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DEVELOPMENT OF A HOLISTIC PARAMETRIC FRAMEWORK FOR MULTI-PERFORMANCE LIFE-CYCLE EVALUATION OF POST-TENSIONED TIMBER BUILDINGS

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Abstract

Catastrophic events and climate change represent major challenges for modern society, which calls for new solutions able to provide acceptable performances with low carbon footprint. The environmental impact of buildings, already accounting for 39% of Carbon Dioxide (CO2) emissions in the European Union (EU), becomes much more important in seismic prone areas, where buildings are vulnerable to extensive damage, significantly influencing the sustainability as well as the resilience of the entire community. The low-damage post-tensioned engineered timber structural system, also known as Pres-Lam (Prestressed Laminated timber), meets the need for a shift towards a damage-control approach while using sustainable materials. Beside the material choice, the design phase has a strong influence over the environmental impact along the life cycle of buildings. Hence, decision-making process has to take into account multiple aspects related to the proposed solution, that have to be combined into a comprehensive framework. This paper proposes a holistic parametric approach able to evaluate simultaneously the seismic performance and the environmental impact of three different Pres-Lam case studies, developing an integrated model within Rhino-Grasshopper platform using independently developed packages. The seismic response is assessed through a probabilistic approach, whereas the carbon footprint is estimated through the Life-Cycle Assessment (LCA) procedure using the extensive database of the Grasshopper plugin One Click LCA. Given the parametric nature of the framework, a wide range of solutions can be analysed to make the optimal choice, with the possibility to include also energy simulations and combine all the results within a Multi-Criteria Decision Analysis to guide the decisional process.

Keywords: Post-tensioned timber, Pres-Lam, Low-damage, Seismic performance, Sustainability, Integrated parametric design.

1 INTRODUCTION

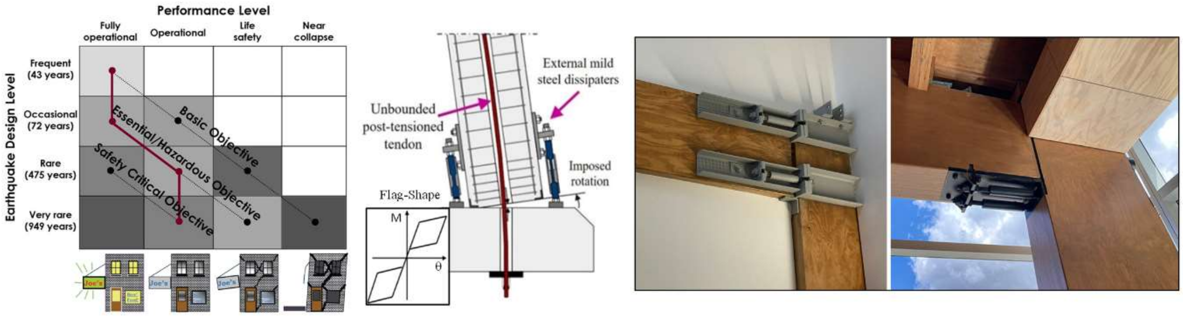
In line with the 2030 Agenda for Sustainable Development [1], the construction sector is moving towards the promotion of sustainability in all its activities. A sustainable construction is a multi-performance product, dealing with the different requirements related to Planet preservation, People satisfaction and Profit achievement, according to the three Ps (or Pillars) of Sustainability. Hereby, it is necessary to include all the possible hazards, such as earthquakes, that may occur during the building life cycle compromising its sustainable features, showing the mutual dependency between the structural performance and the environmental footprint [2, 3].

The material and socio-economic consequences of the recent earthquakes on the built stock have highlighted the crucial need to build up a resilient community, able not only to ensure life-safety and safeguard to the cultural heritage, but also to look at the future providing a smart and sustainable building environment. The modern buildings designed following the current seismic code approach targeting Life-Safety, although performing as expected as per Hierarchy of Strength principles, might incur in severe damage to their structural and non-structural components which can be deemed as not cost-effective to repair [4, 5]. To overcome the equivalence between damage and ductility in code-compliant earthquake-resisting buildings, earthquake engineering community has been recently focusing on innovative high-performance technologies aiming at raising the bar in seismic design, shifting the no-more adequate targeted performance to a more appropriate damage-control objective (Figure 1a). Among these technologies, the so-called PRESSS system (PREcast Seismic Structural System) has been largely investigated and tested in the past two decades starting from the US-PRESSS programme, in the 1990's, at the University of California San Diego (UCSD) with substantial developments and actual implementations on site at the University of Canterbury in New Zealand. [6, 7, 8]. Based on the use of precast concrete elements joined together through "dry" ductile connections, this technology replaces the traditional plastic hinge (expected in monolithic solutions) with a peculiar rocking and dissipating mechanism at the interface between structural members by the use of two types of reinforcement: (i) unbonded post-tensioned cable/bars ensuring the self-centering capacity of the structure, and (ii) internal mild steel or external fuse-type replaceable Plug&Play dissipaters [9], which ensure the energy dissipation (Figure 1b). During the earthquake, a rocking mechanism is expected at the interface between structural members, while at the end of the shacking, the post-tensioned reinforcement ensures the pre-existing gap closure between members, leading to negligible residual displacements/deformations. The combination of the self-centring and energy dissipation capabilities of the system defines the so called "flag-shape" hysteresis rule of the connection system.

More recently, such technology has been extended to the use of laminated timber with the Pres-Lam (Prestressed Laminated Timber) systems [10] (Figure 1c). Today, it is well recognized how the use of timber can be a way to achieve the concept of sustainability in construction. The state-of-the-art technologies have made possible to have engineered products (the so-called mass timber) with structural performances comparable to the more common steel and concrete, with the lightness and renewability that characterize the wood. Hence, mass timber creates an opportunity to use renewable methods of constructions while still ensuring the expected building performances [11]. This development represents a step towards a circular model in constructions, which, in its highest expression, aims to keep products in use maintaining their embedded value as long as possible, avoiding waste and energy-consumer processes and leaving recycling as the "last-resort" in favour of the more resilient-based concept of re-use [12]. The high seismic structural performance of Pres-Lam technology could make it a competitive choice when dealing with the need of a durable construction, capable of withstand hazardous events during the building life cycle, modular to be easily replaced and made by materials easily separated for recycling if re-use it is not possible.

To date, many assessment tools have been employed and developed to effectively drive decision-making processes in the direction of achieving sustainability goals in the construction sector. Some methodological frameworks analyse single or multiple aspects of environmental scenarios that are related to construction activities (protocollo ITACA [13], LEED [14], DGNB [15], BREEAM [16], CASBE [17]). Besides these tools, the Life-Cycle Assessment (LCA), regulated by ISO 14040 and ISO 14044, has the potential to analyse overall environmental factors related to the entire life cycle of a building [18]. For this reason, its use is spreading among the engineering community. The LCA allows to quantify the environmental impact of a building during its life cycle, from raw materials extractions to the End-of-Life (with different bounding conditions depending on the scope of the analysis), not only in terms of CO2 emissions but also in the form of different impacts on the ecosystem, the use of resources and the human health (Life-Cycle Impact Assessment). Given that, the LCA can be usefully adopted in the construction industry to evaluate different design options for a new building in the early design stage, in order to guide decision-makers towards the adoption of a more sustainable solution.

Nevertheless, the current approach to the LCA of buildings that involves gathering the relevant environmental data of the different materials manually in an Excel file tends to discourage designers from applying LCA. Implementing an automated LCA in a dedicated parametric design software tool, such as Rhino+Grasshopper (McNeel, 2007) [19] can help to achieve a time-effective process while creating an integrated environment that enables to stay on top of all the different aspects of a complex building system, considering them simultaneously. Furthermore, the parametric nature of the software enables to assess different solutions in pursuing the optimal choice, making this design approach ideal for (multi-)decision-making processes.



a) b) c)

Figure 1. a) Proposed modification of the seismic performance design objective matrix [20], with the identification of the damage state at each performance level; b) Example of low-damage column-to-foundation connection using external Plug&Play dissipaters and a sketch of the "flag-shape" hysteresis rule [21]; c) Pres-Lam beam-to-column connections with two different configurations of Plug&Play dissipaters: on the face of the beams and columns, Trimble building (left), on top and bottom of beams, Young Hunter House, Merritt Building (right).

1.1 Pres-Lam State-of-the-Art

The Pres-Lam technology is a low-damage solution for earthquake-resisting structural systems making use of mass timber products.

Despite being relatively new, the technology was proved to be effective by extensive testing [22, 23, 24, 25] that showed how the engineered connections are able to withstand several loading cycles while maintaining a stable response. By combining frames and walls is possible to achieve a complete and robust structural system able to withstand higher levels of drift without showing significant damage [26, 27].

The technology, making extensive use of timber, is characterized by easier prefabrication, shipping, and assembly processes, making it a prime solution even for low-seismic areas. Several buildings have already been built using this technology as it was deemed cost-effective for different applications [28, 29, 30, 31, 32, 33] (Figure 2).

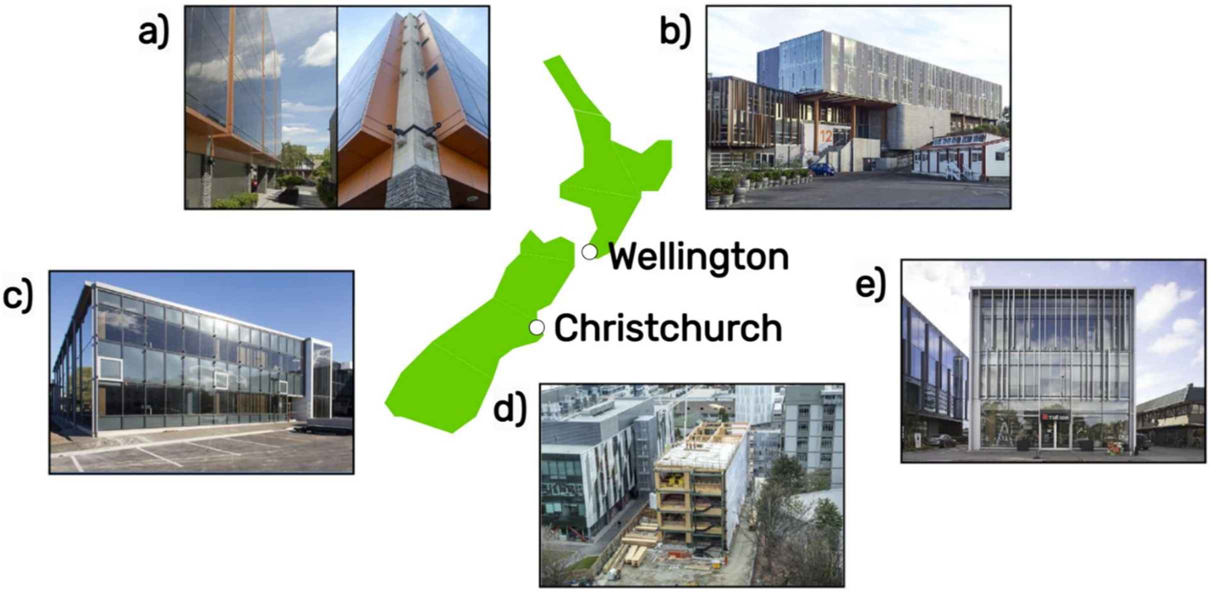


Figure 2. Examples of buildings that make use of Pres-Lam frames in New Zealand: (a) St. Elmo Courts building, Christchurch, (b) College of Creative Arts building, Wellington (courtesy of Andy Buchanan/PTL structural consultants), (c) Trimble building, Christchurch, (d) Beatrice Tinsley building, Christchurch (courtesy of University of Canterbury), and Young Hunter House, Christchurch (modified after [34]).

One major shortcoming of the technology is the strong anisotropy (actually orthotropy) of the timber which exhibits a lower stiffness when loaded perpendicular-to-the-grain, when compared to parallel-to-the-grain, leading to a reduced connection stiffness in the beam-to-column joint connection. To address this issue, several protecting solutions have been proposed and implemented regarding the joint interface detailing using nails, screws, and steel plates [34]. Some authors even proposed and tested solutions which make use of different materials for columns such as reinforced concrete or steel [35, 36]. Moreover, the combination of this technology with non-structural components able to withstand high levels of drift, made it possible to develop an integrated solution capable of facing high-intensity level seismic events without reporting any significant damage [37].

A detailed state-of-the-art on the structural systems regarding testing against seismic and fire hazards can be found in [38].

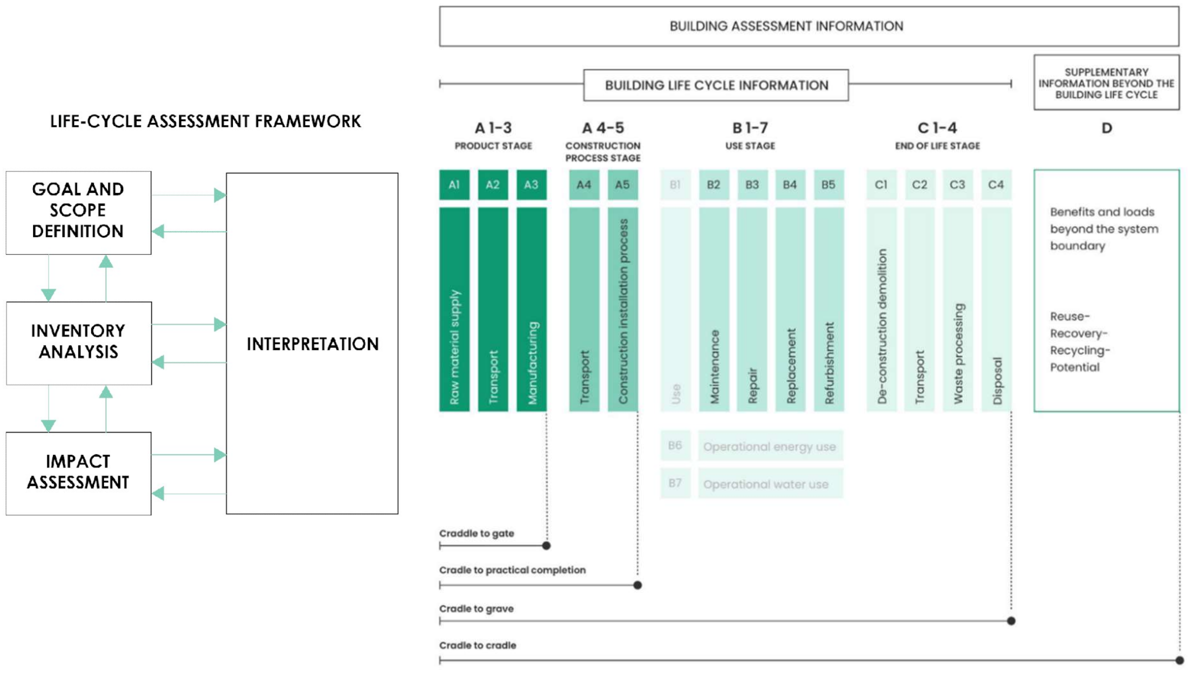
2 AIMS AND METHODOLOGY

This paper proposes an integrated methodology for the seismic and environmental performance of low-damage laminated timber buildings. The two performances are evaluated individually but, combining them within the same parametric framework in the Rhino+Grasshopper environment, it allows for a comprehensive understanding of the proposed solutions and for a time-saving automated evaluation process. Among the scopes of the work, the authors want to investigate and confirm that the achievement of high seismic performance in building design, through the use of pre-cast low-damage structural technologies, does not hinder low carbon footprint.

2.1 Life-Cycle Assessment

A Life-Cycle Assessment (LCA) procedure is an effective tool that helps to monitor the direction through less environmental impact. Regulated by ISO 14040 and ISO 14044 [39, 40], the aim of the method follows the one of the study. The main steps in which the analysis is divided are (Figure 3a): (i) Goal and Scope Definition; (ii) Inventory Analysis; (iii) Life-Cycle Impact Assessment; (iv) Interpretation.

The first phase establishes the functional unit, i.e., the reference parameter for the results of LCA (in our case the Gross Floor Area (GFA) of the building), the reference time, set as 50 years for residential/commercial buildings, and the boundaries of the system, according to which four LCA alternatives are possible [41, 42] (Figure 3b): (i) Cradle-To-Grave, where the complete life-cycle of the product is assessed, from the manufacturing processes to the End-of-Life (EoL) scenario; (ii) Cradle-To-Gate, which involves the phases between the manufacture and the factory; (iii) Cradle-To-Cradle, that consider the product back on the market after the recycling process at the EoL; (iv) Gate-To-Gate, considering only the processes in the factory. In this paper, a Cradle-To-Grave LCA is performed, with the possibility to select the recycling of steel and glass components as their EoL scenario, as well as the reuse of timber elements enabled by the low-damage structural system; the operational phase is neglected because it would not be meaningful in the comparison, having the case-study buildings roughly the same GFA and the same envelope. It is worth saying that this work considers the recycling and reuse EoL scenarios just as a reduction of CO2 emissions in the EN 15978/EN 15804 C1-C4 stages, without taking into account the consequential cutting of the required raw-materials (stages A1-A3) in the following product cycle.



a) b)

Figure 3. a) LCA framework according to ISO 14040; b) Life-Cycle stages according to EN standards and the related four different LCA alternatives (modified from One Click LCA website).

As far as the Inventory Analysis phase is concerned, the energy flows of each material and processes involved in the study are analysed. This is the part where the software tool comes handy, since the Environmental Product Declaration (EPD) of the project's components and data on energy and consumption must be collected. The framework proposed in this paper uses the extended database of the One Click LCA software for building design, consisting of both manufacturer-specific data, useful if a particular product has already been chosen, and country-specific average data, convenient in the early-design of the project.

Once the environmental data of the project materials and components are gathered, the results of LCA can be presented in the form of Green-House Gases Emissions, computed as kgCO2 equivalent, and Embodied Energy (GJ). If one wants to assess the impact on different aspects of the eco-system and the human health, the Life-Cycle Impact Assessment should be carried out. This phase assigned each energy flow to impact categories represented, for example, by Climate Change (Global Warming Potential), Acidification, Eutrophication, Ozone Depletion Potential. However, this phase is often avoided, since it relies on the assessment models chosen and, hence, it's not standardized.

The interpretation and the evaluation of the results of LCA can eventually bring the process back to its initial phase and lead to changes in the proposed design; therefore, the automation of the entire design and assessment procedure makes this iterative process less daunting.

2.2 Seismic Performance

To assess the seismic performance of the frame structural systems, a probabilistic approach was chosen making use of fragility curves to obtain the Mean Annual Frequency of Exceedance (MAFE) related to various limit states.

To develop the fragility curves for the case-study buildings a Non-Linear Time History Analysis (NLTHA) approach is used implementing the Incremental Dynamic Analysis (IDA, [43]) methodology. The procedure employs a suite of ground motions that are progressively increased until the onset of the desired limit state is achieved. The suite of 44 ground motions (22 recordings times 2 directions) provided by FEMA P-695 [44] is used to perform the procedure.

The considered limit states for the Pres-Lam frames are:

- DS1: failure of the external mild steel dissipaters, considered as the gap opening that induces a 6% axial deformation in the fuse-shaped devices.
- DS2: yielding in compression of the timber beam's interface parallel to the grain.
- DS3: yielding of the post-tensioning tendons inside the beam elements.

The global onset of each limit state is achieved once at least one section reaches the defined limit state.

Because every section might reach the above-defined limit states for a different amount of gap opening, the Demand Capacity Ratio (DCR) instead of the gap opening has been defined as the Engineering Demand Parameter (EDP). The DCR is computed as the ratio between the maximum gap opening that occurred during the NLTHA and the gap opening corresponding to the onset of the considered limit state in the specific connection. Finally, the global DCR is defined as the maximum between all the connections (Eq. 1).

$$DCR_{LS} = max_j^n DCR_{LS,j} = max_j^n \frac{D_{gap,j}}{C_{gap,j}(LS)} \tag{1}$$

where:

- $D_{gap,j}$ is the maximum gap opening occurred during NLTHA.

- $C_{gap,j}(LS)$ is the gap opening corresponding to the onset of the limit state for the considered connection.
- n is the number of connections in the frame.

The chosen Intensity Measure (IM) is the spectral acceleration of the first mode period ($Sa(T_1)$).

Because all the different solutions have a different value of the first mode period, the MAFE is used to compare the results. The MAFE is computed by integrating the fragility curves with the hazard curve [45]. However, the values of the hazard curve according to the Italian seismic hazard model [46] do not cover a wide enough range to perform the integration. For this reason, an approach like the one proposed by the SAC-FEMA [47, 48] methodology is used to fit the hazard curve on an analytical model. The analytical model chosen as representative of the hazard curve is the second-order hazard approximation proposed by [49] (Eq. 2):

$$Hazard(im) = k_0 exp[-k_2 ln^2(im) - k_1 ln(im)] \tag{2}$$

Finally, following the same approach as [45], the integration is truncated to a T_R (return period) of 100,000 years after which a probability of 1 is considered for the occurrence of the damage state (Eq 3):

$$\lambda_{LS} = \int_0^{IM_{T_R^*}} P[DCR_{LS} \geq 1 \mid IM = x] \cdot |d\lambda_{IM}(x)| + 10^{-5} \tag{3}$$

2.3 Parametric Integrated Model

As shown in Figure 4, a comprehensive parametric framework is developed in order to investigate the best solution in terms of both seismic and environmental performance. The workflow consists of independently developed packages and Python-based modules all inside the same Grasshopper parametric model, which enables to analyze a wide range of solutions just varying the input parameters in an even user-friendly manner.

Geometry and material properties of the building are set as input as well as the seismic hazard level related to the construction area and the importance class of the building. Through a set of algorithms represented by a series of boxes dragged into the canvas of the visual programming software and linked to each other by wires, the whole building 3D parametric model is defined, considering both the structural and the non-structural components (facades).

Then, the main workflow activities within the model are the following:

- *Structural design.* The Python programming language directly integrated in Grasshopper allows to develop the seismic design procedure within the model; specifically, the Direct Displacement-Based Design methodology [50, 51] is carried out for the lateral force-resisting systems, returning the Base-Shear as output which is in turn the input for the following Python-based box that returns the force demand along the structure. The structural members are then dimensioned to carry the force-demand at the serviceability limit state (SLS), being the size of timber structural elements and the amount of post-tensioning in Pres-Lam structures usually governed by this limit state [34], and then designed in detail and verified at the ultimate limit state (ULS) [52].
- *Structural modelling and seismic analyses.* Once the design phase is completed, the building's parameters, together with connection reinforcement details, are stored and broadcasted to a Python script that defines a numerical model using the OpenSEES software [53, 54]. The script is able to perform non-linear static and dynamic analyses to assess the building's performance against seismic action.

- *Life-Cycle Assessment*. Using the One Click LCA Grasshopper module, LCA is carried out getting data directly from the 3D model and the materials properties set as input. All the building components are parametrically mapped to LCA profiles, defined by the type of material and the EPD database chosen to assess the environmental impact. At this stage, by easily pressing a "button" in Grasshopper, the LCA can be run in the cloud importing the construction to the web platform, where is possible to adjust the feature of the elements concurring to the evaluation of the carbon footprint, e.g., the EoL scenario, the distance from the manufacturing plant and the energy grid used during the production. The results are visualized through a set of diagrams and images.

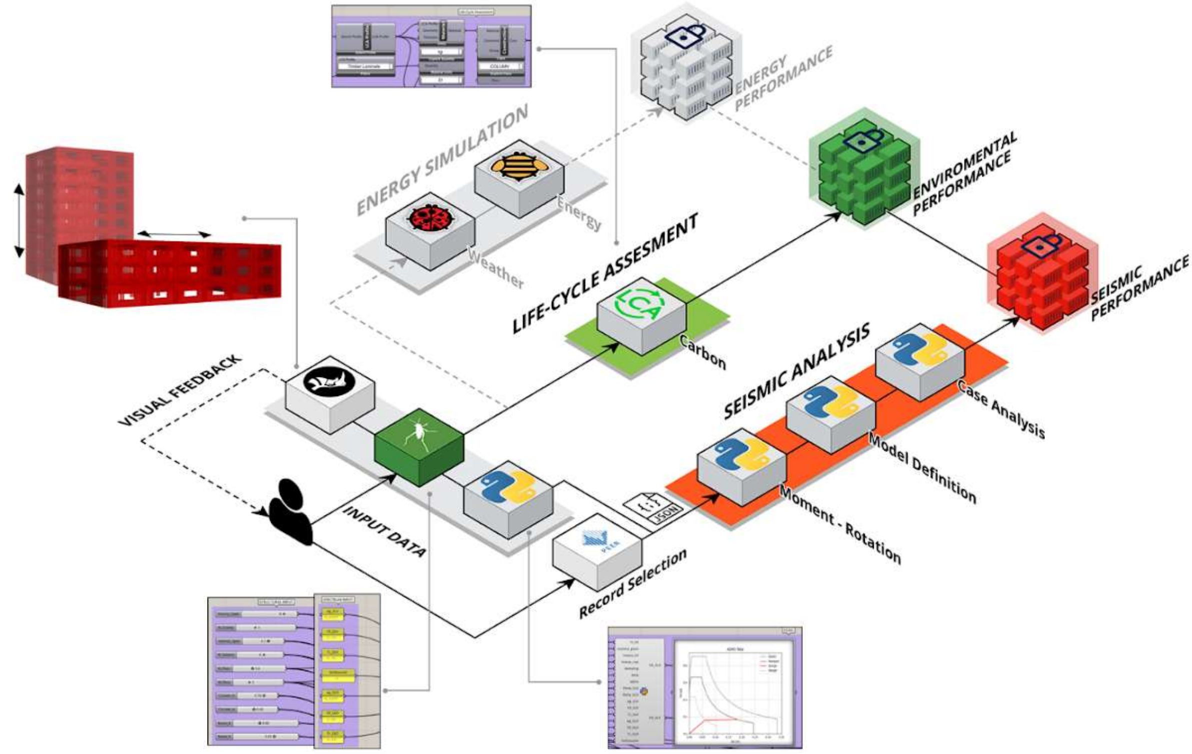


Figure 4. Grasshopper-Phyton parametric workflow for the multi-performance evaluation of buildings, from the selection of input to the 3D geometric model, to DDBD design, to seismic numerical analyses and LCA analysis.

It is worth saying that the Grasshopper-Python-based workflow herein presented allows to account also for the implementation of energy simulation for the building, evaluating the energy efficiency of the building (or set of buildings, given the parametric nature of the model), and use it for the operational phase in the LCA.

3 PARAMETRIC DESIGN

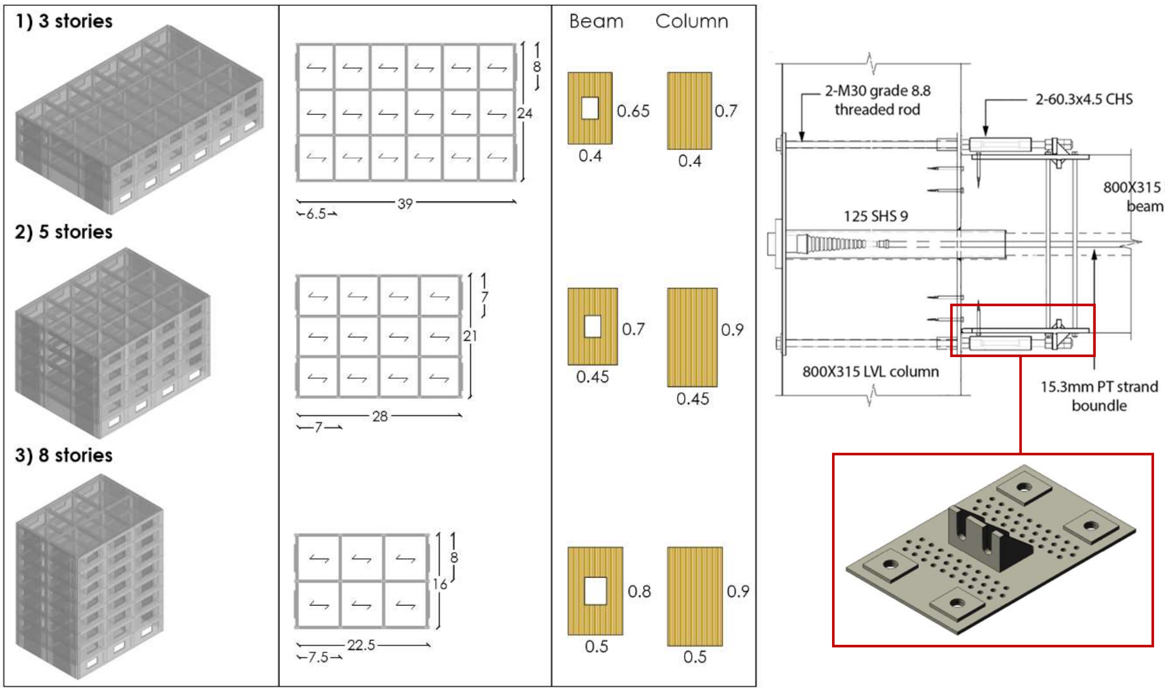
3.1 Case-study buildings

The parametric integrated framework is applied to three different Pres-Lam case-study office buildings, sharing solely the same inter-story height of 3.6 m and the same GFA of around 2800 square meters. All the three buildings feature two lateral force resisting systems: post-tensioned timber frame in the longitudinal direction and post-tensioned timber walls in the transversal one. In this paper, for simplicity, seismic analyses are carried out only for the longitudinal direction, i.e., for the post-tensioned timber frames. The different number of stories, span number and lengths, the number of lateral resisting frames and the beams and columns dimensions are shown in Figure 5a.

The hybrid Pres-Lam frame connections details, i.e., the number and diameters of external Plug&Play dissipaters and the number of post-tensioned tendons, are determined following the DDBD procedure implemented within the Grasshopper-Phyton model, whose key parameters are summarized in Table 1. The buildings are designed considering the high seismicity of L’Aquila (Abruzzo, Italy, C soil type), and an importance class of level 3 [55].

The considered beam-column joint configuration was the one shown in Figure 5b, taking as a reference the Young Hunter House (Merritt) building in Christchurch, New Zealand (2014). The external mild steel fuse-shaped short-bar are placed at the top and the bottom of the beam, while the post-tensioned cables run through the hollow beams at mid-height; structural steel rods passing right through the column reinforce against crushing perpendicular to the grain. The plates, nails and bolts for the Plug&Play dissipater anchorage are dimensioned following the EN 1995-1-1:2004 for timber and EN 1993-1-8:2005 for steel [56, 57].

For timber beams and columns, Laminated Veneer Lumber (LVL) has been chosen, with a flexural strength of 44 MPa and a parallel-to-grain modulus of elasticity of 14700 MPa, while the external dissipaters are made of S355 steel. The internal post-tension occurs through unbonded 7-wire strands characterized by a yielding tensile strength of 1670 MPa.



a) b)

Figure 5. a) Geometry and structural data of the 3 case-study buildings; b) Beam-column connection detail from the Young Hunter House [34], and the top and bottom anchor plate for the Plug&Play dissipaters (courtesy of Federica Felici).

	Case-study 1		Case-study 2		Case-study 3	
Parameter	SLS	ULS	SLS	ULS	SLS	ULS
θ_{design} (%)	0.5	1.7	0.5	1.8	0.5	1.55
Δ_{design} (m)	0.04	0.11	0.06	0.18	0.1	0.24
$m_{effective}$ (ton)	1272	1332	1485	1555	1674	1754
$H_{effective}$ (m)	7.2	7.1	11.9	11.6	19.12	18.64
$\xi_{equivalent}$ (%)	5	11	5	11.1	5	10.7
$T_{effective}$ (s)	0.73	1.1	1.2	2.07	1.93	2.77
$K_{effective}$ (kN/m)	93821	34977	40486	14348	17670	9057
V_{base} (kN)	3392	3729	2408	2578	1689	2205

Table 1. Parameters from the DDBD procedure for the three case-study buildings, at Serviceability Limit State (SLS, SLD in Italian Building Code) and Ultimate Limit State (ULS, SLV in Italian Building Code).

The building skeleton is coated with two types of facades: a timber-based cladding system (Figure 6a) with multiple insulation layers in the frames direction, connected by low-damage bearing connections and UFP connections (Figure 6b) [37, 58], and spider-glazing façades made of 12 + 1.52pvb + 12 mm glass panels in the walls direction. The study of this type of connections and non-structural components is not covered in this paper [59].

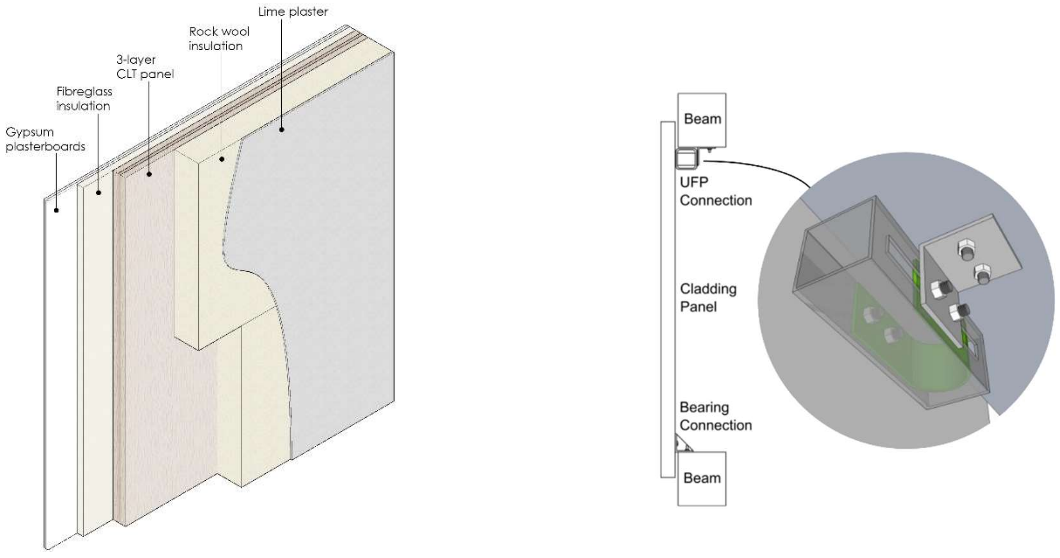


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Figure 6. a) Detail of the facade in the longitudinal direction; b) Cladding system with low-damage UFP connection [58].

3.2 Modelling approach

To model the response of the Pres-Lam frames, a lumped plasticity approach is used as it was shown that it can adequately predict the behavior of the hybrid connections [60].

The beam-column connection was modelled accounting for three different contributions (Figure 7):

- The post-tensioning unbonded tendons are modelled using a multi-linear elastic link.
- The mild steel external damping devices are modelled using a Giuffrè-Menegotto-Pinto (GMP) hysteretic behaviour.
- The joint shear deformation is modelled using a linear elastic link.

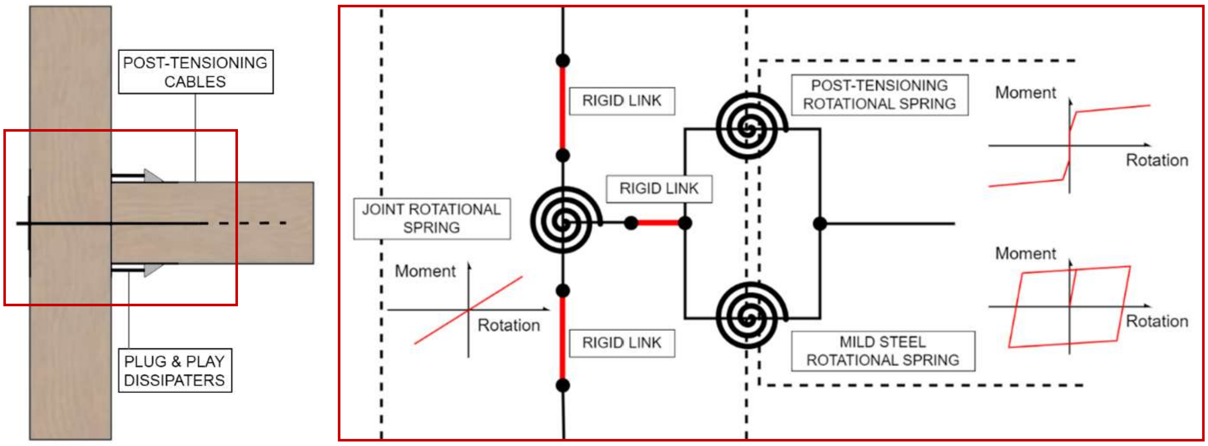

Figure 7. Modelling of a hybrid connection for a beam-column joint.

To define the parameters of the mild steel and post-tensioning, an iterative analytical procedure was used. Originally developed by [61] using the concept of *member compatibility* known as the "monolithic beam analogy" for rocking concrete connections, the procedure was further developed by [62], then adapted to Pres-Lam by [25] and finally revised by [63].

The model was validated on the results of the experimental testing by [64].

The GMP link is set to fail once a gap opening corresponding to a 6% axial deformation in the damping devices is reached. Similarly, the multi-linear elastic link modelling of the tendons is set to fail once a gap opening corresponding to the yielding deformation of the post-tensioning element is achieved. This choice was made because once the tendons are yielded, the residual deformation cannot ensure a correct rocking mechanism leading to the unpredictability of the dynamic behaviour of the connection. Finally, when the yielding deformation of the timber is reached, the moment rotation is computed considering the partially plasticized connection, thus leading to a reduction in stiffness.

The stiffness of the elastic link modelling the panel is derived by the formulation proposed by [52] for internal (Eq. 4) and external (Eq. 5) joint panels:

$$K_{joint,int} = \frac{4}{3}\frac{\alpha_{s,ave}A_{col}h_b G_t}{\left(1-\frac{h_c}{L}\right)(2-\beta)} \tag{4}$$

$$K_{joint,ext} = \frac{2}{3}\frac{\alpha_{s,ave}A_{col}h_b G_t}{\left(1-\frac{h_c}{L}\right)} \tag{5}$$

where:

- $\alpha_{s,ave}$ is the effective shear area assumed 0.85 for rectangular beam.
- A_{col} is the area of the column.
- h_b is the height of the beam.
- G_t is the shear modulus of the timber.
- β is the ratio of the effective height of the beam assumed 2/3.

4 RESULTS AND DISCUSSION

In this section, the results of the Life Cycle Analysis as well as seismic performance assessment are presented first separately then together to evaluate the optimal solution among the 3 case studies presented.

4.1 Life-Cycle Assessment

As shown in the performance matrix of Figure 8, all the three case-study buildings share a low environmental impact when compared to similar buildings, i.e., office buildings, in Italy [65]. Amongst the three case-studies, the 8-storey building set is the one with the highest CO2 emissions both in terms of total value (expected due to the larger size) and per square meter values. The latter is probably due to the highest amount of vertical structures and facades due to the greater height; these are in fact one of the main actors in determining carbon emissions, especially when considering the spider-glazing curtain wall characterized by the two most contributing materials to the Global Warming, glass and steel, even if recycled at the EoL.

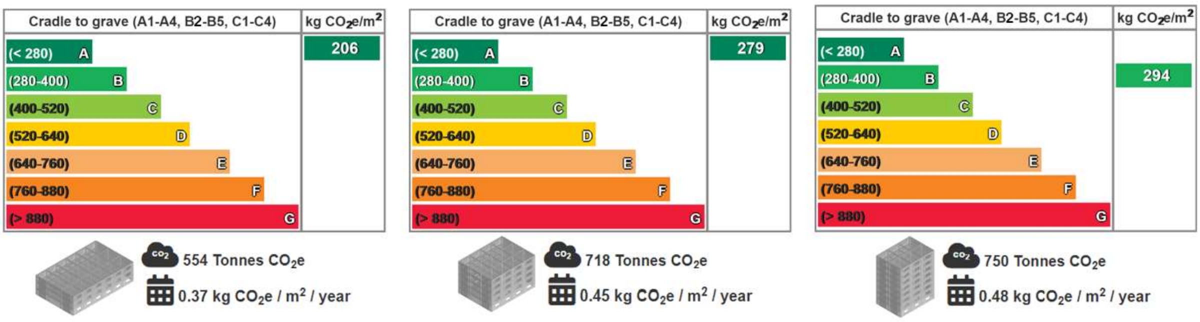

Figure 8. Embodied carbon associated to the three case-study buildings compared to benchmark buildings with the same service class (offices) in the same country (Italy). The performance metric is built on the results of standardized LCA on 1000 anonymized, verified sample buildings with data breakdown for over 100 different materials, developed by building type and countries [65].

When looking at life-cycle stages (Figure 9), having neglected the operational phase, it appears that most of the emissions are related to the A1-A3 production phase, also because all the materials have been considered as virgin resources at the beginning of their life cycle. On the contrary, the C1-C4 End-of-Life phase shows a nearly zero global warming potential, since the majority of the building components, among which an important role is played by the high-performance low-damage Pres-Lam structural system, are designed to be durable and reusable at the end of their life, while those not suitable for that scenario are recycled. As far as the construction stage is concerned, the results are based on the data available for standard prefabricated timber-frame structures; thus, the value of kgCO2eq related to this phase would be cut if considering the easy of assembly of Pres-Lam technology [66].

The results of LCA are expressed also in the form of Embodied Energy, that is the total use of primary energy during the life-cycle stages (Figure 10).

It is worth saying that in this paper the maintenance and replacement stages consider only the impacts from restoring the building products after they reach the end of their service life within the 50-year LCA reference time of the building, without taking into account the rehabilitation required if any type of hazard, such as earthquakes [2, 3, 67], should happen during the life time of the structure, for which further studies are undergoing.

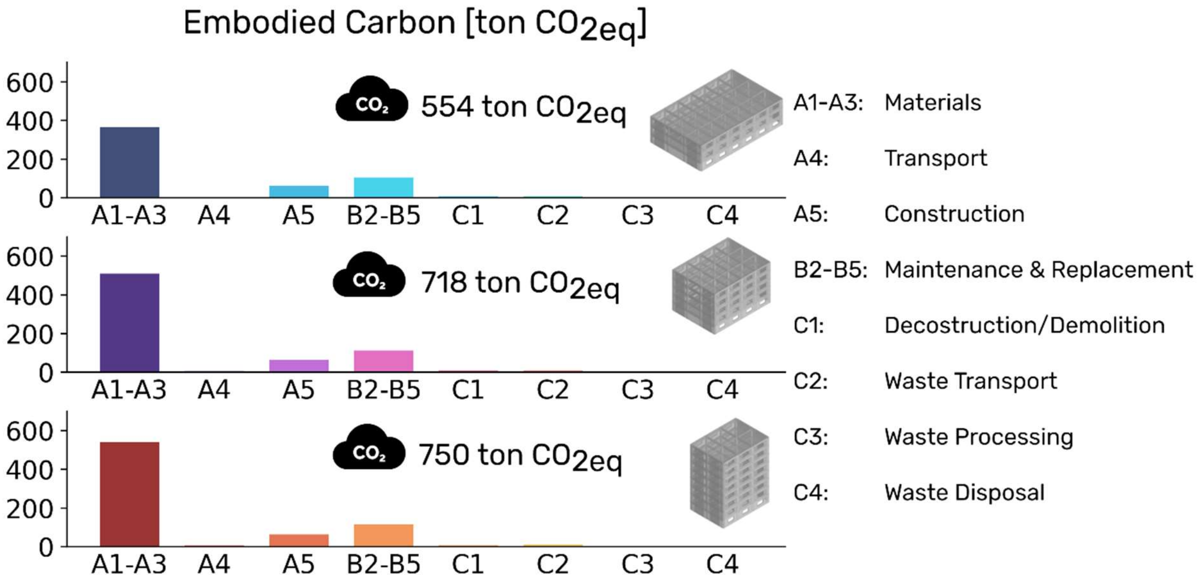

Figure 9. Global Warming Potential (kg CO2 equivalent) associated with the EN 15978 LCA stages and cumulative total values for the three case-study buildings.

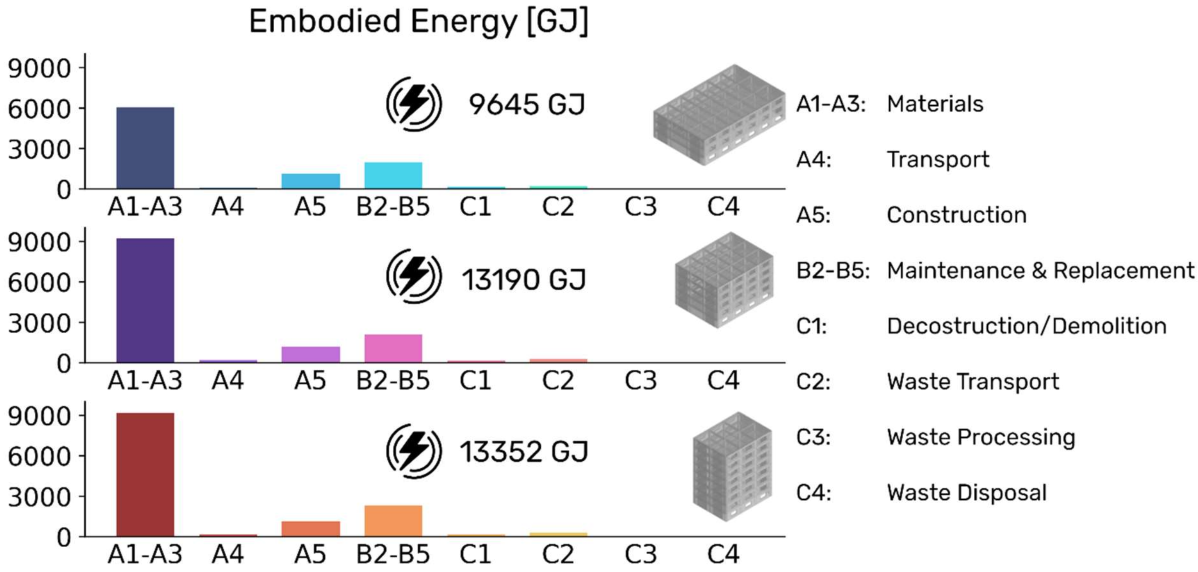

Figure 10. Embodied Energy (GigaJoule) associated with the EN 15978 LCA stages and cumulative total values for the three case-study buildings.

4.2 Seismic Performance

The analyses performed were used to assess the performance of the building under seismic action using time history non-linear analyses with a probabilistic approach. The Mean Annual Frequencies of Exceedance (MAFE) of the various damage states were computed using the fragility curves obtained through the IDA methodology and integrated using the fitted hazard curves.

Since the chosen intensity measure used to compute the fragility curve is the first mode spectral acceleration, the hazard curves had to be fitted for each building using the data obtained by the Italian Hazard model relative to the given first mode period and then adjusted for the soil category C. A modal analysis was performed to determine the periods of the first mode and are reported in Figure 11 along the relative hazard curves.

The fragility curves were finally combined with the hazard curves to compute the MAFE for each limit states. The MAF integrand functions from Eq. 3 are show in in Figure 11.

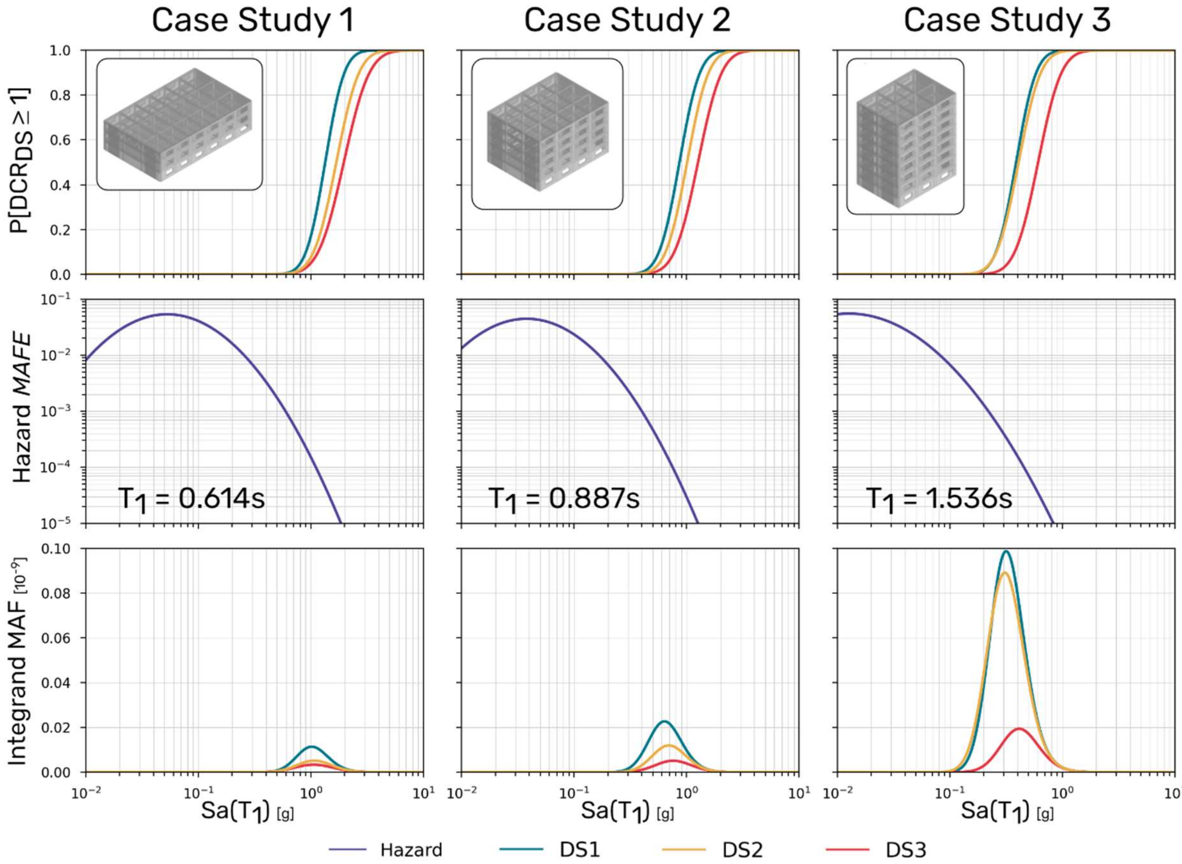

Figure 11. Damage state fragility in logarithmic scale (top); site hazard curve fitted using Eq. (2) for the specific T1 (centre); and MAF integrand scaled by a factor of 10^9 (bottom).

Results show that in every case study the DS2 is achieved after the DS1, as it is desirable, even if the fragilities of the higher building experience a slight crossing which is more evident in the MAF integrand function. The crossing is related to the proximity between the two median values and to the fact that the DS2 experience a higher dispersion, which leads to a higher beta than the DS1. However, despite being undesirable, is possible in certain circumstances to experience the DS2 damage state before the DS1 in sections where the axial load is higher, or even after DS3, especially for sections at the last floor where the axial stress (induced by tendons) is lower. In fact, in the case of the higher building, as the case study 3, the DS2 insurgence is dominated by the base column sections which bear a higher level of axial load.

The values of the MAFE related to the various damage states show how case studies 1 and 2 are less prone to damage and failure respect to the higher building (Figure 12). Moreover, the lower case-study, even if does not exhibit a lower MAFE for the DS3, is less prone to damage both for DS1 and DS2.

It must be noted that the damage associated with DS1 is minimal because of how the connections are designed, as long as external dissipaters are employed. Instead, the DS2 is related to a more severe level of damage which falls into a gap on knowledge due to the lack of experience with this technology. For this reason, would be desirable to keep the DS2 as close as possible to the DS3 that is related to a life-threatening or even a collapse-threshold level of damage beyond which the control over the response might be lost.

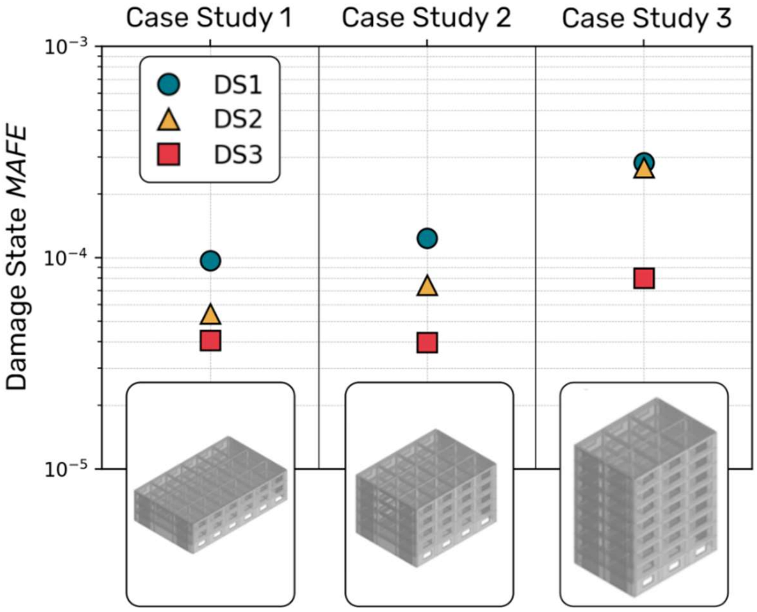

Figure 12. Mean Annual Frequency of Exceedance (MAFE) for the case studies and relative damage states.

4.3 Holistic Performance Assessment

Once the single building performances are evaluated for the three case-study building sets, their combination allows for a comprehensive understanding of which can represent the ideal solution. Thanks to the holistic parametric framework developed within the Grasshopper environment, is possible to control all the aspects involved in the multi-performance evaluation of the buildings in an automated and user-friendly manner and, changing the input parameters, to find out which building features influence the most its performance and adjust them towards the optimal solution.

Figure 13 shows how the 8-stories case-study building set, the highest as well as most slender one, represents the worst solution in terms of both seismic and environmental performance. All the damage states are expected for lower MAFE and its GWP is slightly higher than those of the 5-storey case study building despite being more compact in its floor area (as previously said, the greater amount of vertical facades due to the greater number of floors could be responsible for this difference).

The multi-performance approach becomes much more important when comparing the 5-storey case study to the 3-storey one: in fact, the 5-storey building, despite showing a slightly better performance than the 3-storey over the DS3, related to life-threatening behaviour, it comes with a greater carbon footprint, which can make it a less desirable choice. Furthermore, if the lower damage states are taken into account, the 5-storey shows a worse performance, highlighting how the sensibility and objectives of the stakeholder making the decision influence the outcome of the project. However, a multitude of factors are not included in this evaluation such as the fact that the 3-story requires a larger plot of land leading to a higher land use and higher costs. For this reason, a parametric, yet user-friendly, approach into an integrated environment can become very powerful as it allows the decision-maker to develop ad-hoc procedures that plugs into the model to aid the design process.

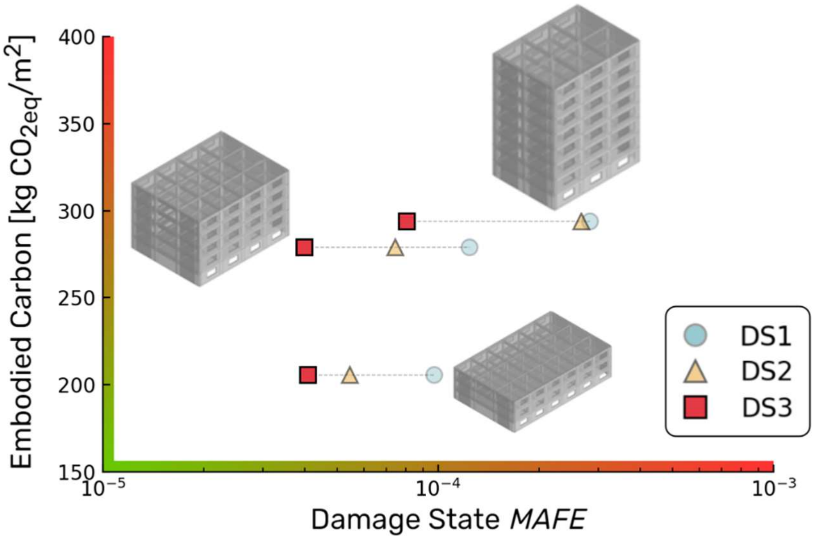

Figure 13. Combined seismic (MAFE for each DS) and environmental (Embodied Carbon, GWP) performance for the three case-study buildings.

The 3-storey case study building set, on the other hand, exhibit a significant better performance in terms of environmental impacts, while it does not really differ from the 5-storey building set in terms of seismic performance. The slightly lower carbon emissions are realistically due to the smaller dimensions of the structural elements, i.e., beams and columns, resulting from the seismic design.

Looking at the overall values for both seismic and environmental performance, it seems clear that the Pres-Lam technology allows for a low carbon footprint while, at the same time, delivering a high capability of withstanding severe earthquakes with a reduced level of damage, which is a fundamental aspect also for the reusability of the building elements in a circular economy perspective, leading, in turn, to a more sustainable performance.

5 CONCLUSIONS

This paper proposes a step towards a holistic multi-performance parametric approach for the seismic and environmental evaluation of Pres-Lam buildings. The framework herein presented is developed within Grasshopper-Python environment and has the potential to enhance the early stages of the design phase allowing for a rapid and user-friendly simultaneous check of multiple building performance towards the optimal solution.

Three Pres-Lam case-study buildings has been analysed using the parametric framework, geometrically defined and directly designed, using the DDBD procedure, within the Rhino+Grasshopper tool through a Python-based algorithm. Using a lumped plasticity model for the Pres-Lam frames, the seismic performance has been evaluated through fragility curves for different damage states obtained by the IDA methodology implemented in a Python script automatically linked to the Grasshopper model, while the environmental assessment has been carried out running the LCA procedure through the extensive EPD database of the OneClickLCA plug-in in the Rhino+Grasshopper environment.

The MAFE related to the various damage states, resulting from the seismic analyses, identified the higher case-study building as the more prone to damage, while the other two buildings are slightly similar in terms of seismic performance. On the other hand, the environmental assessment strongly declared the lower case-study as the best one in terms of both GWP and Embodied Energy, while the other two buildings show approximately the same impact, with the higher one being the worst solution as it falls in a lower environmental class.

When putting together the two performances, a comprehensive understanding of the buildings' behaviour is possible, confirming which of those analysed is the best overall solution. Among the outcomes, particular emphasis shall be placed on how the use of laminated timber low-damage high-performance earthquake-resistant technologies allows also to cut the environmental footprint of buildings and to introduce circular economy principles within the building design.

The workflow introduced in this paper is therefore an easy and useful tool to evaluate if several proposed solutions are suitable for the designer's aims. The way it was conceived enables the stakeholders to monitor various building aspects simultaneously, analysing an unlimited number of options thanks to its parametric nature and identifying which parameter influences mostly the whole building's performance.

As a further development, the framework might also include energy simulations and insert the resulting energy consumptions within the LCA procedure as regards the operational phase of the building life cycle, in order to taking into account all the LCA stages. Similarly, the seismic performance should enter the environmental analysis through a revised Performance-Based Environmental Assessment by a Grasshopper algorithm, further confirming the benefits of using Pres-Lam structures. Finally, the results from all the different analyses could be combined using a Multi-Criteria Decision Making method to select the best solution amongst the alternatives.

6 REFERENCES

[1] United Nations, *Transforming our world: the 2030 Agenda for Sustainable Development– A/RES/70/1*, 2015.

[2] C. Menna, D. Asprone, F. Jalayer, A. Prota, G. Manfredi, Assessment of ecological sustainability of a building subjected to potential seismic events during its lifetime. *The international journal of life cycle assessment*, **18**, 504-515, 2013.

[3] A. Belleri, A. Marini, Does seismic risk affect the environmental impact of existing buildings?. *Energy and Buildings*, **110**, 149-158, 2016.

[4] S. Pampanin, Reality-check and renewed challenges in earthquake engineering: Implementing low-damage systems–from theory to practice. *Bulletin of the New Zealand Society for Earthquake Engineering*, **45(4)**, 137-160, 2012.

[5] S. Pampanin, Towards the "ultimate earthquake-proof" building: Development of an integrated low-damage system. *Perspectives on European Earthquake Engineering and Seismology*, **2**, 321-358, 2015.

[6] J. Stanton, W. C. Stone, G. S. Cheok, A hybrid reinforced precast frame for seismic regions. PCI journal, **42(2)**, 20-32, 1997.

[7] M. N. Priestley, S. Sritharan, J. R. Conley, S. Pampanin, Preliminary results and conclusions from the PRESSS five-story precast concrete test building. *PCI journal*, **44(6)**, 42-67, 1999.

[8] M. N. Priestley, Overview of PRESSS research program. *PCI journal*, **36(4)**, 50-57, 1991.

[9] F. Sarti, A. Palermo, S. Pampanin, Fuse-type external replaceable dissipaters: Experimental program and numerical modelling. *Journal of Structural Engineering*, **142(12)**, 04016134, 2016.

[10] A. Palermo, S. Pampanin, A. Buchanan, M. Newcombe, Seismic design of multi-storey buildings using laminated veneer lumber (LVL). *New Zealand Society for Earthquake Engineering Conference*, Wairakei, Taupo, New Zealand, March 11-13, 2005.

[11] A. Campbell, Mass timber in the circular economy: paradigm in practice? *Proceedings of the Institution of Civil Engineers - Engineering Sustainability*, **172(3)**, 141-152, 2018.

[12] R. Jockwer, Y. Goto, E. Scharn, K. Crona, Design for adaption–making timber buildings ready for circular use and extended service life. *IOP Conference Series: Earth and Environmental Science*, **588 (5)**, 052025, 2020.

[13] ITACA Italia Protocol, Roma, Italy, http://www.itaca.org/valutazione_sostenibilita.asp.

[14] U.S. Green Building Council, Washington, DC, http://www.usgbc.org/leed.

[15] DGNB, German Sustainable Building Council, http://www.dgnb.de/en.

[16] BREEAM, http://www.breeam.org.

[17] CASBEE, Comprehensive Assessment System for Built Environment Efficiency, Japan, http://www.ibec.or.jp/CASBEE/english.

[18] M. C. Caruso, C. Menna, D. Asprone, A. Prota, A., G. Manfredi, Methodology for life-cycle sustainability assessment of building structures. *ACI Structural Journal*, **114(2)**, 323, 2017.

[19] D. Apellániz, P. Pasanen, C. Gengnagel, A holistic and parametric approach for life cycle assessment in the early design stages. *Symposium on Simulation for Architecture and Urban Design (SimAUD)*, April 15-17, 2021.

[20] Structural Engineers Associate of California, *Performance-based seismic engineering*. SEAOC Vision 2000, Sacramento, California, USA, 2000.

[21] D. Marriott, S. Pampanin, D. Bull, A. Palermo, Dynamic Testing of Precast, Post-Tensioned Rocking Wall Systems with Alternative Dissipating Solutions. *New Zealand Society for Earthquake Engineering Conference*, Wairakei, Taupo, New Zealand, April 11-13, 2008.

[22] D. Moroder, T. Smith, A. Dunbar, S. Pampanin, A. Buchanan, Seismic testing of post-tensioned Pres-Lam core walls using cross laminated timber. *Engineering Structures,* **167**, 639–54, 2018.

[23] F. Sarti, A. Palermo, S. Pampanin, Quasi-Static Cyclic Testing of Two-Thirds Scale Unbonded Posttensioned Rocking Dissipative Timber Walls. *Journal of Structural Engineering,* **142**, 2016.

[24] F. Wanninger, A. Frangi, Experimental and analytical analysis of a post-tensioned timber connection under gravity loads. *Engineering Structures,* **70**, 117–29, 2014.

[25] M.P. Newcombe, S. Pampanin, A. Buchanan, A. Palermo, Section Analysis and Cyclic Behavior of Post-Tensioned Jointed Ductile Connections for Multi-Story Timber Buildings. *Journal of Earthquake Engineering,* **12**, 83–110, 2008.

[26] M.P. Newcombe, S. Pampanin, A. H. Buchanan, Global response of a two-storey Pres-Lam building. *New Zealand Society for Earthquake Engineering Conference*, Wellington, New Zealand, March 26-28, 2010.

[27] New Zealand Society for Earthquake Engineering. Kaikoura earthquake special issue. Bulletin of the New Zealand Society for Earthquake Engineering, **50(2)**, 73–362, 2016.

[28] F. Sarti, A. Palermo, S. Pampanin, J. Berman, Determination of the seismic performance factors for post-tensioned rocking timber wall systems. *Earthquake Engineering & Structural Dynamics,* **46**,181–200, 2016.

[29] T. Holden, C. Devereux, S. Haydon, A. Buchanan, S. Pampanin, NMIT Arts & Media Building - Innovative structural design of a three storey post-tensioned timber building. *Case Studies in Structural Engineering,* **6**, 76–83, 2016.

[30] C. Leyder, F. Wanninger, A. Frangi, E. Chatzi, Dynamic response of an innovative hybrid structure in hardwood. *Proceedings of the Institution of Civil Engineers - Construction Materials,* **168**, 132–43, 2015.

[31] B. Curtain, D. Dekker, S. Chung, et al., Design of Carterton Event Centre: An example of innovative collaboration between architecture and timber engineering. *12th world conference on timber engineering (WCTE),* Auckland, New Zealand, July 15–19, 2012.

[32] A. Brown, J. Lester, S. Pampanin, D. Pietra. Pres-Lam in practice - A damage-limiting rebuild project. *Structural Engineering Society (SESOC) New Zealand Conference*, Auckland, New Zealand, November 2-3, 2012.

[33] A. Kirstein, J. Siracusa, T. Smith, The new timber von Haast replacement building in Christchurch. *New Zealand Society for Earthquake Engineering Conference,* Auckland, New Zealand, April 13-15, 2018.

[34] A. Miliziano, G. Granello, A. Palermo, S. Pampanin, Overview of connection detailing for post-tensioned dissipative timber frames. *Structural Engineering International*, **30(2)**, 209-216, 2020.

[35] S. Pampanin, J. Ciurlanti, S. Bianchi, M. Palmieri, D. Grant, G. Granello, A. Palermo, A. Correia, Overview of SERA project: 3Dshaking table tests on an integrated low-damage building system. *4th International Workshop on the Seismic Performance of Non-Structural Elements (SPONSE),* Pavia, Italy, May 22-23, 2019.

[36] M. J. Mancini, S. Pampanin, Numerical and experimental investigation on low damage steel-timber post-tensioned beam-column connection. *16th European Conference on Earthquake Engineering*. Thessaloniki, Greece, 18-21 June, 2018.

[37] S. Bianchi, J. Ciurlanti, S. Pampanin, Comparison of traditional vs low-damage structural and non-structural building systems through a cost/performance-based evaluation. *Earthquake Spectra*, **37(1)**, 366-385, 2021.

[38] G. Granello, A. Palermo, S. Pampanin, S. Pei, J. van de Lindt, Pres-Lam Buildings: State-of-the-Art. *Journal of Structural Engineering,* **146**, 2020.

[39] International Standards Organization, ISO 14040. *Environmental Management—Life Cycle Assessment - Principles and Framework*, Geneva, Switzerland, 2006.

[40] International Standards Organization, ISO 14044. *Environmental Management—Life Cycle Assessment, Requirements, and Guidelines*, Geneva, Switzerland, 2006.

[41] British Standard Institution, EN 15978. *Sustainability of Construction Works - Assessment of Environmental Performance of Buildings - Calculation Method*, 2011.

[42] British Standard Institution, EN 15804. *Sustainability of construction works. Environmental product declarations. Core rules for the product category of construction products*, 2012.

[43] D. Vamvatsikos, C.A. Cornell, Incremental dynamic analysis. *Earthquake Engineering & Structural Dynamics*, **31**, 491–514, 2002.

[44] Federal Emergency Management Agency, FEMA P-695. *Quantification of building seismic performance factors,* Washington, DC, USA, 2009.

[45] I. Iervolino, A. Spillatura, P. Bazzurro, Seismic Reliability of Code-Conforming Italian Buildings. *Journal of Earthquake Engineering* **22**, 5–27, 2018.

[46] M. Stucchi, C. Meletti, V. Montaldo, H. Crowley, G.M. Calvi, E. Boschi, Seismic Hazard Assessment (2003-2009) for the Italian Building Code. *Bulletin of the Seismological Society of America* **101**, 1885–911, 2011.

[47] SAC Joint Venture, Federal Emergency Management Agency, SAC/FEMA. *Recommended seismic design criteria for new steel moment-frame buildings. Report No. FEMA-350*, Washington, DC, USA, 2000.

[48] SAC Joint Venture, Federal Emergency Management Agency, SAC/FEMA. *Recommended seismic evaluation and upgrade criteria for existing welded steel moment-frame buildings. Report No. FEMA-351*, Washington, DC, USA, 2000.

[49] D. Vamvatsikos, Derivation of new SAC/FEMA performance evaluation solutions with second-order hazard approximation. *Earthquake Engineering & Structural Dynamics,* **42**, 1171–88, 2012.

[50] M. N. Priestley, Direct displacement-based design of precast/prestressed concrete buildings. *PCI journal*, **47(6)**, 66-79, 2002.

[51] M. N. Priestley, G. M. Calvi, M. J. Kowalsky, Displacement-Based Seismic Design of Structures. *Earthquake Spectra*, **24(2)**, 555–557, 2007.

[52] S. Pampanin, A. Palermo, A. H. Buchanan, *Design Guide Australia and New Zealand-Post-Tensioned Timber Buildings*, 2013.

[53] F. McKenna, OpenSees: A Framework for Earthquake Engineering Simulation. *Computing in Science & Engineering,* **13**, 58–66, 2011.

[54] M. Zhu, F. McKenna, M.H. Scott, OpenSeesPy: Python library for the OpenSees finite element framework. *SoftwareX,* **7**, 6–11, 2018.

[55] Ministero delle Infrastrutture e dei Trasporti (MIT), NTC 2018. *D.M. del Ministero delle Infrastrutture e dei trasporti del 17/01/2018. Aggiornamento delle Norme Tecniche per le Costruzioni,* 2018 (in Italian)

[56] European Committee for Standardization (CEN), *Eurocode 5 - Design of timber structures - Part 1-1: General - Common rules and rules for buildings*, Brussels, Belgium, 2004.

[57] European Committee for Standardization (CEN), *Eurocode 3 - Design of steel structures - Part 1-8: Design of joints*, Brussels, Belgium, 2005.

[58] A. Baird, A. Palermo, S. Pampanin, Controlling seismic response using passive energy dissipating cladding connections. *New Zealand Society for Earthquake Engineering Conference,* Wellington, April 26-28, 2013.

[59] S, D'Amore, S. Bianchi, J. Ciurlanti, S. Pampanin, Seismic assessment and finite element modeling of traditional vs innovative point fixed glass facade systems (PFGFS). Bulletin of Earthquake Engineering, 2023.

[60] A. Di Cesare, F.C. Ponzo, D. Nigro, S. Pampanin, T. Smith, Shaking table testing of post-tensioned timber frame building with passive energy dissipation systems. *Bulletin of Earthquake Engineering,* **15**, 4475–98, 2017.

[61] S. Pampanin, M.J.N. Priestley, S. Sritharan, Analytical modelling of the seismic behaviour of precast concrete frames designed with ductile connections. *Journal of Earthquake Engineering,* **5**, 329–67, 2001.

[62] A. Palermo, The use of controlled rocking in the seismic design of bridges. *PhD Thesis*, Technical Institute of Milan, Milan, Italy, 2004.

[63] T. Smith, Post-tensioned timber frames with supplemental damping devices. *PhD Thesis*, University of Canterbury, Christchurch, New Zealand, 2014.

[64] A. Iqbal, S. Pampanin, A. Palermo, Seismic performance of prestressed timber beam column sub-assemblies. *New Zealand Society for Earthquake Engineering Conference*, Wellington, New Zealand, March 26-28, 2010.

[65] P. Pasanen, R. Castro, Carbon Heroes Benchmark Program–whole building embodied carbon profiling. *IOP Conference Series: Earth and Environmental Science,* **323(1)**, 012028, 2019.

[66] T. Smith, R. Wong, M. P. Newcombe, D. Carradine, S. Pampanin, A. Buchanan, R. Seville, E. McGregor, The Demountability, Relocation and Re-use of a High-Performance Timber Building. *9th Pacific Conference on Earthquake Engineering (PCEE): Building an Earthquake-Resilient Society*, Auckland, New Zealand, April 14-16, 2011.

[67] Federal Emergency Management Agency, *Seismic Performance Assement of Buildings, Volume 1. Technical report FEMA-P-58-1*, Department of Homeland Security, Washington, DC, USA, 2012.