resilient and sustainable built environment is a key priority for current policies worldwide. In seismic prone areas, this means prioritizing seismic safety and energy efficiency, while minimizing the embodied carbon of buildings. To achieve this overarching goal, it is essential to adopt high-performance resilient technologies that can reduce the post-earthquake damage and minimize the related socio-economic-environmental losses: modular systems made from bio-based materials are very promising in this regard and can also reduce construction waste over the entire life cycle of the building, including demolition and recyclability. But their economic, environmental and resilience benefits have yet to be proven. Focusing on new-build, this paper focuses on the application of a low-damage & low-carbon technology for improving the seismic resilience of buildings in a sustainable manner. A high-rise building is considered as a case study for developing the investigation, due to the large impact of these structures on communities and their significant economic value involved from the design through construction and use. A prefabricated low-damage or (quasi-)"earthquake-proof" timber-concrete building is designed, consisting of innovative cost-affordable details for structural components and facades that are modular, easily demountable and relocatable. A numerical model of the building is developed to perform non-linear time-history analysis and intensity-based loss modelling simulations to quantify the damage-related economic and environmental losses as well as the seismic resilience. A life-cycle analysis is also performed to determine the sustainability level associated with the use of low-carbon and energy efficient solutions. The proposed system is compared to a traditional code-compliant reinforced concrete building. The results demonstrate that the use of low-damage low-carbon technologies can enable significant reductions of approximately 40%, 50%, and 35% in economic, environmental, and resilience loss, respectively. These findings suggest that low-damage low-carbon technologies offer a promising solution for creating a more sustainable and resilient built environment.*

Introduction

Recent earthquake disasters, such as the devastating Turkey and Syria earthquake of 2023, have once again brought to the spotlight the vulnerability of our built environment, highlighting the significant impact of seismic events on communities. The aftermath of such disasters can lead to severe consequences, including economic losses, casualties, and environmental damage, underscoring the critical need for safer and more resilient structures. In parallel, there is an urgent need to improve the energy efficiency of buildings, with global efforts being made to support the transition towards a sustainable society that reduces carbon emissions. Therefore, building a resilient and green society is now recognized as a socio-economic and political priority, and the overarching goal of risk reduction and management policies. Within the construction sector, this means that buildings should be designed to withstand and recover from the effects of external events while adapting to the changing environment.

In recent years, there has been a growing focus on the urgent need to improve the resilience of the built environment, leading to the emergence of studies on loss assessment and resilience analysis. Although empirical models have been developed to estimate damage and losses (e.g., Crowley et al. 2021), the Performance-Based Earthquake Engineering (PBEE) methodology provides a more comprehensive probabilistic component-based approach to earthquake loss modelling (Moehle and Deierlein 2003, Porter 2003). PBEE allows for the direct evaluation of

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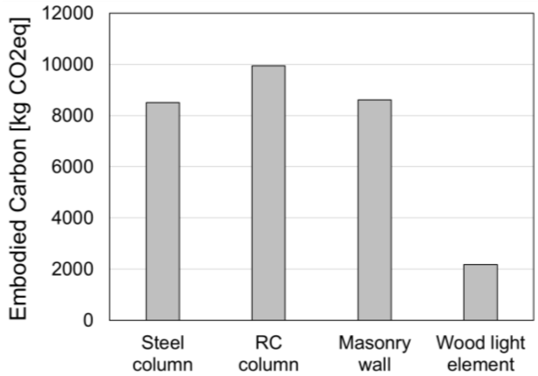
performance measures such as economic losses, downtime and casualties, that are relevant to stakeholders for managing decisions related to investments and seismic risk mitigation. Several assessment investigations are therefore available in the literature, including scenario or intensity-based analyses as well as time-based assessments (e.g., Cardone et al. 2019, Arifin et al. 2021). Recent studies are also exploring the potential negative impact of seismic damage within life-cycle assessments, in order to quantify the embodied carbon associated with repairing the post-earthquake damage (Figure 1a). Integrated investigations are also being conducted to assess the overall potential damage-related impacts in terms of socio-environmental-economic losses (e.g., Gavrilovic and Haukaas 2021). These findings emphasize the need to improve the seismic design of buildings to target integrated safety and environmental sustainability levels. Meanwhile, general frameworks have been developed to assess the seismic resilience of buildings (Figure 1b), with practical applications mostly focused on exploring solutions to enhance the resilience of existing buildings designed according to pre-seismic code provisions and further affected by natural aging and potential deterioration of mechanical properties of materials (e.g., Samadian et al. 2019). Although methods are still being developed and research efforts are growing, resilience considerations should be incorporated into the design process for both new construction and retrofitting interventions to ensure that buildings can withstand the impacts of disasters.



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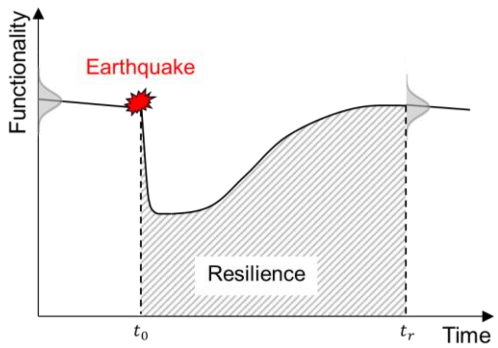

(b)

Figure 1. (a) Embodied carbon associated to the full replacement of different single structural members (data elaborated from Simonen et al. 2018). (b) Definition of resilience within a functionality vs. time curve, including degradation.

Technological advancements are also crucial for enhancing the resilience of the built environment, and researchers are focusing on developing innovative solutions for this purpose. Traditional strengthening interventions and conventional designs are no longer acceptable as they disregard sustainability principles and may result in post-earthquake damage. Instead, cost-affordable low-damage solutions are being explored, such as rocking dissipative hybrid connections. These connections (referred to as PRESSS technology for concrete, Priestley et al. 1999) consist of precast elements jointed together through unbonded post-tensioning tendons/cables, creating moment-resisting connections with very high seismic performance and negligible residual or permanent deformations after earthquakes. Additionally, there has been an increasing demand for low-carbon construction materials, leading to the extension of hybrid systems to engineered timber or mixed timber-concrete buildings (Palermo et al. 2005; Pampanin et al. 2020). Researchers are also focusing on low-damage solutions for non-structural components, by introducing simple modifications to existing construction details or by employing dissipative connections. A collection of alternative low-damage technologies for architectural components is discussed in Bianchi and Pampanin (2022). These low-damage solutions for structural and non-structural systems can be combined with nature-based materials to create the next generation of low-carbon resilient buildings characterized by enhanced safety, energy efficiency, environmental sustainability and improved quality of life.

Based on the above discussion, this paper explores the application of cost-effective low-damage technologies for timber-based structural/skeleton systems and multi-layer facades to create a (quasi-)"earthquake-proof" low-carbon building system. The benefits of the proposed solution when compared to a traditional solution are presented in terms of economic losses, life-cycle carbon emissions and resilience quantification.

Research Methodology

This paper discusses the advantages of using low-carbon and low-damage solutions for improving the resilience of high-rise buildings. These types of buildings have indeed significant impacts on society, urban planning, and the economy of cities. In the past, these structural systems were primarily designed for business purposes, and each project was treated as an isolated case. However, with the increasing popularity of high-rise buildings worldwide, they are now being used for residential and commercial purposes as well.

The flexibility of rocking dissipative connections makes this low-damage technology a highly attractive option for enhancing the design of high-rise buildings, as proven by initial studies by Ciurlanti et al. (2019). This technology can be efficiently implemented in a dual wall-frame lateral-resisting system configuration, which provides a better control of inter-story drift levels for high-rise buildings. The counter-balancing stiffnesses and deformed shapes of the wall at lower floors and of the frame at higher floors allows for an overall enhanced control of the displacements of the structural/skeleton system throughout the elevation.

To enhance the sustainability of high-rise buildings, this research studies the feasibility of implementing a cost-effective low-damage timber-concrete system covered by lightweight timber facades. The combination of concrete and timber offers an efficient solution, as concrete provides the required stiffness to the structure, while timber's lightweight properties help to reduce demands on the superstructure and foundation system. Additionally, the use of timber can provide significant benefits from a life-cycle analysis viewpoint, including easy recyclability and minimal waste during demolition. Furthermore, the use of dry jointed precast structural connections and *Plug & Play* facade systems offers modular replaceable and easily relocatable components, as well as advantages in construction phases, such as increased quality control, erection speed, and safer and cleaner work areas.

This study compares the performance of a low-damage, low-carbon system with a traditional cast-in-situ concrete structure. The two buildings are designed using a displacement-based design procedure, modified to take into account the effect of higher modes on the building's displacement profile (Abellán et al. 2012). Numerical investigations are conducted using adaptive push-over, cyclic push-pull, and non-linear time-history analyses, employing a lumped plasticity model. Following the PBEE methodology, the numerical results are used in a loss assessment to quantify the overall post-earthquake damage, as well as the related economic and environmental impact. A whole life-cycle analysis is also conducted to consider the expected operational and embodied energy of both buildings. The results from the loss assessment are further analysed to determine the resilience associated with a maximum credible earthquake intensity. Finally, a practical multi-criteria approach is adopted to visualize the overall benefits of applying the proposed strategy in earthquake-prone countries. This simplified approach combines economic, environmental and resilience indicators to assess the potential of applying the low-damage low-carbon system. It is highlighted that, although research on multi-criteria procedures exist and it is further developed especially in façade engineering, existing studies have focused on the construction and the operational energy efficiency (choice of technology, design of control strategy, occupant comfort) (e.g., Montali et al. 2019), whilst there is little or no research that includes resilience.

Application to a case study

The case study is a 18-story reinforced concrete high-rise building located in Messina, a high seismic area in Italy. The building scheme derives from a previous study conducted by the same authors (Ciurlanti et al. 2022). The building properties are shown schematically in Figure 2. The building has a plan dimension of 22.05 m in both structural directions, with each direction featuring three spans of 7.35 m. It stands 54 m tall and has an inter-story height of 3 m. The building's lateral loads are resisted by two internal frame-wall systems in each direction. A 0.25 m thick, two-way spanning flat slab act as a floor diaphragm and is properly connected to transfer floor forces to the seismic-resistant systems. The building has a seismic mass of 736.0 t per floor, with an additional 719.8 t of mass on the roof. The building's façade is a modular prefabricated steel-stud panel system with external insulated precast cladding panels and double-glazing windows, connected to the structural system by means of tie-back connections. (thermal transmittance of 0.22 W/m2K, in order to satisfy the national guidelines for energy efficiency of building envelopes). Furthermore, all the other architectural components (drywall gypsum partitions, suspended ceilings), equipment (ideal HVAC systems) and contents (desktops, modular office tables, etc.) are identified and included in the loss modelling.

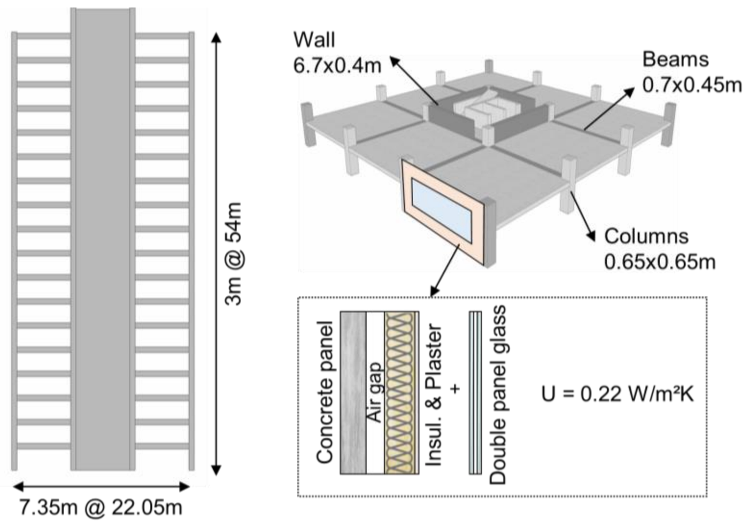

Figure 2. High-rise building dimensions and components' properties.

An alternative design solution is proposed based on this building scheme. This solution consists of a timber-concrete low-damage structure with concrete core walls, timber-concrete frames (consisting of glued laminated timber beams and concrete columns), cross-laminated timber floors and stairs. Low-damage structural connections are employed, consisting of external *Plug & Play* dissipaters (Sarti et al. 2016) in the beam-column joints and wall-foundation connection, and internal post-tensioned tendons/bars in the beams and walls. The building's facade utilizes modular prefabricated panel systems, external insulated wood-based cladding panels and double-pane low-e coating windows. The facades are connected to the main structure by means of dissipative U-shaped connections.

Structural design

Both the conventional monolithic (cast-in-situ) and low-damage timber-concrete structures were designed using the principles of Direct Displacement Based Design (DDBD) (Priestley et al. 2007, Pampanin et al. 2010), adapted for dual frame-wall systems (Abellán et al. 2012). A design drift limit (θ_d) was assumed for both structures taking into account relevant codes, best practices, and material strain limits. A frame overturning-moment ratio (β_F) of 40% was also considered, which represents the contribution of the frame-only system to the total (frame-wall) system's overturning moment. For the low-damage connections, a minimum Re-Centring ratio (λ_F) of 1.25 was selected as minimum value suggested by codes. This ratio defines how the overturning moment is distributed between the re-centring elements (tendons/bars) and the energy dissipation devices. The design of both high-rise building systems is based on a Maximum Considered Earthquake scenario with a return period of 2500 years (T_R). To determine the appropriate design seismic demand, a corner period (T_D) of 5.5 s and a peak (plateau) displacement spectral ordinate (Δ_D) of 997.63 mm were computed using the equations provided by Faccioli et al. (2004). These values are a function of the Moment Magnitude (M_w = 7.5 according to the fault characteristics of Messina), fault rupture distance r (20 km), and local soil factor Cs (assuming a firm ground soil with Cs = 1). Given the earthquake scenario and the high fundamental period of the building (2.6 s), the elastic pseudo-displacement response spectrum was defined and used to develop the DDBD procedure for both case-study buildings. Table 1 summarizes the main design parameters obtained from the displacement-based design approach.

Parameter	**Monolithic**	**Low-damage**
Effective Height, H_e [m]	38.3	38.7
Design Displacement, Δ_d [mm]	660.8	669.6
Effective Mass, m_e [t]	9377.5	5165.5
Effective period, T_e [s]	5.5	4.7
System Damping, ξ_{sys} [%]	19.6	11.6
Effective stiffness, K_e [kN/m]	11990.2	9113.2
Total Overturning Moment, OTM [kNm]	151867.4	118184.8
Total Base Shear, V_b [kN]	3961.4	3051.1

Table 1. Design parameters for the dual system.

As observed from Table 1, the low-damage timber-concrete structure exhibits a lower seismic mass than the conventional reinforced concrete system, due to the lightweight nature of timber components. In addition, the low-damage structure has lower damping as a result of the high contribution of the elastic structural behaviour and a less dissipative hysteresis loop. Finally, the base shear was distributed throughout the two lateral-load resisting systems to design the details of the monolithic vs. low-damage connections, i.e. the steel reinforcement (number and diameter of rebars) of the monolithic members, and the properties of the post-tensioned cables/tendons (type, initial force) and the external dissipaters (diameter, fuse) for the low-damage system.

Seismic analysis

The case-study buildings were numerically modelled using Ruaumoko2D (Carr 2003) software. A lumped/concentrated plasticity approach was used to represent the beam-column, column-foundation or wall-foundation connections where inelastic behaviour is expected. The joint panel zones were modelled as rigid elements, while the structural elements were represented as elastic members connected via rotational springs with moment-rotation relationships and proper hysteresis rules. For the monolithic reinforced concrete building, the connections were designed to develop a beam sidesway mechanism for the frame system, and the rotational springs represented the plastic hinge regions characterized by a Takeda hysteresis rule. For the low-damage building, two rotational springs were introduced in parallel at the end/interface sections of the structural members to simulate the combined action of energy dissipation (using the Ramberg-Osgood hysteresis rule) and re-centring (using the multi-linear elastic hysteresis rule). The base joints were fixed (translational/rotational), ignoring the contribution of soil-structure interaction. The building facades were not modelled in this investigation.

The numerical models were first validated through non-linear static analyses, including adaptive push-over and cyclic adaptive push-pull analyses. These analyses improved the understanding of the buildings' behaviour before dynamic analyses were conducted. The timber-concrete solution was found to have, in general, lower stiffness and strength, as expected, when compared to the monolithic reinforced concrete counterpart The assumption made during the initial design, which required the displacement shape to be equal for both systems, was confirmed through the push-over analyses. Non-linear dynamic analyses were then conducted to compare the seismic behaviour of the buildings in terms of floor accelerations, floor displacements, inter-story drift ratios and residual drift ratios. To this end, seven spectrum-compatible accelerograms were selected from the European Strong Motion database (Figure 3a). The numerical results from the time-history analyses are presented in Figure 3b for both buildings.

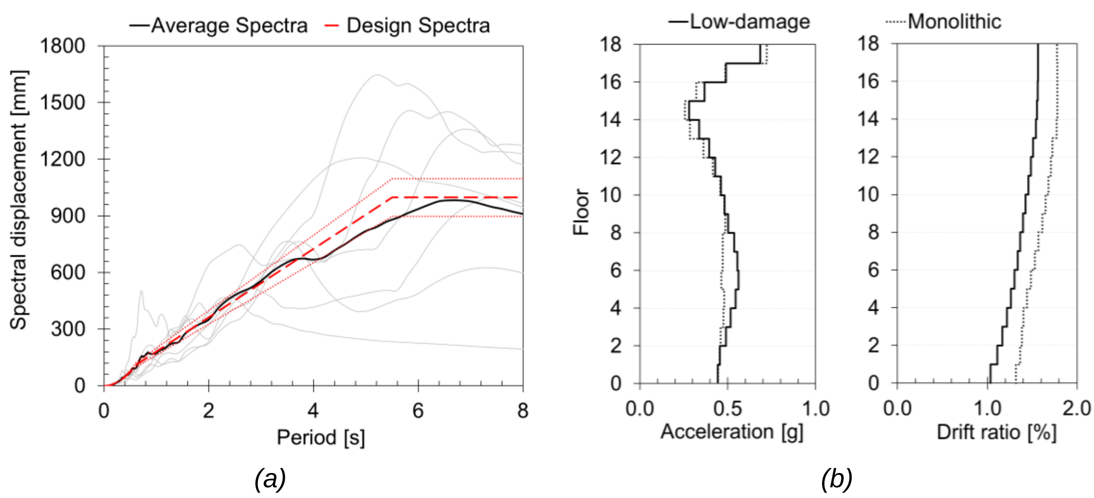

Figure 3. (a) Selected ground motions with average displacement spectrum. (b) Results in terms of peak floor accelerations and inter-story drift ratio.

The results of the study show that the low-damage system produces higher accelerations at lower floors, while both buildings experience increased acceleration at upper stories due to higher mode effects. This heightened demand for acceleration-sensitive components may result in higher damage. In terms of inter-story drift ratios, the monolithic building exhibits higher values when compared to the low-damage structure, which aligns with the design procedure as no value exceeds the design level drift of 1.8%. Additionally, the implementation of the innovative technology greatly reduces the post-earthquake residual displacements, which are crucial in determining the level of structural safety after earthquakes and can have significant socio-economic consequences if not managed effectively. Numerical results show residual drift ratios as high as 0.4-0.5% for the monolithic building, while almost negligible values of 0.02-0.06% for the low-damage structure.

Post-earthquake losses

A probabilistic loss assessment methodology, based on FEMA P-58-1 (2018), was developed to investigate the intensity-based post-earthquake losses in terms of repair costs and repair time. The intensity-based analysis assumed a 15% higher replacement cost for the low-damage building compared to the benchmark cost of the monolithic building, but with a 25% lower replacement time (Bianchi et al. 2021). Input data for the loss analysis are the predicted accelerations and drift ratios as well as the fragility functions, thus the potential damage states of all the structural and non-structural building elements. Fragility data for the monolithic structural members were sourced from the FEMA P-58 database, while equivalent fragility functions for the low-damage connections were developed as discussed in Bianchi et al. (2021). Consequence functions were assumed based on data available for the monolithic connections, although this assumption may be more conservative since repair costs and time associated with the substitution of external dissipaters can be substantially less. Fragility specifications for all the other non-structural systems, including facades, partitions, ceilings and services/contents, were also defined using existing published data (e.g., Bianchi and Pampanin 2022).

Figure 4 presents the main findings obtained from the investigation. Figure 4a compares the loss curves of both buildings in terms of probability of exceeding a certain level of cost given the seismic intensity under consideration. By analysing the data in terms of repair costs, it is found that the Probable Maximum Loss (PML) is 67% and 35% of the replacement cost for the monolithic and low-damage building, respectively. The low-damage structure can therefore reduce the PML by around 40%, resulting in economic savings of 5.3M€.

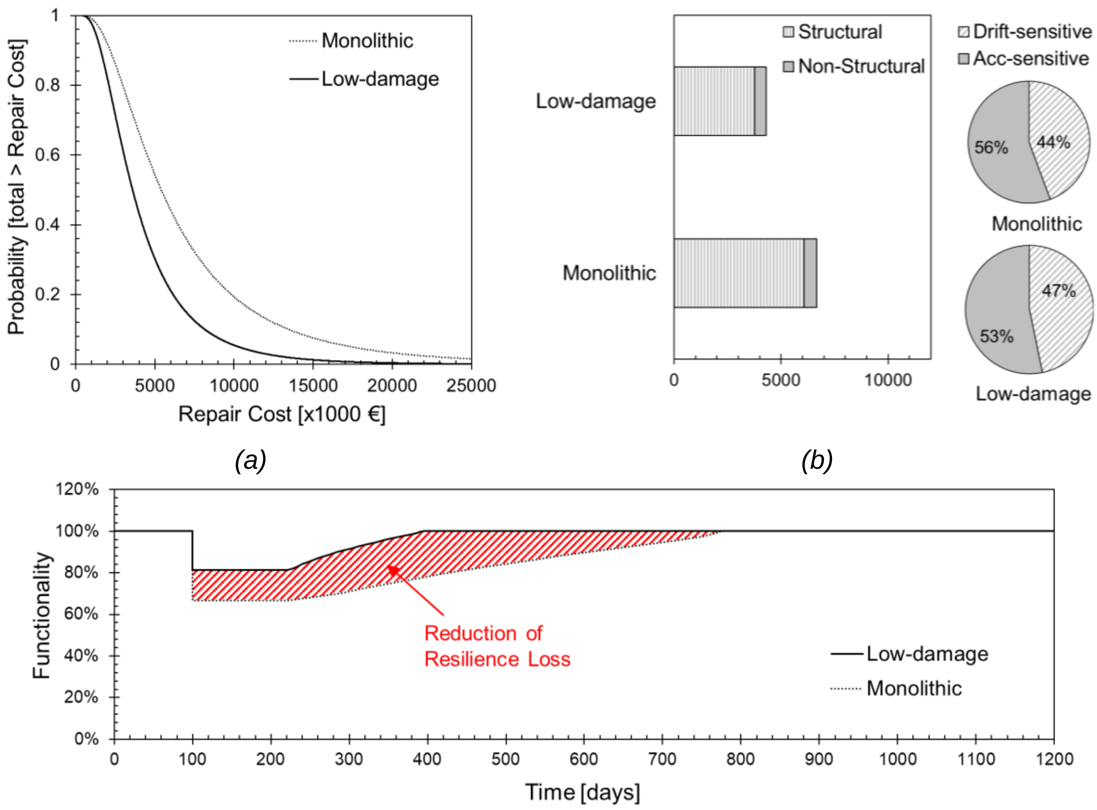

Figure 4. Loss assessment of low-damage vs. monolithic buildings: (a) Loss curves in terms of repair cost. (b) Disaggregation of total repair cost (mean value). (c) Resilience curves.

The reduced PML is attributed to the lower damage in the structural system, which accounts for a significant portion of the total losses (Figure 4b). This figure also shows that the acceleration-sensitive components experienced higher damage due to the higher accelerations at the upper stories of both buildings. Loss assessment results are further elaborated to calculate the expected downtime. The sequence of repairing actions and the impeding factors (post-earthquake inspections, engineering and contractor mobilization, financing, permitting) were identified following the procedure outlined in Almufti et al. (2013). The recovery time was then combined with the damage-related loss of functionality to define the resilience curves and expected loss of resilience for both buildings. A resilience index of 0.76 and 0.88 was found for the monolithic system and the low-damage structure, respectively. This equates to a 35% reduction (mitigation) of the resilience loss area. It is highlighted that this study was conducted on new buildings therefore the conventional code-compliant structure was already expected to have an acceptable level of resilience loss, which could be further mitigated/reduced with the application of a low-damage system for the new concrete building.

Environmental sustainability

To evaluate the effectiveness of the design strategies in terms of sustainability, a full life-cycle assessment of both case-study buildings was conducted. The assessment was implemented to measure the environmental impacts (operational and embodied energy) of the buildings, taking into account all stages of their life cycle. The results obtained from the analysis of both building solutions are summarized in Figure 5a.

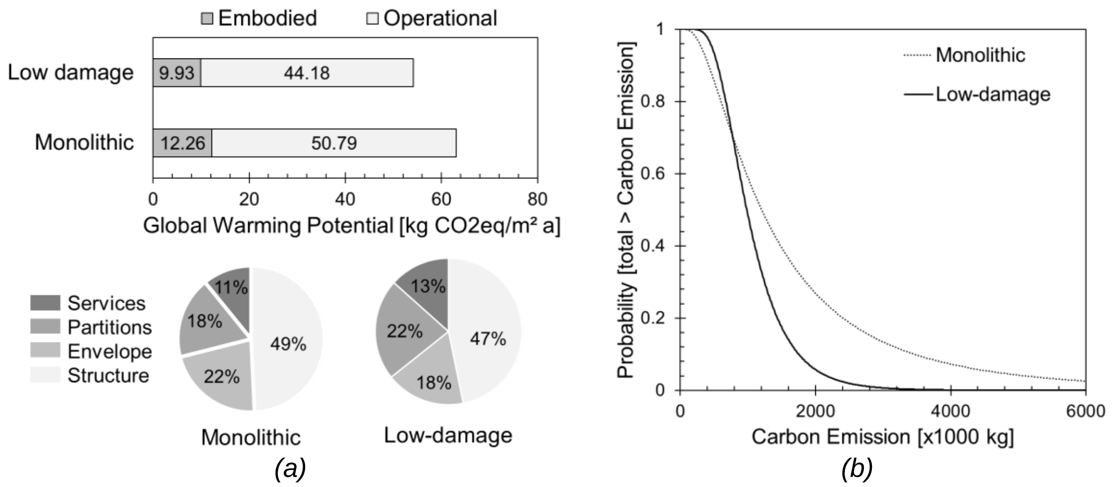

Figure 5. Life-Cycle Analysis of low-damage vs. monolithic buildings: (a) Environmental impact. (b) Loss curves in terms of carbon emissions associated with the seismic repairs.

The operational energy consumption of the buildings was defined through dynamic energy simulations in EnergyPlus software. The energy model was created in Grasshopper environment (for parametric modelling purposes) by accurately representing the building's thermal properties using a combination of geometry, material properties, and system specifications. This included modelling the walls (with a Window-to-Wall ratio of 0.4), roofs, floors, windows (with double-pane glass), and doors, and assigning appropriate values for thermal conductivity, specific heat, density, and emissivity to each building element. The building model was thus divided into thermal zones based on occupancy and thermal characteristics, which are critical for capturing the dynamic interactions between different building elements and the HVAC system. Design requirements were set to ensure the internal comfort of building occupants, including a cooling set point temperature of 24°C and a heating set point temperature of 19°C. The model also considered the internal heat gain from equipment (5 or 10 W/m2), artificial lighting (10 or 5 W/m^2), and the density of occupation (0.01 or 0.005 persons per square meter), as well as the desired rate of outside air infiltration (0.0003 m^3/s per square meter of floor). To model the HVAC system, an Ideal Load System was assumed. Despite not taking into account inefficiencies of the system, this allowed the building's operational energy consumption to be simulated accurately. The embodied energy of the buildings was assessed from cradle to grave, which includes the production, transportation, construction, use, maintenance and end-of-life phases. The embodied impact was quantified by means of the Bombyx plugin (Basic et al. 2019) within the same

Grasshopper environment. The tool includes an SQL material and component database and allows users to choose different materials and building systems to assess the embodied impact. The analysis accounted for all building components, including the structure, external walls, internal systems, and services, as well as the transport of people and materials. It is found that the use of timber as a construction material (combined with concrete in this specific structural application) can reduce the embodied energy by approximately 22%. Furthermore, the implementation of additional energy efficiency measures in the low-damage configuration, such as double-glazing windows with low-e coatings and measures to improve air infiltration, can also result in a similar reduction in terms of operational energy. This creates an integrated solution that is resilient, seismic-efficient, and sustainable.

The environmental impact associated with the potential earthquake damage was also assessed. This study was implemented following the FEMA P-58-4 (2018) guidelines and tools/database, which account for the global warming potential and primary energy use of the repair actions of all the building components. The extent of repairs was taken into consideration, with more extensive repairs being more material-intensive and less extensive repairs being more labour-intensive. In order to maintain consistency with the seismic analysis approach, an intensity-based evaluation was employed to identify the probable maximum carbon loss. Figure 5b provides a comparison of the carbon losses obtained for the two buildings. The results confirm the great benefits of applying the low-damage technology for high-rise buildings, as there is a reduction of approximately 50% (when referring to the maximum probable loss) in the carbon emissions due to the implementation of advanced and more environmentally sustainable earthquake-resistant solutions. It is also highlighted the higher dispersion in the results for the monolithic system compared to the low-damage structure, which therefore provides more reliable estimates.

Multi-criteria assessment

Table 2 presents a summary of the results obtained from the intensity-based seismic loss assessment and the life-cycle analysis for both buildings. The reduction values shown in the table demonstrate the significant benefits of the low-damage timber-concrete system. In particular, the low-carbon earthquake-proof solution has a greater impact on reducing the repair time (and consequent downtime) and the carbon emissions associated with seismic damage. Most of the repairing actions are due to the replacement of the external dissipators in the structural members, which is a low-cost rapid intervention when compared to repairing damaged reinforced concrete components. Although the integrated low-damage and energy-efficient building requires a higher investment cost, the cost-effectiveness of this solution is reflected in the expected economic savings over the building's life-cycle (Bianchi et al. 2021). It is worth mentioning that this study focused on new buildings, therefore no casualties were found from the loss assessment. Both buildings were designed to meet life-safety criteria, resulting in no loss of life.

	Monolithic	**Low-damage**	**Reduction**
Damage-related losses			
Repair cost [x1000 €]	13450	8160	39.3%
Repair time [days]	557	174	68.8%
Downtime [months]	23	10	56.5%
Carbon emission [t C02 eq]	3470	1760	49.3%
Environmental annual losses			
Operational carbon [t C02 eq a]	444	387	13.0%
Embodied carbon [t C02 eq a]	107	87	19.0%

Table 2. Summary of damage-related and environmental impacts.

Additionally, the effectiveness of the low-damage building is further visualized in Figure 6. This graph presents the overall loss “map” associated with both buildings considering the following components: (a) economic loss, as a function of the replacement cost; (b) environmental loss, converted into cost by taking into account the carbon price and normalized based on the total building cost; (c) resilience loss, representing the complement of the resilience index. These parameters are crucial factors in the selection process when designing new building systems or retrofitting/rehabilitating existing ones. Figure 6 shows that applying the low-damage strategy has an overall positive impact on the building, reducing the total area by 36% when the same weight is assumed for all criteria. This reduction in the loss area reinforces the potential of low-damage low-carbon systems as a sustainable and resilient solution for building design.

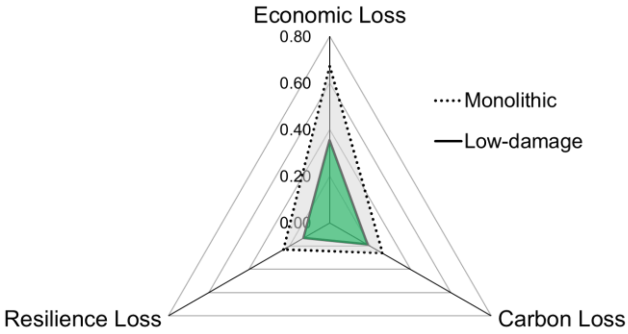

Figure 6. Multi-criteria assessment loss map based on Economic, Carbon and Resilience Losses.

Conclusions

This study investigated the benefits of using low-carbon low-damage technologies to enhance the resilience and sustainability level of high-rise buildings. Specifically, the study assessed the economic, environmental and resilience advantages of implementing such solution by comparing two design options: a monolithic reinforced concrete structure and a timber-concrete low-damage modular system. The results demonstrated that using *Plug and Play* connections in the low-damage system can significantly reduce the post-earthquake losses. Despite the advanced (than code-compliant methods) displacement-based design procedure used for the monolithic building, the results demonstrated that implementing low-damage systems would be very convenient. At the same drift level, the low-damage system has less damage, and its repair costs are associated with the low-cost substitution of the damaged external dissipaters. Moreover, the re-centering contribution provided by the unbonded post-tensioned tendons in the low-damage system reduce the residual inter-story drift, which further minimizes the damage. The research quantified the substantial loss reductions achieved through the low-damage system, including repair costs (around 40%), repair time (more than 60%), and damage-related emissions (around 50%). The study also involved a full life-cycle analysis to account for the overall environmental impact, including operational and embodied energy. Finally, a radar graph was used to visualize the overall results and confirm the effectiveness of the earthquake-proof low-carbon system as a sustainable and resilient solution for building design.

However, the investigation was limited to intensity-based analysis. To fully assess the advantages of implementing these cost-effective solutions in both high and low seismicity zones, future research should develop time-based loss analysis to evaluate the annual losses and the overall resilience across different intensity levels. Moreover, the study suggests the implementation of a more refined multi-criteria decision-making approach that integrates the resilience index to facilitate informed decision-making and seismic risk reduction strategies. By taking a more holistic approach, decision-makers will be able to better weigh the trade-offs between different criteria and select the most effective solutions for their specific needs.

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