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A NOVEL HYBRID WOODEN STRUCTURAL SYSTEM FOR MULTI-STOREY BUILDINGS IN SEISMIC PRONE AREAS

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ABSTRACT: The development of innovative engineered wood products has greatly increased the possibility of using timber as structural material, opening new markets in the construction sectors, such as multi-storey residential and collective (e.g., schools) buildings. The use of timber structures is in fact still confined to low- and mid-rise buildings. The HyWood4Buildings project aims to overcome the existing constraints in the timber construction sector, proposing a novel hybrid structural system for taller timber buildings. This system combines two distinct but interacting components: a modular hybrid steel-timber lateral load resisting (HyST-LaR) system and a solid-sawn wall (SoN-Wall) system. This paper presents the structural characterization of the innovative HyST-LaR system through an experimental campaign at component-level and numerical analysis with a first glance to the development of an analytical model.

KEYWORDS: timber, mid-rise buildings, seismic design, hybrid

1 – INTRODUCTION

Timber structures have become a valuable alternative to traditional materials, mainly due to their light weight, speed of construction and the high strength-weight ratio of timber products, especially in seismic prone areas. The use of timber structures, however, has been mainly confined to low to mid-rise buildings, mainly due to limited resistance of proprietary mechanical anchors ([1] and [2]).

Steel-timber hybrid (STH) structural systems have emerged in the last decades as a promising solution for sustainable and resilient constructions. Such systems combine the ductile behaviour of steel moment resisting frames (SMRF) with the stiffness and lightweight of timber elements, typically made with cross-laminated timber (CLT) or light frame timber (LFT) shear-walls.

1.1 STATE OF THE ART

Several studies have investigated the performance of hybrid systems under lateral loads.

An investigation on single, multi-storey and multi-bay STH frames with CLT infills [3] showed the influence of mechanical properties of CLT panels (thickness, compressive strength, and confinement gap) on the overall behaviour of such STH system. In particular, these studies showed how these parameters are relevant to characterise the strength, the drift capacity and post-peak behaviour.

Further investigations have focused on high-rise applications [4], demonstrating the potential of combining SMRF with balloon-type CLT shear-walls to achieve a significant reduction in inter-storey drifts, compared to conventional SMF buildings. This approach offers an economically and environmentally friendly alternative for high-rise building constructions.

Other studies aimed to better understand the seismic performances of STH systems with LFT shear-walls infills through experimental observations and the development of validated numerical models. As an example, Li et al. [5] highlighted the importance of understanding the load-sharing mechanism between the steel frame and the timber infill, introducing a load-sharing parameter.

Experimental investigations have provided valuable outcomes regarding the dynamic behaviour of STH

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structures through shaking table tests [6]. The experimental results confirmed the significant contribution of the infill timber walls to lateral resistance and demonstrated the valuable performance of the systems under various seismic intensities.

A comprehensive review of existing hybrid timber structures and research contributions was presented by Gallo et al. [7] showing the growing interest in this field and the need for further research to address the challenges associated with their design and seismic performance.

Seismic vulnerability assessments, through non-linear dynamic analysis and fragility curve development, showed the effectiveness of varying CLT infill configurations on SMRFs for STH buildings to achieve different performance objectives and reduce seismic vulnerability [8].

1.2 THE HYWOOD4BUILDINGS PROJECT

The HyWood4Buildings project aims to overcome the existing constraints in timber sector by proposing two different but interacting innovative structural systems as represented in Figure 1a: an innovative STH lateral load resisting structural frame (HyST-LaR), and a solid-sawn wall (SoN-Wall) system.

The HyST-LaR system is designed to ensure the lateral stability and the load-bearing capacity for taller buildings, combining steel frames and CLT panels as shown in Figure 1b.

The SoN-Wall system is primarily designed to resist gravitational loads and is composed of multiple light-frame timber shear-walls sheathed with diagonal boards (LFT-DB) as represented in Figure 1c.

LFT shear-walls sheathed with wooden based panels (i.e., OSB and gypsum fibre boards) are generally adopted to provide lateral and vertical stability of low- to mid-rise timber buildings. However, as an alternative, light-timber frames can be laterally stabilized using diagonal wooden boards as an alternative to traditional panels. The lateral behaviour of LFT-DBs was investigated in various studies ([9], [10] and [11]) through full-scale experimental campaigns and numerical analyses. The results showed that performance of single layer LFT-DB is strongly influenced by the direction of the lateral load acting on the shear wall. Conversely, double-crossed layer LFT-DB exhibited symmetrical behaviour under cyclic loading comparable to traditional LFT shear-walls with panels.

CLT platform-type structures are generally subjected to restrains due to both limited resistance of mechanical anchors and the forces flow transmitted from a structural element to another, as represented in Figure 1d.

In addition, non-engineered wood products such as LFT-DBs require a low-level production process that is accessible to small companies.

For these reasons, the HyWood4Buildings project aims to propose an innovative approach for multi-storey timber buildings in seismic prone areas, with the purpose to meet high-performance design demand and promote a fair use of the resources and support local supply chain in the timber sector.

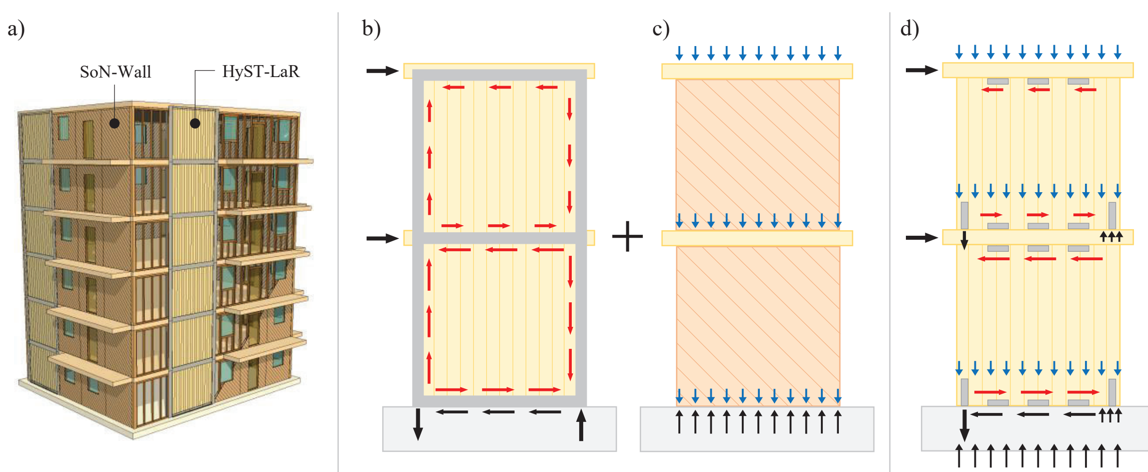

Figure 1. HyWood4Building hybrid structural system concept (a), main force distribution within HyST-LaR system (b) and SoN-Wall system (c). Force distribution of typical CLT plat-form type buildings (d).

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2 – THE HYST-LAR SYSTEM

The HyST-LaR system consists of a modular bracing system for multi-storey buildings, designed to withstand horizontal loads due to earthquake and wind events. The base unit of HyST-LaR system is prefabricated and consists of a CLT panel connected to a steel frame, as shown in Figure 2.

The steel frame components are:

- two steel HEB lateral columns;
- coupled UPE steel beams as top element;
- four steel plates welded to the columns and bolted to the beam.

The CLT panel, inserted within the steel frame, is provided with longitudinal cuts designed to accommodate the steel plates. The connection between the CLT panel and the frame is ensured by dowels (i.e., panel-to-frame connections) arranged in correspondence with the holes of the perforated plates.

The column-beam joint consists of a T-shaped plate, whose web is inserted and bolted between the two UPE beams of the top beam, while the flange is directly bolted to the column.

The top beam of the steel frame is connected to the CLT panel by a perforated plate. The upper part of such plate is inserted between the coupled UPE beam and connected to their webs by means of bolts. The lower part of the plate is inserted into the CLT panel cut and connected by means of dowels. Similarly, the plates welded to the columns are placed into the two lateral CLT panel cuts and connected with dowels.

The HyST-LaR module at the ground floor is anchored to the foundation with ad-hoc mechanical anchors, specifically designed for easy installation.

These elements consist of:

- two steel column base elements reinforced with lateral plates;
- two L-shaped steel beams anchored to the foundation and connected to the bottom plate of the module.

The upper storeys of the HyST-LaR frame can be realised by bolting the columns together and inserting and connecting the lower plate of the new HyST-LaR module between the two UPE beam of the module below as represented in Figure 3.

Unlike traditional multi-storey platform-type CLT buildings, where mechanical anchors (e.g., angle brackets and hold-downs) need to transfer shear loads and bending moments (between every storey), the HyST-LaR system behaves differently: in fact, the panel-to-frame connections (i.e., connections between the CLT and steel frame) are subjected only to shear loads, while the cumulative tensile loads, due to bending moment, are directly transferred to the foundation by the steel columns.

Furthermore, differently from the SMRF system, the beam-to-column joints of the HyST-LaR system are not designed to transfer bending moment.

Additionally, the panel-to-frame connection (i.e., steel-to-timber dowel connection) spacing and diameter represent a critical aspect that must be defined in the design phase, as the main dissipative behaviour is supposed to occurs within such connection, avoiding brittle failures, especially during seismic events.

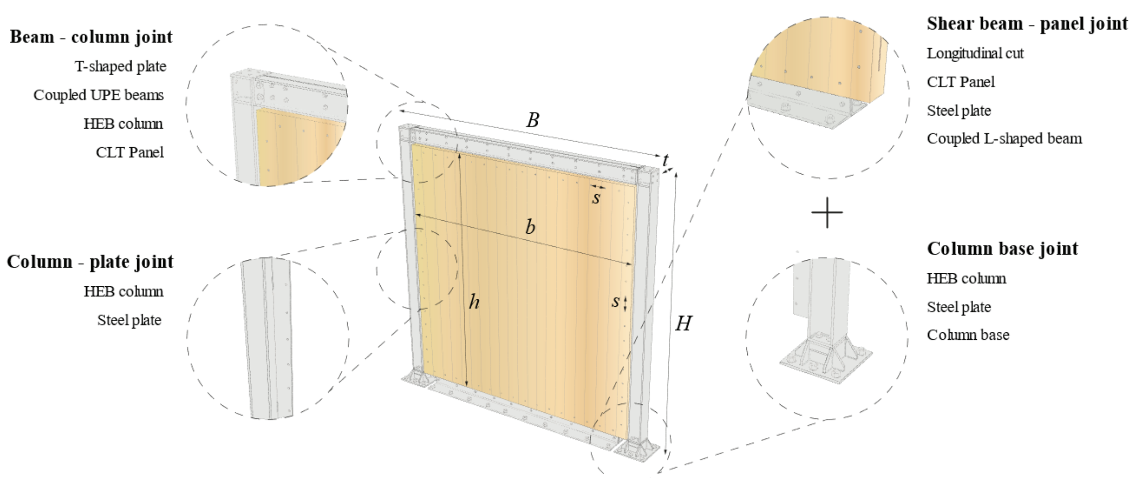

Figure 2. Base module of HyST-LaR system.

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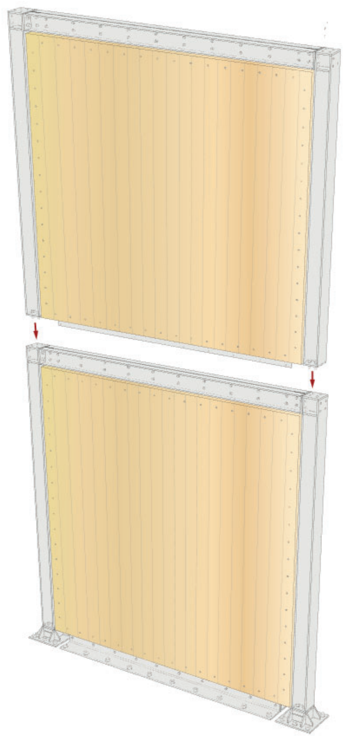

Figure 3. HyST-LaR system assembly procedure.

3 – COMPONENT-LEVEL TESTING

In order to conduct numerical analyses to predict the actual behaviour of HyST-LaR systems in different configurations and propose an analytical solution for the calculations, an experimental campaign was carried out at the component-level to characterise the behaviour of the panel-to-frame connections (i.e., steel-to-timber dowel connections).

3.1 TEST SET-UP

Monotonic tests were performed in accordance with EN 26891 [13] on six specimens which simulate the panel-to-frame connection of the HyST-LaR system.
The test set-up adopted for the experimental campaign is represented in Figure 4. Each specimen consists of a 5 layers 160 mm thick CLT panel with 8.5 mm cut where an 8 mm plate was inserted and connected to the panel with a single 12 mm dowel.
In order to characterize the influence of the angle between the applied load and the grain direction of the outer layers of CLT panel, both parallel and perpendicular configurations (i.e., angle α_p equal to 0° and 90° respectively) were tested.
For each test the CLT panels were anchored to the base plate of the testing machine, whereas the plates were connected to the actuator.

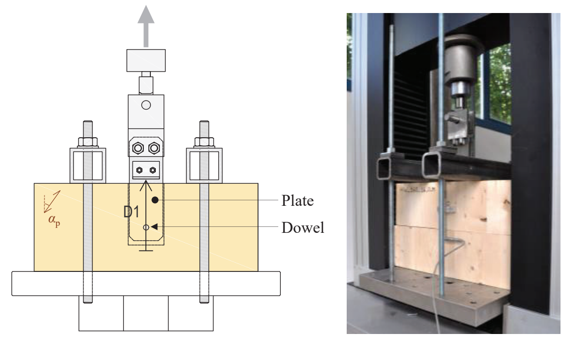

Figure 4. Set-up adopted for component-level testing.

The relative slip (δ) between the CLT element and the plate were monitored through two Linear Variable Displacement Transducers (LVDTs) placed on the two sides of the panel (D1 and D2). A constant rate of 0.08 mm/s was adopted for the test campaign.
Test results are reported in Table 1 in terms of peak load ($F_{con,max}$) and stiffness (k_{con}) according to EN 12512 [14].
A peak load at the displacement of 15 mm is assumed for tests which did not show any descending trend on load-slip curve.
The mean load-slip curves are represented in Figure 5.
The results from the component-level testing showed the influence of the direction between the load and the grain of the CLT panel. As expected, steel-to-timber dowel connection exhibited high ductility values.

Table 1. Test results from monotonic test on steel-to-timber dowel connection of HyST-LaR system.

Test	α_p	$\delta_{F,con,max}$	$F_{con,max}$	k_{con}
	[°]	$[mm]$	$[kN]$	$[kN/mm]$
001	0	15.00	23.31	14.15
002	0	15.00	29.79	13.11
003	0	15.00	32.20	18.46
004	0	10.22	25.27	17.17
005	90	15.00	25.20	13.00
006	90	15.00	24.02	13.08

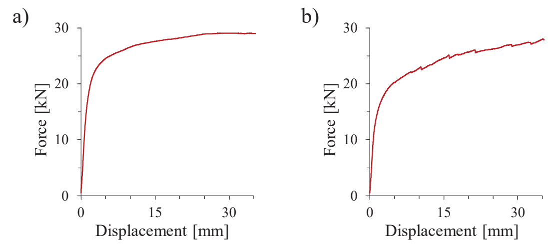

Figure 5. Mean load-slip curves from experimental testing on dowel connection of HyST-LaR system with 0° (a) and 90° (b) angle between the applied load and the grain of the CLT panel.

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4 – ANALYTICAL AND NUMERICAL ANALYSES

The HyST-LAR system has been designed to resist the horizontal forces, including wind and seismic loads. In order to evaluate the horizontal bearing capacity of the single-storey module, the response of the system to horizontal forces applied at the top of the base unit was investigated. The load-bearing capacity of the system was then assessed through the determination of its structural behaviour, which was found to be comparable to that of a fully anchored LFT shear-wall as described by Källsner and Girhammar [12]. This assumption is substantiated by the observation that, in both the LFT shear-wall and HyST-LAR system, the connections between the frame and the panel are exclusively subjected to shear loads. Consequently, an elastic analytical model of the HyST-LAR system was developed.

In order to validate the analytical model and to evaluate the plastic behaviour of the unit, a numerical model developed with the finite element analysis software Straus7 was assessed.

4.1 ELASTIC ANALYSIS

The purpose of the elastic analysis is the determination of the horizontal elastic load-bearing capacity and the stiffness of the HyST-LAR module. In accordance with the assumptions proposed in [12], the deformation behaviour of the system is determined by two contributions: the panel-to-frame connections slip and the shear deformation of the CLT panel.

The geometric parameters of the base unit of the HyST-LAR system are shown in Figure 2. In particular, b and h are the horizontal and vertical lengths of the CLT panel respectively, whereas s is the spacing between the dowels as shown in Figure 6. For ease of calculation b' and h' are assumed (see Figure 6) and defined by (1).

$$b' = b - 2e \quad ; \quad h' = h - 2e \tag{1}$$

For assembly reasons of the HyST-LaR module the geometrical layout of the dowels is designed to ensure the proper distances from CLT corners and longitudinal cuts. As a result, it is necessary to guarantee the appropriate interspace between the panel corners and the beginning of the row of dowels.

Considering the case of a square-shaped panel, it is assumed that b is equal to h. Therefore, the number of connectors each side of the panel is defined by the equation (2).

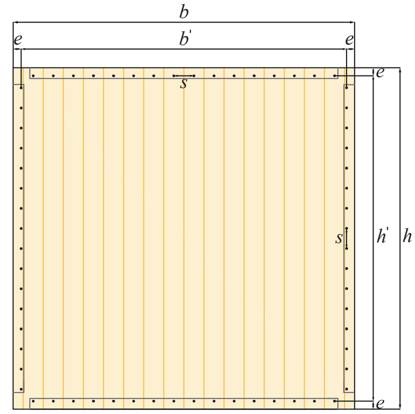

Figure 6. Geometric dimensions for the analytical model of HyST-LaR module.

$$n = \left\lfloor \frac{b'}{s} \right\rfloor \tag{2}$$

n is taken by rounding down the b'/s ratio; this ensures the necessary distance from the corners.

Hence, following the procedure indicated in [12], the horizontal elastic load-bearing capacity of the HyST-LaR module ($F_{w,el}$) is given by equation (3) and corresponds to the horizontal load on the shear-wall when at least one dowel reaches the load-carrying capacity F_{con} (i.e., the dowel most distant from the centre of gravity of the fasteners).

$$F_{w,el} = \frac{F_{con}}{b'\sqrt{\left[\dfrac{\frac{(n-1)s}{2}}{\sum_{i=1}^{n}\hat{x}_i^2}\right]^2 + \left[\dfrac{\frac{b'}{2}}{\sum_{i=1}^{n}\hat{y}_i^2}\right]^2}} \tag{3}$$

Consequently, it is necessary to calculate the moment of inertia of the connectors, placing the reference system in the centre of the panel. Therefore, it is obtained by equation (4).

$$\begin{aligned}\sum_{i=0}^{z}\hat{x}_i^2 = \sum_{i=0}^{z}\hat{y}_i^2 = \\ = \sum_{i=0}^{4n}\hat{x}_i^2 = \frac{1}{6}n\,s^2(n^2-1) + \frac{nb'^2}{2}\end{aligned} \tag{4}$$

Where $(\hat{x}_i, \hat{y}_i)$ are the coordinates of the i-th fastener.

Combining (3) and (4), the horizontal load-bearing capacity of the wall $F_{w,el}$ is obtained in equation (5).

$$F_{w,el} = \frac{n\,F_{con}}{b'}\frac{\frac{1}{3}(n^2-1)s^2 + b'^2}{\sqrt{(n-1)^2s^2 + b'^2}} \tag{5}$$

Then, the maximum horizontal displacement at the top of the HyST-LaR module, due to the contribution of connectors deformation, is determined by equation (6), employing a formulation analogous to that presented in [12].

$$\begin{aligned}\Delta_{sh} &= \frac{F_{w,el}\, b'^2}{k_{con}}\left(\frac{1}{\sum_{i=1}^{n}\hat{x}_i^2}+\frac{1}{\sum_{i=1}^{n}\hat{y}_i^2}\right)= \\ &= 4\,\frac{b'}{k_{con}}\frac{F_{con}}{\sqrt{(n-1)^2 s^2+b'^2}}\end{aligned} \tag{6}$$

Where k_{con} is the slip modulus of the dowel.
Therefore, the stiffness of the HyST-LaR module is given by equation (7).

$$K_{sh} = \frac{k_{con}\, n}{4b'^2}\left[\frac{1}{3}(n^2-1)s^2+b'^2\right] \tag{7}$$

With the aim of simplifying and considering $b/s \approx n$, an approximated formulation for (5), (6) and (7), is obtained respectively in (8), (9) and (10).

$$F_{w,el} = \frac{F_{con}}{3}\frac{4n^2-1}{\sqrt{2n^2-2n+1}} \tag{8}$$

$$\Delta_{sh} = \frac{4n}{k_{con}}\frac{F_{con}}{\sqrt{2n^2-2n+1}} \tag{9}$$

$$K_{sh} = \frac{k_{con}}{12n}(4n^2-1) \tag{10}$$

It is noteworthy to mention that the discrepancy due to such approximation, within the typical values of the dimensions of the panels and of the spacing of the fasteners, is negligible.
As regards the contribution to the horizontal displacement of the system of the shear deformability of the CLT panel, it is deemed as comparable to the contribution of the shear deformability of the sheathing panel on horizontal displacement of a fully anchored LFT shear-wall as presented in [12]. Then, for the square-shaped CLT panel, the definition proposed is reduced as indicated in equation (11).

$$\Delta_p = \frac{F_{w,el}\, h}{G_{CLT}\, t\, b} = \frac{F_{w,el}}{G_{CLT}\, t} \tag{11}$$

Where G_{CLT} and t are respectively the shear modulus and the thickness of the CLT panel. As a result, the stiffness due to the shear deformation of the CLT panel is determined as in equation (12).

$$K_p = G_{CLT}\, t \tag{12}$$

Once the two contributions are obtained, the lateral stiffness of the HyST-LaR module is determined by equation (13).

$$K_w = \frac{K_p\, K_{sh}}{K_p + K_{sh}} \tag{13}$$

4.2 NUMERICAL MODEL OF THE HYST-LAR SYSTEM

A numerical model of the base unit of the HyST-LaR system was developed, by means of the finite element analysis software Straus7 [16]. The model consists of a pinned frame connected to a shell element representing the CLT panel as shown in Figure 7.
The panel-to-frame connection of the HyST-LaR system was modelled with bi-directional spring elements (Figure 7).
The base beam and the column base joints of the foundation system were represented by pinned restraints. A 2.5 x 2.5 m CLT panel 140 mm thick and S235 12 mm dowels with 150 mm spacing were used in this study. Two HEB140 were adopted as the lateral columns, and the top beam was modelled with coupled UPE140.
The behaviour of the bi-directional spring implemented in the model was defined by using the mean load-slip curves obtained from the experimental campaign on panel-to-frame connection (see Figure 5). These curves represent the response of the modelled panel-to-frame connection under shear load depending on the angle between the load direction and the grain direction of the CLT panel.

4.3 COMPARISON BETWEEN THE MODELS

In order to compare the numerical analysis responses with the elastic analysis, the same geometry was applied to the analytical elastic model. Furthermore, the maximum load-bearing capacity F_{con} and stiffness k_{con} of the panel-to-frame connection assigned to the model connectors were assessed according to the procedures of ASTM E2126 [15] by using the mean load-slip curves of the component-level tests.
The comparison between the models indicates that the elastic response is approximately similar as shown in Figure 8.
It is important to note that the analytical model well represents the elastic behaviour of the basic unit and allows for the estimation of its elastic limit.
The numerical model also enables the observation of the behaviour in the plastic field with a high degree of accuracy.

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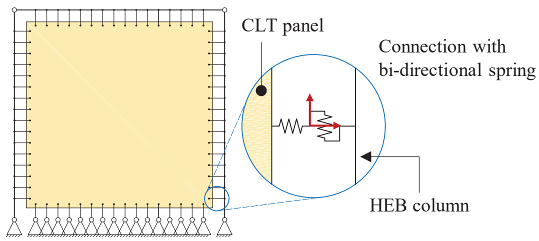

Figure 7. Numerical model of the base unit - HyST-LAR system.

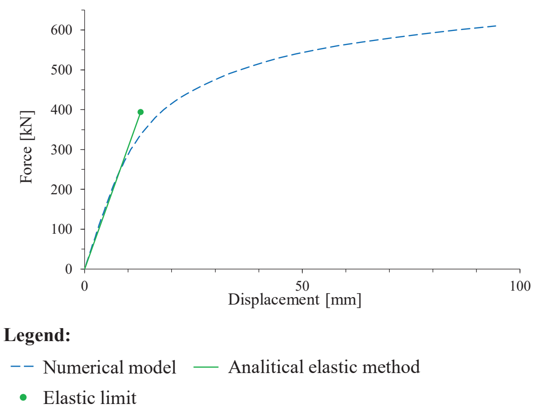

Figure 8. Force-displacement curves of the analytical elastic model and the numerical model.

5 – CONCLUSION

The HyWood4Buildings project proposes an innovative hybrid wooden structural system for multi-storey buildings in seismic prone areas. Two interacting systems, HyST-LaR and SoN-Wall, are coupled in order to provide a novel solution for high performance and optimised steel-timber hybrid (STH) buildings.

The HyST-LaR system presented in this study, is designed primarily to enhance the seismic response of platform-type CLT buildings.

The HyST-LaR system consists of a modular STH frame made up of base units designed as prefabricated modules. Such STH frame is assembled vertically and each module is joined to the next one by means of bolted connections. An experimental component-level testing was carried out on HyST-LaR module panel-to-frame connections in order to assess the advantages and the peculiarities of these steel-to-timber dowel connections. The component-level testing of such connections has shown high levels of load-bearing capacity and ductility, which are critical for energy dissipation during seismic events.

In this study both analytical elastic and numerical models were developed. The elastic method presents a preliminary calculation of HyST-LaR module's elastic properties, such as maximum elastic lateral load-bearing capacity and stiffness, whereas the numerical model captured its lateral structural response. A good matching was achieved between the numerical and analytical model for the elastic behaviour of HyST-LaR module.

6 – ACKNOWLEDGMENTS

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