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RESEARCH ARTICLE

Performance assessment of Timber High-rise Buildings: Structural and Technological Considerations

Giulia Angelucci[1,*], Fabrizio Mollaioli[1], Milena Molle[1] and Spartaco Paris[1]

[1] *Department of Structural Engineering and Geotechnics (DISG), Sapienza University of Rome, Rome, Italy*

Abstract:

Background:

Nowadays, a renewed momentum on the use of timber material is ensured by the development of high performing engineered wood products, which enables larger and taller structures to be built. Although the design of multi-story timber buildings is still in its early stages, the active interest shown by designers and researchers in advancing awareness and technologies in this field bodes well for the proliferation of an increasing number of tall wooden buildings.

Objective:

As a consequence of the difficulties with designing a nominally all-wooden tall structure, whilst utilizing its beneficial aspects, dual timber-concrete systems are considered in this work. In detail, the study aims to investigate the contribution of a reinforced concrete core coupled to timber stability systems for the effective control of lateral drifts in multi-storey buildings subjected to severe loading scenarios.

Methods:

The design of a 26-storey structural model, conceived by combining concrete cores with three design alternatives for the perimeter structure (namely a GLT frame, a CLT shear walled system and a GLT diagrid), provides the opportunity for discussing its lateral bearing capacities.

Results:

The building models show high lateral stiffness in withstanding seismic and wind induced loads. This result is mainly attributable to the introduction of the rigid concrete core, which nearly supplies the demand for shear and bending stresses alone. Compared to a typical cross laminated core, the concrete tube results in a stiffness increment of 68% for the frame variant, 45% for the wall variant and 23% for the diagrid variant. Therefore, the serviceability requirements, both in terms of top displacements and inter-story drifts, are inherently satisfied and kept well below the prescriptive limitations.

Conclusion:

The results confirm the excellent behavior of the diagrid systems, for which any variations of the inner core have almost insignificant impact on the global building performance. In addition, previous research works suggest that the timber member sizing is mainly governed by stiffness requirements, which materialize through monitoring of the lateral sway, while member strength demands are deemed to be implicitly satisfied. The paper demonstrates that strength and stiffness demands can be of equal significance during the sizing process of dual systems.

Keywords: Tall buildings, Laminated timber, Shear wall, Diagrid, Seismic design, Wind load.

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1. INTRODUCTION

Raising awareness about the risks of natural resource depletion has made environmental sustainability a recurring focus of recent building designs. Although the conceptual design of a tall building implicitly embodies the inherent sustainability of reduced land consumption, for years, it has been awarded the title of "highly environmental impact type" due to the large consumption of natural resources required during its construction and operational life. Nevertheless, the latest generation designs are disproving this reputation, endowing high-rise buildings with a new sustainable identity, making them perceived as symbols of a renewed cultural and

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[*] Address correspondence to this author at the Department of Structural Engineering and Geotechnics (DISG), Sapienza University of Rome, Rome, Italy. Email: giulia.angelucci@uniroma1.it

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social consciousness for modern cities. A substantial impulse to this design reversal was certainly offered by the evolution of structural systems for tall buildings from traditional solutions to more efficient and economic ones. Enhanced performance has been achieved by locating the lateral resisting systems on the outer perimeter of the buildings, providing higher stiffness and strength against both vertical and lateral loads. A more significant role is attributed to the external envelope through tessellated façades, whose structural behavior and expressive potential are entrusted to the geometric configuration of modular schemes. A new generation of evocative grids has emerged by juxtaposing regular or irregular unit cells, such as DiaGrid, PentaGrid, HexaGrid, OctaGrid, and Voronoi-grid. Adopting nature-inspired mimetic patterns has investigated innovative and unconventional schemes [1, 2]. An in-depth and updated review of previous research works on tessellated tubes is reported in Scaramozzino *et al*. [3], where special attention is paid to the sustainable design of tall buildings. Among different geometrical patterns for tubular systems, diagrids have undeniably been the most popular. The triangulated pattern makes them especially effective in resisting static and dynamic actions [4]. Researchers have also made recent efforts toward evaluating enhanced diagrid-based topologies by introducing optimization techniques [5 - 7]. Although optimization procedures aimed to minimize the structural weight of lateral resisting systems for multi-story buildings have demonstrated robust efficiency in finding cost-effective solutions [8, 9], these features alone are insufficient to fulfill design sustainability requirements. In this regard, the employment of 'green' materials certainly represents a strategic measure for energy-saving and efficiently contributes to reducing the environmental impact of the tall building construction industry. In North America, Japan and northern Europe, wood culture is rooted in ancient traditions and timber is largely preferred to modern construction materials. In most of Europe, timber has historically had more limited use. However, a socio-cultural change has begun recently, for which timber buildings have received wide positive appreciation.

Since the development of advanced engineered wood products (EWP), which enable large-scale structures to be built, timber has entered a renaissance period, showing great potential as a sustainable and renewable construction material. By reducing the inherent variability of raw wood through homogenization, engineered timber products, such as Glue Laminated Timber (GLT or glulam), Laminated Veneer Lumber (LVL) and Cross Laminated Timber (CLT), have thrived as viable alternatives to typical steel and concrete solutions for building designs [10]. The last decade has witnessed a worldwide proliferation of multi-story timber buildings consistent with these premises. Relevant examples include the proposal for the 62 m high Tree Tower in Toronto (Canada), the 49.4 m high Treet tower in Bergen (Norway) completed in 2015, the 85.4 m high Mjøstårnet in Brumunddal (Norway) built in 2019 and the proposed 133 m high Trätoppen tower in Stockholm (Sweden). An overview of the tallest timber buildings designed in recent years is illustrated in Fig. (**1**), which shows new trends in timber engineering and reveals forward-looking proposals to push the height limits of timber for use in sustainable constructions.

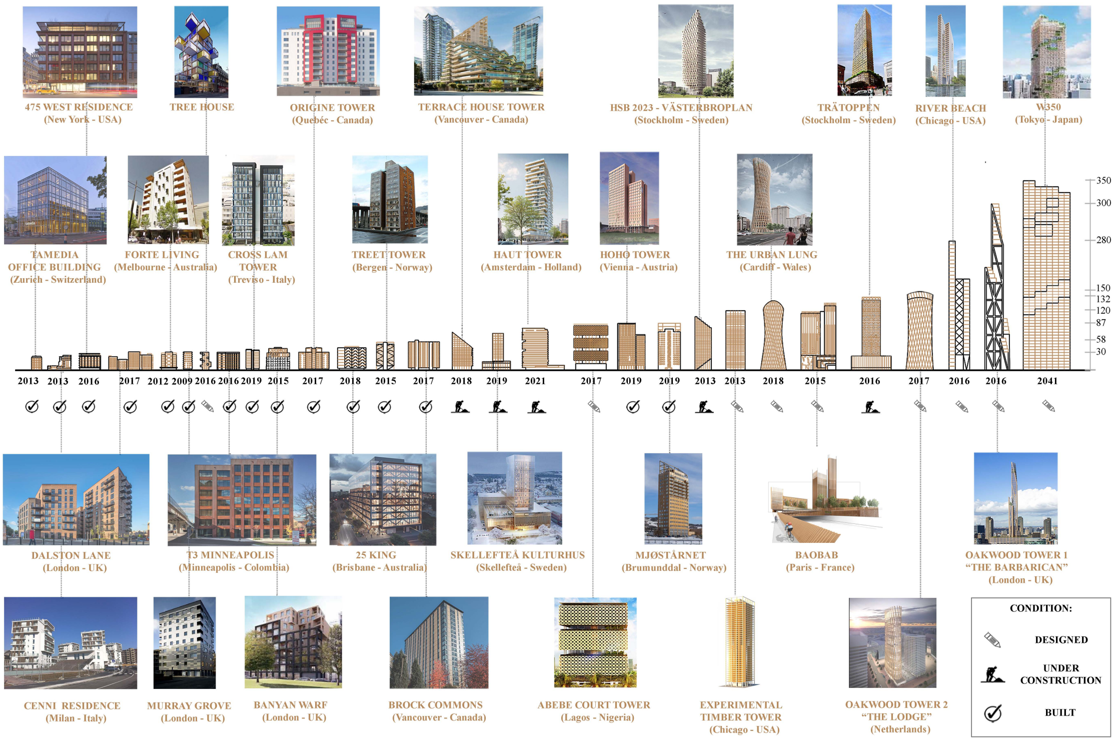


Fig. (1). Classification of the world's tallest timber buildings.

This revived interest in timber structures, fostered by a greater awareness of its potential compared to the past, is also witnessed by an increasing attention of the scientific community in this regard. Because timber is, on average, a low-density material, the self-mass of structural members is relatively small compared to typical building materials (about 4.5 times lighter than concrete and about 15 times lighter than steel), resulting in lower seismic demands and reduced foundation cost. However, as the building height rises, increased stiffness is required to withstand the lateral action from wind and seismic hazards, yielding to massive timber systems. It might be observed that the lateral action governs the design of timber buildings at considerably lower slenderness ratios than they might be necessary for steel or concrete buildings. As a result, buildings using structural timber would require typical tall-building technologies at lesser heights; namely, the tallness threshold is activated earlier than in buildings with conventional materials. These features, in turn, make tall all-timber buildings uneconomical, albeit structurally feasible, as confirmed by SOM (Skidmore, Owings & Merrill LLP) [11]. The current trend toward the design and construction of timber structural systems is provided in Pei *et al*. [12] and Foster *et al*. [13]. As for the latter work, stimulating emphasis is placed on clarifying and extending current criteria for the terminology and definition of tall buildings to accommodate the use of structural timber. Current architectural limitations and diseconomies associated with nominally all-timber systems have encouraged the development of innovative emerging design proposals based on hybrid and integrated structural systems, especially effective in seismic-prone areas. Recent research advances have shown great potential for alternative solutions that integrate timber products with typical building materials to achieve enhanced performing structural systems and enable new possibilities for building more complex and ambitious timber constructions [14]. Timber-concrete systems are a successful hybrid example aiming to maximize the structural efficiency of constitutive materials while improving their individual performance. The feasibility of a wood-concrete skyscraper is discussed in Van De Kuilen *et al*. [15], where CLT elements, inner concrete core and outriggers are combined in the design of a 150 m tall model. Innovative timber-steel hybrid structures, consisting of prefabricated infill wood shear walls and moment-resisting steel frames, were proposed by He *et al*. [16] and Li *et al*. [17]. Timber frames and structural glass infills bonded to form a lateral-resisting wall system have also shown encouraging results in sustaining larger story drifts and dissipating considerable energy during seismic events [18, 19]. These recent achievements in engineered wood technologies have raised complementary insights into the structural design of tall timber buildings. The intense transformations undergone by steel systems have positively inspired new developments for timber structures. In fact, promising alternatives to typical frame and shear wall systems have emerged to meet the demands imposed by increased gravity and lateral loads, including outrigger systems, diagrids, braced tubes, walled tubes and buttressed tubes mega-truss. The availability of superior construction materials integrated with efficient construction techniques could address the challenges of building mega-scale timber skyscrapers in the near future.

According to recent trends, the present paper aims to investigate the feasibility of timber structural systems for tall buildings by exploring the efficiency of different stability systems. The literature review recognizes that the lateral sway requirement is a dominant issue for tall timber buildings subjected to horizontal actions, leading to inherent difficulties in satisfying code standards. It follows that the economic viability of timber buildings strongly depends on serviceability and comfort prerequisites. This study investigates whether introducing a reinforced concrete core can effectively improve the overall lateral stiffness. Therefore, the occupant comfort, in terms of top displacement and inter-story drift, is monitored together with the demand-to-capacity ratio of the load-bearing members. A comparative survey is presented for a reference case study with a hybrid structure consisting of a concrete core and a lateral resisting system with three design alternatives, *i.e*., a GLT frame, a CLT shear walled system and a GLT diagrid. Within the elastic range, static and response spectrum numerical analyses are performed to demonstrate the feasibility of timber buildings in severe wind areas or high seismic zones. A discussion in terms of different response parameters, *i.e*., natural frequencies, top displacements, inter-story drifts, member strength demand to capacity ratio and contribution to lateral stiffness, is also presented considering each solution's material consumption. Design implications are finally emphasized.

2. MATERIALS

The worldwide proliferation of multi-story timber buildings, namely buildings of which most of the engineered parts are made of timber products, calls for a deep reflection on the implications offered by this building material in today's construction industry. This section discusses the benefits associated with using timber, with special emphasis on the mechanical and dynamical performance provided when adopted for multi-story buildings.

The current propensity for wood compared to steel and concrete is to be found in the environmental advantages offered by its renewable nature, low embodied energy and ability to store carbon dioxide. Wood as a natural construction material, in fact, requires less energy both during the production and construction stages. In addition, wood is the only building material with a negative carbon dioxide balance,*i.e*., it stores CO_2: each cubic meter of wood captures an average of 1 ton of CO_2. Conversely, during the production stage, steel and concrete materials release 5300 kg/m^3 of CO_2 and 120 kg/m^3 of CO_2, respectively. Furthermore, the energy required to produce one metric ton of wood falls between 5-7.5 kWh/t, while cement and aluminum alloys require 1,000 kWh/t and 72,000 kWh/t, respectively. A further inherent feature of timber buildings relates to the anisotropic nature of wood, which significantly affects the overall structural strength and stiffness. Considering the stresses parallel to the grain, it is possible to consider wood as a material with good structural efficiency (ability to withstand the load per mass unit) compared to other building materials. In fact, wood has a structural efficiency close to that of steel and 5 times greater than reinforced concrete. Additionally, the hygroscopic behavior, shrinkage and swelling effects, and the creep behavior of timber strongly depend on the grain's direction, affecting the structural detailing of the joints.

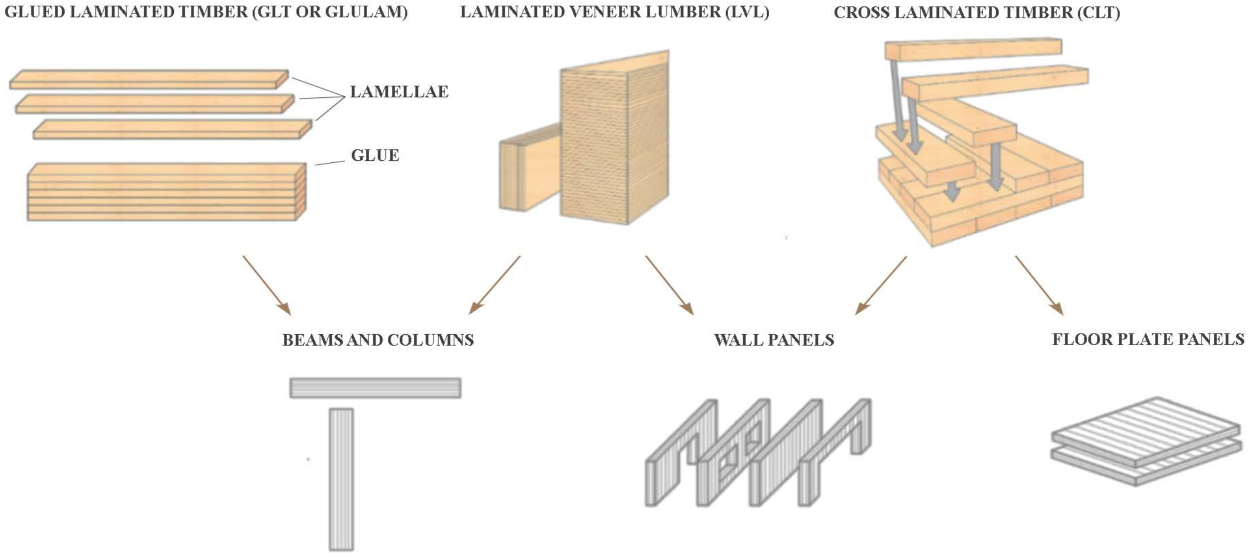


Fig. (2). Engineered timber products.

Recent technological innovations in timber engineering products have been developed to improve the overall timber behavior on anisotropy, such as cross-laminated timber, laminated veneer lumber and glue-laminated timber, among others, to exhibit better shrinkage behavior and higher strength and stiffness properties compared to massive timber. Furthermore, the excellent fire resistance of laminated timber structures, far exceeding steel, makes them especially suitable for public buildings.

In most of today's tallest timber buildings, adequate stiffness to withstand lateral and gravity loads are supplied either by using planar elements such as shear walls, assembling CLT and/or LVL plates, or using GLT frames Fig. (**2**). Within the scope of this work, only CLT and GLT products are described below. For further insights on the seismic performance of laminated veneer lumber, the reader is referred to Palermo *et al*. [20 - 22].

Glued laminated timber is manufactured from layers of parallel laminations stacked on each and glued together using adhesive. This gives the product high strength primarily in one-way spanning members, such as columns, beams and roof trusses. Cross-laminated timber is made similarly to glulam, except that each timber board is placed orthogonally to each other before being glued. The assembly increases the product strength in both directions, making CLT highly efficient as an alternative to pre-cast concrete panels when walls, floors and roof systems are constructed.

Compared to reinforced concrete and steel, timber products possess a significantly lower elastic modulus and smaller density, resulting in a greater mass/strength ratio. The reduced weight ensures the construction of lighter structures, whose low permanent gravity loads allow the reduced sizes required for the foundations and make them especially attractive for seismic-prone regions, as, in turn, seismic accelerations associated with inertial masses of the structure are expected to lessen.

As timber is a non-ductile material, the dissipative behavior of these seismic resisting systems is mainly governed by inelastic deformation of the connections, such that acceleration and displacement levels are satisfactorily monitored. Unlike steel and concrete seismic design, where energy dissipation occurs in the element itself, timber members are designed to crush after steel fasteners have yielded to ensure that proper ductile failure mechanisms occur, according to capacity-based design principles. Brittle failures of the timber members are avoided by accurately designing the corresponding components for the overstrength of the connections [23].

In CLT constructions, uplift-restrain connectors at wall ends and shear-restrain connectors at the wall base are conceived to behave ductile through the attainment of plasticization in the steel fasteners [24]. CLT constructions provide two levels of potential benefits compared to concrete structures: (*i*) environmental performances, considering the entire Life Cycle Analysis (LCA) with reduced carbon-intensive materials and (*ii*) optimization of the design and construction phases (*e.g*., speed, waste and logistics, health and safety on site) [25]. However, a medium-to-high building requires adequate rigidity to limit the lateral sway due to horizontal loads, which signifies the need for CLT constructions to rely on a supermassive system to increase its structural performance.

Full-scale shaking table tests carried out within the SOFIE research project [26] have confirmed the superior seismic performance of cross-laminated timber structures, demonstrating high capabilities to dissipate energy together with self-centering properties after ground motion excitations. Analogously, in GLT frames for multi-story buildings, energy dissipation in the connections between timber members is achieved by providing sufficient ductile behavior to steel components, generally designed as dowels-type mechanical fasteners.

Recent shaking table tests and numerical simulations have shown the excellent seismic performances of timber structural systems due to their flexibility and the high damping capabilities of mechanical connectors. The structures showed relatively large drifts but no brittle-type failure even when subjected to strong ground motions, proving that they can undergo significant large deformations without failing. However, to limit the horizontal sway within the thresholds prescribed by codes, moment-resisting frames with rigid beam-column connections are required, which are particularly difficult to obtain in laminated timber structures due to the low rotational stiffness exhibited. Many fasteners would be required to produce moment rigid nodes, resulting in overdesigned member cross-sections to accommodate them without incurring brittle failures. In laminated systems, these challenges may lead to an additional demand for stronger connection systems or alternative design solutions, yielding smaller connections' seismic forces. Recently proposed strategies included pre-stressed re-centering walls, multi-story rocking walls, stiffness links, energy dissipators, tuned mass dampers, base isolation systems and a combination thereof [27]. In addition, the low natural frequencies of timber systems associated with low stiffness/mass ratios magnify the discomfort of wind-induced dynamic responses in medium- to high-rise buildings and actualize the challenge of limiting top floor accelerations and inter-story drifts [28]. As a result, issues related to stability and serviceability requirements for high-rise timber buildings become of major concern for much lower heights compared to steel or reinforced concrete counterparts. In detail, the feasibility of designing multi-story timber structures primarily depends on the ability to control lateral deflections and provide fastening connections capable of handling high uplift forces between the superstructure and foundations, especially in seismically active regions [29]. To adequately mitigate excessive lateral drifts and ensure that ever-increasing heights can be safely reached, integrated strategies might be adopted.

3. METHODOLOGY

Within the context previously outlined, this work investigates the feasibility of tall timber buildings, in which the predominance of the structural parts consists of engineered wood products assembled according to different structural types, such as the environmental impact and the energy consumption of the construction are minimized.

Due to the difficulties with designing a nominally all-wooden structure while utilizing its beneficial aspects, an alternative strategy is pursued here to cope with the excessive inherent flexibility and the massive cross-sections required in timber buildings to adequately accommodate the designed fasteners. For the scope of this work, dual systems are considered, where strengthening structures are obtained by combining timber (CLT or GLT) members with reinforced concrete (RC) cores. In this hybrid design, both elements contribute to the definition of the lateral resisting system as the seismic demand in the timber structure is transmitted to the RC core through floor diaphragms.

The structural perimeter types assumed for the comparative analysis of the integrated systems are selected based on the technological possibilities currently available for laminated timber constructions together with considerations of the structural systems typically adopted for tall buildings. The lateral stability systems are embedded within three variants: a framed model consisting of GLT linear members (columns and beams), a shear-walled model made up of CLT panels and a diagrid model with glulam diagonal members. A paradigmatic model is assumed to investigate the feasibility of the dual systems and evaluate how different structural systems influence the global behavior of tall buildings when subjected to severe wind and seismic excitations. An intentionally simple and symmetrical base geometry is conceived to facilitate comparing the design variants.

In the early stage of the design, an extensive study was devoted to existing tall timber buildings to define the adequate tallness of the reference model before performing the numerical analyses. For the comparative study presented in this work, a height of 104 m (26 stories) is deemed adequate to incorporate the definition of a tall building, for which the effects of lateral loads are reflected in the structural design.

A squared footprint of 30 m is assumed to avoid any potential torsional effect related to planning irregularities observed during experimental tests performed on an RC core coupled with a flexible timber frame [30]. An internal modular grid of 10 m width portions the plan to facilitate the positioning of the core and the arrangement of the integrated structural systems.

Within the scope of the present study, external loading scenarios are selected for structural systems to experience severe conditions. Seismic action is determined assuming a ground acceleration of 0.5g; wind action is calculated assuming a base speed of 40 m/s. Dead loads acting on each floor are 4 kN/m^2. Live loads of 2 kN/m^2. Self-weight is calculated assuming 4.2 kN/m^3 for timber elements and 25 kN/m^3 for concrete.

In the design of multi-story buildings, it is customary to consider the mass primarily located at the story levels and the external wind loads acting on each floor. Therefore, the mass and external loads are further lumped at the center of mass of each level by assuming floor diaphragms rigid in their plane. This latter assumption is extremely desirable when dual systems with different horizontal deformability characteristics are adopted since high in-plane stiffness is required for the floor slabs, connecting the perimeter frame with the inner core to ensure a combined action in resisting horizontal forces.

The RC core has the material properties of C28/35 with a thickness of 250 mm for all the building variants. Based on the construction experience of existing tall timber buildings, coniferous wood with a resistance class of 24 is chosen for both glued (GL24h) and cross (C24) laminated members. The floors are modelled as 200 mm thick CLT plates.

Timber cross-sections are sized to comply with stiffness and strength criteria prescribed in Eurocode 8 (EN 1998-1:2004/ A1) provisions and are designed to provide a Demand to Capacity Ratio (DCR) of up to 80%. Glulam beams have a cross-section size of 650 mm × 450 mm. A comprehensive description of the three variants is provided below.

3.1. Design Variants of the Dual Systems

For the first structural model of the multi-story building illustrated in Fig. (**3**), timber frameworks and RC core are deployed as the gravity and lateral supporting system.

Past research has documented that timber-framed systems can undergo large drifts and significant deformations without failing compared to other materials and construction types. However, to prevent excessive drifts, moment-resisting (MR) frames require nearly rigid connections, which are almost impractical to reproduce due to the anisotropy of wood and the need for mechanical fasteners. Furthermore, structural members of timber buildings are traditionally connected with dowel-type fasteners resulting in pinned or semi-rigid connections. Consistently, in this work, the beams are pin-connected to the GLT columns and the RC core by applying appropriate rotational end-releasers to simulate the presence of slotted-in steel plates and dowels.

The columns are fixed to the foundation and designed to have variable cross-section sizes along with the building height, tapering from 975 mm x 975 mm at the base to 450 mm x 450 mm on the top floor.

In the design of tall buildings, especially in the case of multi-story timber buildings, shear walls are often adopted to further stiff the lateral resisting systems. The structural variant illustrated in Fig. (**4**) is designed with -laminated infill panels extending over one story with variable lengths of 4, 6, and 10 meters. The walls have a thickness of 300 mm at the base and are tapered to 100 mm at the top. The selected dimensions of the CLT panels strictly depend on the commercially available thicknesses for manufacturable laminated products. The wall system gives the structure a nearly box-like behavior, which makes the overall structure more rigid against wind and seismic loads than pure frameworks. Connections of shear walls employ hold-down anchors and angle bracket shear connectors.

Due to the improved efficiency exhibited and the limited use of structural material, diagrid systems have emerged rapidly in the last decades as high-performing solutions for high-rise steel buildings. By recognizing its superior behavior under severe lateral loading scenarios, the diagonal grid is selected as a third design alternative for the comparative study. The diagrid is a perimeter resisting system composed of diagonal members only, which fulfill the bending and shear requirements of the building against both vertical and horizontal actions. Its structural effectiveness mainly derives from the fully axial behavior of the diagonal members arranged in a triangulated configuration. The geometrical pattern makes the structure more effective in reducing shear deformation than typical systems, which rely on vertical columns to carry shear forces. Great efforts have been devoted by researchers towards the survey of effective design procedures [31, 32], geometrical arrangements of diagonal members [33 - 35] and performance evaluations [36, 37].

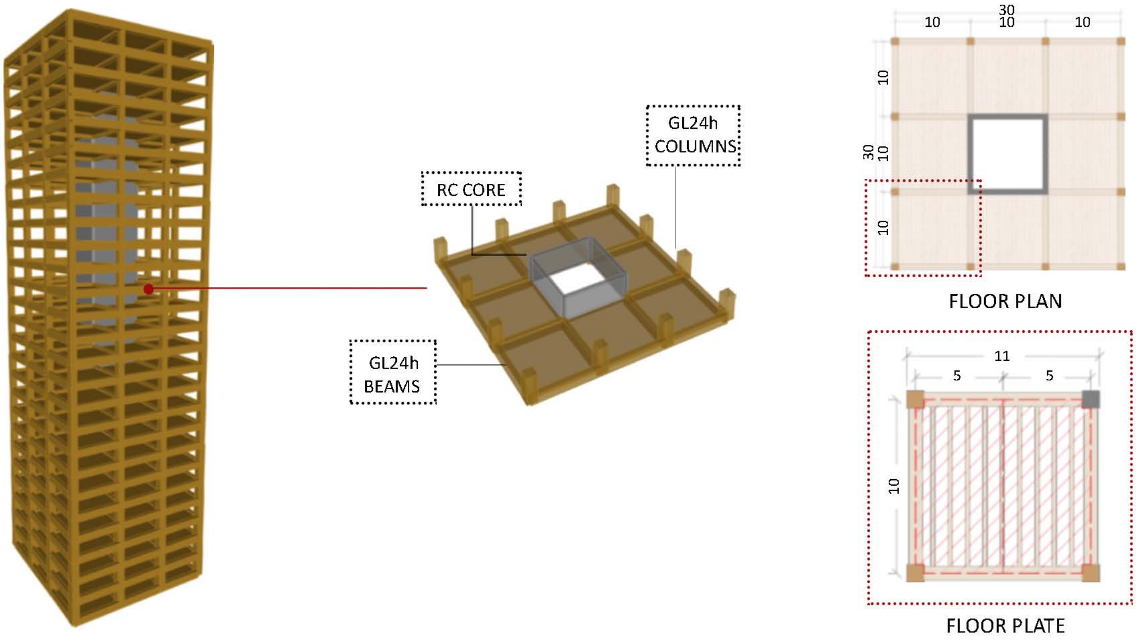


Fig. (3). Schematic of the framed variant and typical floor plan.

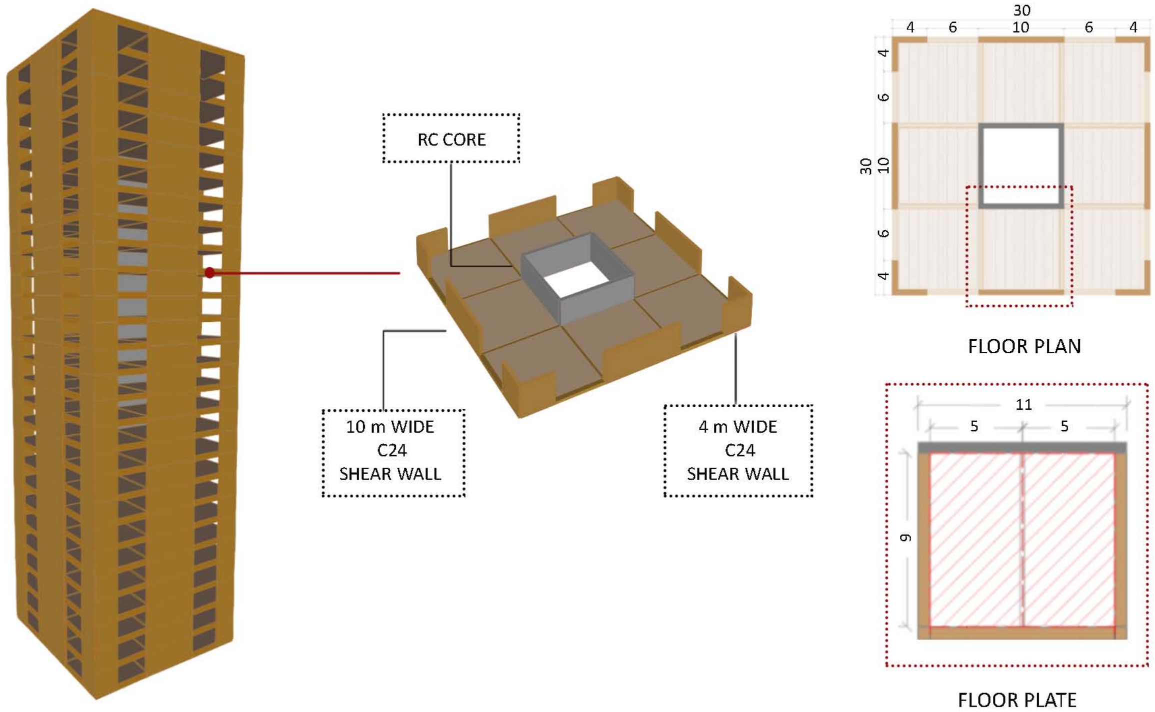


Fig. (4). Schematic of the shear-walled variant and typical floor plan.

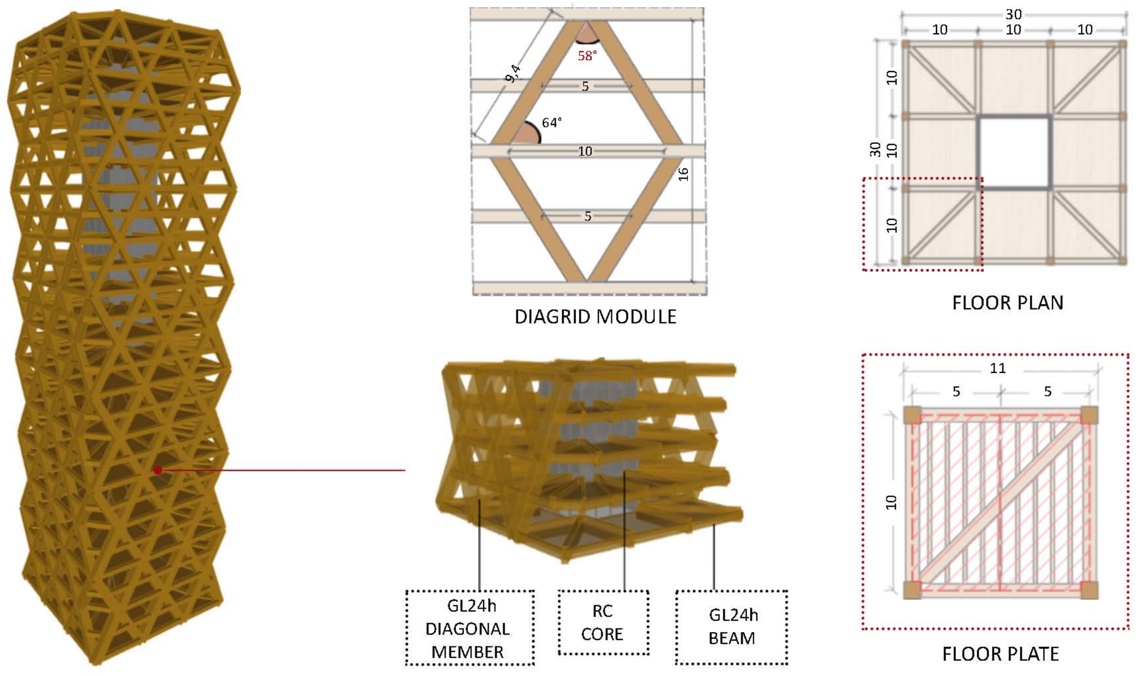


Fig. (5). Schematic of the diagrid variant and typical floor plans.

In the dual system, the timber diagrid (outer tube) and the RC core (inner tube) collaborate in resisting lateral and gravity loads. Floor slabs are placed between the two resisting systems, providing high in-plane stiffness to constrain the tubes to have the same horizontal displacement.

The perimeter structure consists of diagonal members extending over four floors to form an angle of 64°, which falls within the optimal range of 53°-76° for building heights comprised between 20 to 60 stories, as identified in the literature. The diagonal members are assumed to be pin-ended, resisting overturning moment and shear force through axial action only. Diagonal cross-sections for each module are assessed according to the stiffness-based approach firstly proposed by Moon [31] and gradually adjusted from the bottom module (875 mm x 875 mm) toward the top one (230 mm x 230 mm).

4. RESULTS

The numerical simulations performed on the multi-story buildings, modelled according to the recommendations given in the previous section, are presented and discussed here. Modal response spectrum analyses and static analyses are carried out in the elastic range to evaluate the incidence of severe seismic and wind actions on different lateral resisting systems.

As already discussed in Section 2 of this work, typical problems encountered when designing multi-story timber buildings are mostly mass-stiffness ratio (or strength-stiffness ratio) related, resulting in large lateral drifts that may cause damage in the non-structural elements and discomfort experienced by occupants. Therefore, research objectives must address the dynamic behavior in the Serviceability Limit States (SLS) and Ultimate Limit States (ULS) under seismic and wind actions.

Table **1** shows the modal analysis outcomes for the building models' first three vibration modes. Each variant identifies two predominantly bending motions (MU,x and Mu,y) and one torsional motion (MR,z). These results, albeit on a preliminary basis, summarize different stiffness contents between the analyzed models, which increase with the transition from the diagrid structure (T_1 = 1.9 s) to the frame system (T_1 = 2.6 s).

The literature review recognizes that the lateral sway requirement is a dominant issue for tall timber buildings subjected to wind, leading to inherent difficulties in satisfying code standards. It follows that the economic viability of timber buildings strongly depends on serviceability and comfort prerequisites. The maximum deflection allowable at the top (Δ) is constrained to 1/500 of the building height, which results in a threshold of 208 mm for the specific case. The inter-story drift (δ) limitation is set to 20 mm, corresponding to 1/200 of the story height. However, since the early stages of the design, it was noted that the presence of a reinforced concrete core, notwithstanding a reasonably small thickness, can provide high stiffness to the overall system, effectively making the engineering demands for strength more stringent than stiffness criteria. In the design sizing process, the cross-section dimension of individual timber members is mainly bound by the force demand for the ULS condition. Therefore, the occupant comfort, in terms of top displacement and inter-story drift, is inherently satisfied while the load-bearing members' Demand to Capacity Ratio (DCR) is between 70-80%. The charts in Fig. (**6**) provide the deflection characteristics of the analyzed buildings, obtained from linear static and response spectrum analyses under wind and seismic loads, respectively. In particular, Fig. (**6a**) shows the lateral displacements as a function of the building height, while Fig. (**6b**) shows the Inter-story Drift Ratios (IDRs). The numerical IDRs compare with the inter-story drift limitation specified in Eurocode 8 for buildings having brittle non-structural elements, which corresponds to 0.5%. Although this specification only applies to displacements obtained from analyses performed along with Damage Limits States response spectra, the resulting threshold represents a convenient measure for appraisal.

The drift growths provide information on the stiffness distribution along with the building height. A more significant indicator of how the design variants are effectively working is offered by the relative contribution between the timber structures and the RC cores in resisting unfactored wind, seismic and gravity loads. A summary is provided in Fig. (**7**) with information on relative material consumption in unit timber and concrete mass, calculated as the ratio of the total structural material used by the gross area of the building variant. The demand-to-capacity survey is consistent with the lateral stiffness contribution detected for timber structural systems. In fact, the strength check under compressive stresses is more stringent for the frame and diagrid variants, while shear stress is dominant for the wall system.

Table 1. Results of the modal analysis.

	Framed Variant				Shear Walled Variant				Diagrid Variant			
No. Mode	**T**	**$M_{U,x}$**	**$M_{U,y}$**	**$M_{R,z}$**	**T**	**$M_{U,x}$**	**$M_{U,y}$**	**$M_{R,z}$**	**T**	**$M_{U,x}$**	**$M_{U,y}$**	**$M_{R,z}$**
(-)	**(sec)**	**(%)**	**(%)**	**(%)**	**(sec)**	**(%)**	**(%)**	**(%)**	**(sec)**	**(%)**	**(%)**	**(%)**
1	2.6	62.5	0.0	0.0	2.1	63.3	0.0	0.0	1.9	14.2	47.5	0.0
2	2.6	0.0	62.5	0.0	2.1	0.0	63.3	0.0	1.9	47.8	14.2	0.0
3	1.0	0.0	0.0	81.8	0.9	0.0	0.0	78.7	0.6	0.0	0.0	75.7

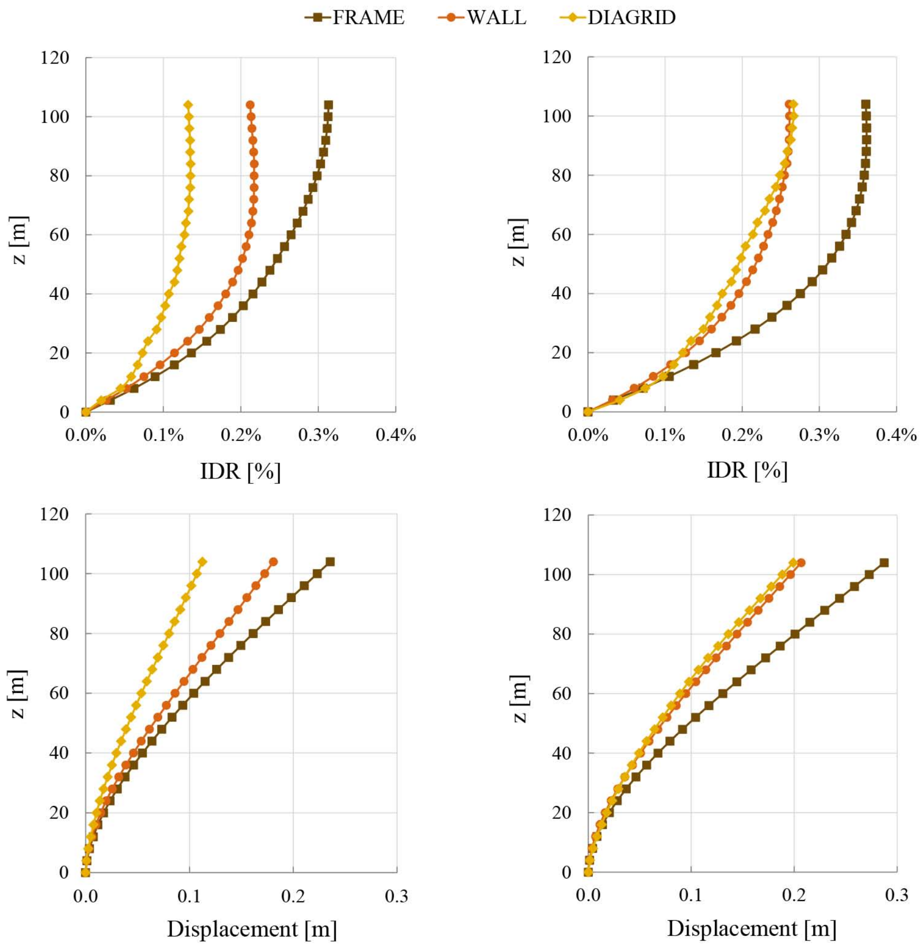
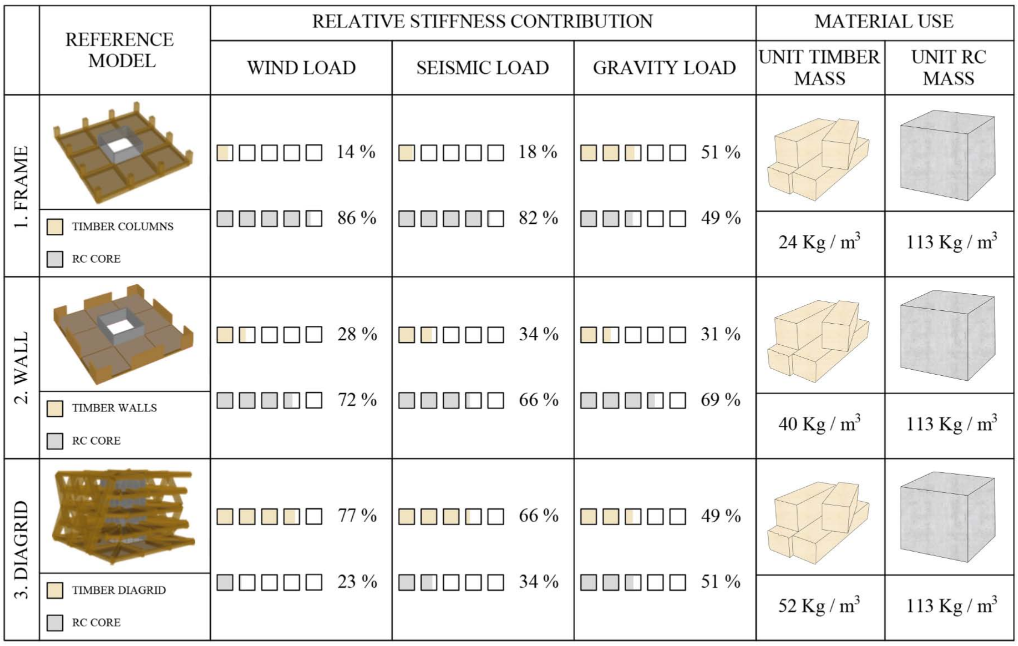


Fig. (6). Results of the three variants under wind load (**a**) and seismic load (**b**): inter-story drifts (top) and lateral displacements (bottom).



	REFERENCE MODEL	RELATIVE STIFFNESS CONTRIBUTION			MATERIAL USE	
		WIND LOAD	SEISMIC LOAD	GRAVITY LOAD	UNIT TIMBER MASS	UNIT RC MASS
1. FRAME	☐ TIMBER COLUMNS	14 %	18 %	51 %		
	☐ RC CORE	86 %	82 %	49 %	24 Kg / m^3	113 Kg / m^3
2. WALL	☐ TIMBER WALLS	28 %	34 %	31 %		
	☐ RC CORE	72 %	66 %	69 %	40 Kg / m^3	113 Kg / m^3
3. DIAGRID	☐ TIMBER DIAGRID	77 %	66 %	49 %		
	☐ RC CORE	23 %	34 %	51 %	52 Kg / m^3	113 Kg / m^3

Fig. (7). Summary of each variant's relative contribution to base reactions and material usage between timber systems and RC cores.

5. DISCUSSION

In the *frame* model, regardless of the nature of loading, the overturning moments and shear forces due to lateral loads are primarily counteracted by the RC core, with a relative contribution of 86% and 82%. This result is consistent with the modelling assumption of pin-ended beams, making the perimeter structure less stiff than rigid connections. However, modelling rigid connections between timber beams and columns leads to large inaccuracies and higher base shears. The overall system would unrealistically stiffen, overestimating the lateral performance and load-bearing capacity. Although this significant alteration does not compromise the general stability of the buildings (unless second-order effects have a remarkable impact), it may lead to underrated damage estimation due to vibration periods being in the range of the increasing spectrum, as emphasized by Fragiacomo *et al*. [38]. In the dual-framed variant, it emerges that the RC core plays a more predominant role than in any other case studied, being the most rigid element to which the global lateral stability, stiffness and strength are entrusted. On the other hand, the timber frameworks efficiently contribute to the vertical load-bearing capacity of the whole system, displayed by the prevailing function in resisting gravity loads (51%).

Since the seismic demand in the timber structure is transmitted to the RC core through floor diaphragms, whose stiffness dictates the magnitude of the load transferred, potential damage to individual GLT members is reduced. However, extensive damage could occur in the glulam-to-concrete connections, identified as a critical and vulnerable part of the system in past experimental tests [30], and therefore must be carefully designed.

In the *wall* design variant, the box-like behavior of the timber panels imparts enhanced lateral performance to the entire structure. Similar to the previous case, the RC core significantly contributes to the overall lateral performance of the dual system by absorbing most of the shear and bending actions of applied loads. However, the timber walls positively participate in resisting shear forces associated with lateral loads, providing doubly improved performance against both wind (28%) and seismic loads (34%) compared to the frame alternative. Even increased efficiency can be allocated to the laminated structural system by supplying additional compartmentalization through panels placed orthogonally to the inner core. This would lead to an increase in stiffness of 40%, making the dual system comparable, in terms of lateral performance, to that with diagrid and, therefore, effective for the construction of taller buildings.

Ever-growing performance can be appreciated when the *diagrid* is adopted as an alternative perimeter solution. The results of the modal analysis in Table **1** and the displacement curves in Fig. (**6**) confirm the superior performance of the tubular structures compared to traditional framed and shear wall systems. The overall deflections are rather small due to the design process performed on the members of each module. In particular, the results show that the ultimate strength limit state controls the timber sizing procedure rather than the serviceability limit state. Furthermore, it might be observed here that the deflection trends of the diagrid solution intertwine or almost overlap with those of the wall variant when the tall building is subjected to seismic excitation, indicating that comparable global performance arises under earthquake loads. This result might be imputable to the influence of higher modes in the diagrid case, for which the first three vibration modes excite less than half of the overall building mass, unlike the other variants (Table **1**).

Due to the geometrical arrangement of external diagonals, shear forces and overturning moments induced by external lateral loads are mainly resisted through axial action of the diagrid (relative contribution to the lateral stiffness of 77% and 66% for wind and seismic loads, respectively), rather than by flexure in the RC core. These results are consistent with the expected theoretical behavior of steel diagrids with optimal bracing angle, which predicts a relative contribution to the global lateral rigidity in the range of 80%-85% when combined with a steel core. In fact, compared to the other two systems, the diagrid alone provides adequate bending and shear stiffness without leaning on the high shear rigidity core, possibly employing internal tubes designed to resist gravity loads only. Nevertheless, this assumption reflects a purely theoretical behavior since the core contribution improves the structure reliability against horizontal excitations, especially under critical conditions. Accordingly, a stiff concrete core is not strictly required in dual systems with diagrids, and lighter internal stability systems can be designed.

As typically adopted in other research works, interesting results can be appreciated by replacing the concrete core with a cross-laminated one. The adjustment results in a stiffness loss of 68% for the frame variant, 45% for the wall variant and 23% for the diagrid variant. While maintaining the same member cross-sections for the design alternatives, serviceability limitations are largely exceeded for the frame and wall variants while diagrid remains verified with a great margin. This result confirms the excellent behavior of the grid structural systems, for which any variations of the inner core have an almost insignificant impact on the global building performance.

The key effect of the concrete core on the structural response of the frame and wall variants is that it acts as the stiffest part of the building. Consequently, it requires proper design by placing the core symmetrically in a plan to prevent torsional contributions, which would produce significant shear stresses in the core. Furthermore, the results of the stiffness loss demonstrate that, in tall buildings with conventional timber frames or shear walls, inter-story drifts might exceed the standard prescribed. As the feasibility of designing multi-story buildings closely depends on the ability to control lateral drift, this reflects that medium- to high-rise timber buildings can be prone to high lateral flexibility during design-level seismic events.

On the other hand, diagrid systems could represent an efficient design solution for tall timber buildings since serviceability criteria can be easily met compared to typical typologies. The central core can even be swapped for a lighter gravity timber frame (resulting in a stiffness loss of 35% concerning the RC core) without compromising the overall lateral performance. Because of the triangulated configuration, the diagonal members carry both gravity and lateral loads, and the core can be designed to be ‘soft’ as it does not provide primary lateral stability to the building. Shifting the concrete core to a timber one provides substantial environmental advantages as it requires less energy during the manufacturing of the elements and the construction stage.

CONCLUSION

Modern technologies for timber lamination have evolved rapidly over recent decades. However, limitations to their applicability in multi-story building designs are mainly attributable to an inherently low stiffness of the structural material. This may lead to poor dynamic response associated with the relatively low fundamental frequency. The structural flexibility, in turn, generally translates into large drifts, which, although not necessarily yield failure since structural elements can accommodate significant deformations, may result in occupant discomfort.

The present paper evaluated the static and dynamic performance of multistory timber buildings under severe lateral loading scenarios. Three design variants of dual systems, namely combinations of perimeter timber structures and RC inner cores, have been modelled and numerically evaluated in the elastic range. The building models have shown high lateral stiffness in withstanding seismic wind-induced loads. This result is mainly attributable to introducing a rigid concrete core, which nearly supplies the demand for shear and bending stresses alone, especially evident in the frame and wall variants. The synergistic behavior of the dual frame-core system fails as the building becomes taller, and a greater premium for height is paid due to lateral loads. Although moment-resisting frames are suitable candidates for steel and concrete buildings up to 20-30 stories, this efficient limit height is drastically reduced when timber material is adopted, given the substantial difficulty in reproducing effective rigid moment connections.

The diagrid alternative shows, on average, the stiffest behavior among all analyzed models. The diagonalized pattern combined with a concrete core displays extreme rigidity, though not strictly required for the reference building height assumed. This holds a twofold implication. First, it confirms that even for timber structures, the diagrid efficiently contributes to the overall strength and stiffness performance without relying on the lateral bearing capacities of internal cores. This statement suggests the adoption of lighter cores, such as steel or timber frames or CLT wall systems. Secondly, the results bode well for constructing multi-story wooden buildings of ever-growing heights coupled with modest material consumption. Based on the reference building tallness assumed, the hybrid variant with timber shear walls shows the best compromise among the three design alternatives selected for the comparative study.

Furthermore, it has been observed that the strength design can be dominant in dual timber-concrete systems, potentially resulting in larger member sizes than according to stiffness requirements. The opposite occurs in the case of solely timber structures, where deflection limitations mainly govern the design procedure. Therefore, the analytical assessment of the numerical solutions under design loads allows for stating the following remarks. Stiffness and strength criteria are both necessary to exhaustively size the load resisting timber members and cannot be separately conceived since it is impossible to predict in advance whether the design will be governed by serviceability or ultimate limit state conditions under wind or earthquake loads. However, it should be emphasized that the results discussed have been obtained from a single reference case study. A wider range of building attributes, lateral loads and timber properties is required to converge towards a more comprehensive and generalized appraisal of the problem.

In conclusion, this paper has corroborated the viability and potentiality of designing multi-story buildings with engineered timber structural systems. Although related studies and experimentations are still in their infancy, great efforts are emerging to encourage the use of timber products for an ever-increasing number of high-rise design applications. The research and benefits of this structural material lay the foundations for a new era of sustainable designs.

LIST OF ABBREVIATIONS

EWP = Engineered Wood Products
LVL = Laminated Veneer Lumber
CLT = Cross Laminated Timber
RC = Reinforced Concrete
DCR = Demand to Capacity Ratio
MR = Moment-Resisting

CONSENT FOR PUBLICATION

Not applicable.

AVAILABILITY OF DATA AND MATERIALS

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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