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COMPARISON OF A SEISMIC DESIGN OF A 10-STORY ALL TIMBER BUILDING AND OF A 10-STOREY HYBRID STEEL-FRAME CLT FLOORS BUILDING USING RESILIENT TECHNOLOGY

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ABSTRACT: Environmental awareness is a major challenge for our generations, especially in the construction sector which is notorious for its polluting impact. This awareness is stimulating the development of new construction techniques in which the optimization of materials is a priority. Concrete stands out for its excellent resistance to compression, water, and heat, while steel offers advantageous properties in compression and tension. At the same time, timber, and its derivatives, such as CLT, are emerging as credible alternatives to concrete in certain situations. By combining these materials, we can exploit advantages of each, developing composite structure. However, a major challenge in construction is the safety of occupants and their surroundings, especially in the face of hazards such as earthquakes. The aim of this document is to demonstrate the differences in outcomes when constructing a multi-story building either constructed entirely of timber or combining steel and CLT, and both using resilient seismic technology in earthquake-prone zones in Europe. To achieve that, a case study prototype building was conducted using resilient braces as the lateral load resisting members. The seismic analysis consisted in performing a lateral forces analysis, a pushover and a nonlinear time history analysis following European standards. This paper shows the design outcomes, particularly the amount of timber and steel used, the amount of carbon emissions and the overall structural performance for both buildings.

KEYWORDS: ***Multi-story, seismic, CLT, steel, resilient***

1 – INTRODUCTION

The adoption of mass timber construction in multi-storey buildings is gaining momentum globally. However, steel and concrete are still very much prevalent in the lateral load resisting systems. Indeed, timber is used to support gravity loads, and steel or concrete are used to support lateral loads (earthquake, wind). In order to optimize the use of timber, it becomes imperative to be able to replace steel or concrete structures in order to obtain a complete timber structure being able to resist to earthquakes. Cross laminated timber shear walls can be used efficiently for low rise buildings (up to 4 story) but to date, concrete or steel remain prevalent for wind and earthquake resistance in multi-story situations as CLT walls become too flexible. However, timber braces using resilient seismic technology can resist higher lateral loads in a very stiff way, allowing for multi-storey all timber designs.

In an effort to determine the advantages of an all-timber structure, a comparison is made on a 10 story commercial building concept (Figure 1), between an all-timber solution and a hybrid steel frame-CLT floor solution. Comparison of the quantity of timber, steel, carbon emissions, etc are made to highlight the differences in outcome for the two structural solutions deigned in accordance with Eurocode 8.

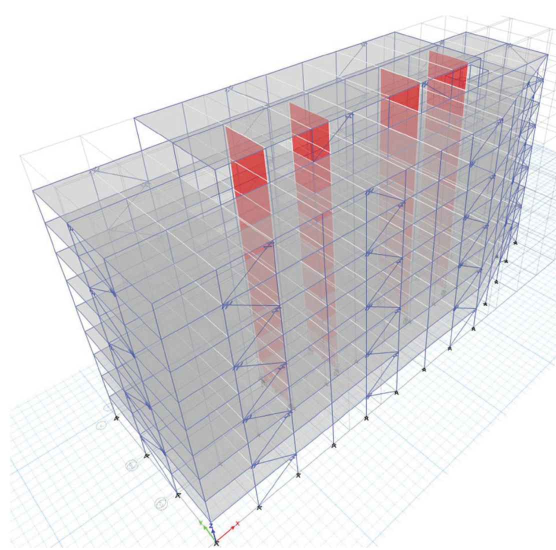

Figure 1. 3D model of 10 storey building.

2 – METHODOLOGY

The study focuses on two 10 story commercial buildings situated in Europe; one is entirely built out of timber members (columns, beams, CLT floors, shear walls and braces) and the other one is made of a steel framework with CLT fllors. The idea is to demonstrate the feasibility of designing a a multi-story commercial building that allows for movement, generally known as a low-damage approach, in both timber and as an hybrid, in accordance with EC 8 [1]. In the event of an earthquake, the primary structure should only sustain minor damage. This philosophy was introduced to decrease the repair and reconstruction cost post-disaster. Implementing a resilient technology would be a great interest to reduce the damages caused to the main and secondary structural members. Therefore, it is to incorporate the possibility of repairing the building and introduce the concept of sustainability. This paper is divided into three main sections: firstly, presenting the building's design and modeling on ETABS; secondly, showing the seismic results; and finally, concluding with the findings and results from the preceding analyses. In all three sections, the comparison between the all-timber building and the steel-timber hybrid one is made.

The design of the multi-storey buildings was carried out separately in two studies; one by Loris Douare [2] and the second one by Tom Bousquet [3], as part of their Master's thesis at Tectonus Ltd, in New Zealand..

2.1 MASS TIMBER BUILDING

The mass timber building layout used in this portion of the study is based on the 10 storey timber building recently erected in Vancouver, Canada. This building was engineered by Fast+Epp of Vancouver and utilised Tectonus resilient seismic dampers for damping and self-centering. This present study consists in performing a seismic analysis according to Eurocode 8 of the multi storey timber building constructed in Vancouver, Canada by considering that it is located in a high seismic area in Europe. For this building, the building is located in Ljubjana, Slovenia. For this location, the peak ground acceleration (PGA) is equal to 2.698 m/s^2. The objectives are to show that such structure is resilient and that it complies well with he requirement of Eurocode 8.

The structure was replicated and the model built using the ETABS and analysed and designed. The seismic force resisting system (SFRS) is composed of an exterior perimeter timber braced frames and four interior CLT shear walls. The CLT shearwalls are located near the stairs and the elevator to accommodate the large open floor plan. The design criteria for Ljubljana are as shown in Table 1.

Table 1. Ljubljana seismic characteristics used.

City	Ljubjana	
a_{gR} (m/s²)	2.698	T_{NCR} = 475years
Soil type	A	*Table 3.1
Spectrum Type	1	*Note 3.2.2.2 (2)
Ductility class	DCM	*Table 8.1
Coefficient q	3	*Table 8.1
Importance factors γI	III	*Table 4.3
Peak ground acceleration	3.238	T_{NCR} = 475years
a_g calculation	0.330 g	
Others structure as timber for example		

A first simple seismic analysis was performed using the Lateral Force Method on the structure to get a first appreciation of the forces involved. The ultimate limit states forces obtained per storeys are given in Table 2.

Table 2. ULS Force values using the Lateral Force Method.

	Mass (kN)	Height (m)	z_i (m)	F_i (kN)
Story 10	5,000	4	40	1,090
Story 9	16,400	4	36	3,210
Story 8	11,100	4	32	1,930
Story 7	11,100	4	28	1,690
Story 6	11,100	4	24	1,450
Story 5	11,100	4	20	1,210
Story 4	11,100	4	16	970
Story 3	11,100	4	12	730
Story 2	11,100	4	8	490
Story 1	11,100	4	4	250
	110,200	40		

The resulting base shear using the Lateral Force Method was determined to be 12,910 kN.

A subsequent analysis was performed using a non-linear pushover analysis approach. In this approach, the SFRS incorporated the Tectonus resilient dampers. The structure was tuned so that it would be self-centering and the load-deformation for the building in

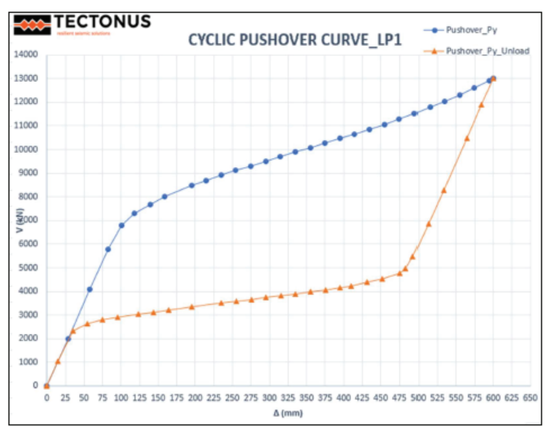

Figure 2. Hysteresys damping of the structure in the x direction using a non-linear push-over analysis.

the x-direction is shown in Figure 2.

Using the resilient dampers on the timber structure had the effect of reducing the base shear on the structure to the values shown on Table 3.

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Table 3. Base shears for the x and y direction from the non-linear push-over analysis.

Direction	$\zeta_{elastic}$	$\zeta_{hysteresis}$	coefficient η	Base Shear (kN)
X	2.5	11.5	0.73	9,400
y	2.5	10	0.76	9,800

The last seismic analysis conducted on the mass timber structure was an non-linear time history analysis. The purpose of this analysis was to show the behaviour of the Tectonus RSFJ and the structure using the records of real earthquakes. It enabled the verification of the design of the RSFJ for the ultimate level state and the maximum credible earthquake (MCE) level.

The various records used in the NLTHA were as listed in Table 4.

Table 4. Earthquake records used for the NLTHA.

RSN	Soil Type	Name	Fault type	Region	Magnitude	Vs30 (m/sec)
125	D	Friuli Italy-01	Reverse	Italy	6.5	505
169	D	Imperial Valley-06	Strike Slip	California	6.5	242
721	D	Superstition Hills	Strike Slip	California	6.5	192
828	D	Cape Mendocino	Reverse	Nothern California	7.0	422
953	D	Beverly hills, Mulhol	Reverse	Southern California	6.7	355
960	D	Northridge- 01	Reverse	Southern California	6.7	325
1116	D	Kobe, Japan	Strike Slip	Japan	6.9	256
1485	D	ChiChi, Taiwan	Reverse oblique	Taiwan	7.6	704
1602	D	Duwce, Turkey	Strike Slip	Turkey	7.1	293

The average base shears obtained from the NLTHA were 8,450 kN for the x direction.

The main advantage of the use of dampers in the mass timber structure was the reduction of the forces in the members and the resulting smaller member cross-sections. For example, the sizes of the braces in the building for the same building with and without dampers is shown in Table 5.

Table 5. Brace section forces and cross-sections.

	With RSFJ		Without RSFJ	
	Force demand (kN)	Section (mm^2)	Force demand (kN)	Section (mm^2)
Brace1	2,250	450x450	8,200	950x950
Brace2	1,400	350x350	5,500	760x760
Brace3	800	300x300	3,000	550x550

The important difference between these two sets of values have many consequences. First thanks to the RSFJ the size of the section is almost divided by 2, which is huge. The weight of the structure will also decrease significantly and enable to save a lot of money in construction. This will also enable to save a lot of cost for the timber connections. In addition, the connection with the use of RSFJ are less complicated and require less materials than the conventional design. Moreover the force present in the brace is divided by 4 thanks to the RSFJ, which also influences the total base shear of the structure. Indeed, the difference results of the base shear obtained previously with the NLTHA and the value obtained with a behaviour factor of 1 shown an important reduction of the base shear, greater than 4. This is summarize in the Table 5. Therefore the cost of foundation will decrease significantly with the use of RSFJ.

Table 5. Behaviour factor q calculation.

	Base Shear ULS	Behaviour factor q
Both directions	38,900	**1**
x-direction with RSFJ	8,540	**4.55**
y-direction with RSFJ	9,370	**4.15**

The different analysis performed enabled to show all the benefits and how to use RSFJs with the Eurocode 8. Even though the regulation about dampers and resilient devices is not clearly described in the standard, this study shows that it is possible to implement this kind of technology in Europe.

2.2 STEEL FRAMED BUILDING WITH CLT FLOOR

The objective of this part was to study a commercial building of 10 stories in a seismic zone in Europe. Sicily is well known for its tourism attractiveness; however, it is also susceptible to strong earthquakes. In the last few decades, more than four earthquakes with a magnitude of over 5 have been recorded, with the most recent one occurring in 2018, which resulted in significant impact, including 30 injuries and damage to several buildings. Therefore, this building project was to be located in Italy, more precisely in Catania, Sicily.

This project has also numerous innovative characteristic link with environmental issues. It aims to demonstrate the relevance of replacing a composite floor made of steel and concrete by a steel and CLT one. Thus, the building is composed of CLT floors playing the role of diaphragm. The main structure is made of steel and bracing will be provided by Tectonus resilient dampers used in a steel brace frame.

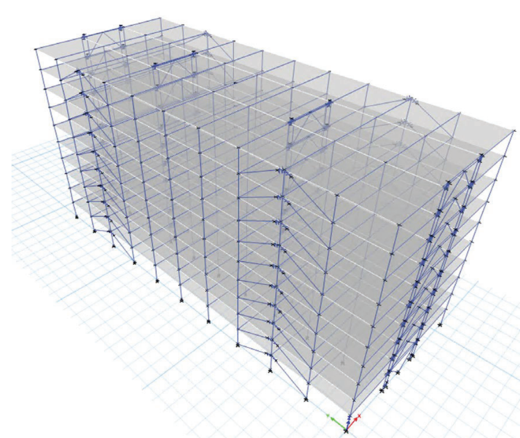

Figure 3. 3D view of the steel framed building with CLT floors.

The the structure is 40m high, 70m long, 27m wide and designed for soil type D in Catani, Sicily. The peak ground acceleration is 2.746 m/s^2. A 3D view of the model is shown in figure 3. One can note that the braces are positioned in different pattern and positions.

To achieve the same structural resistance, the steel-concrete composite beam solution requires a 160 mm concrete floor. The weight of the concrete floor is 400 kg/m^3, compared to 140 kg/m^3 for a CLT solution. The seismic response will thus be much higher as it depends directly on the mass. However, on another hand, the concrete is better suited to decreases the deflections.

In seismic areas, it becomes advantageous to use CLT panels instead of concrete. This leads to a reduction in the floor's weight, eliminating the need for secondary beams if CLT is preferred. Consequently, the dimensions of the columns and bracing would also be smaller. In this building example (without using dampers), the base shear using concrete floor is 96 MN, whereas it is 64 MN using CLT, indicating a possible reduction of seismic demands of 20 %. Therefore, by utilizing CLT for floors in this building example, we can save a total of 54.4 tons of steel, meaning around 18 % steel on the columns.

Again for this building example, a first seismic analysis was performed using the Lateral Force Method on the structure to get a first appreciation of the forces involved. The ultimate limit states forces obtained per storeys are given in Table 6.

Table 6. ULS Force values using the Lateral Force Method in the steel-CLT building.

level	∑ h (m)	G (kN)	Q (kN)	Mtot (kg)	hixmi	Fi X (kN)	Fi Y (kN)
1	4	8152	9450	1,41E+06	5,64E+06	1271	1271
2	8	8160	9450	1,41E+06	1,13E+07	2544	2544
3	12	8128	9450	1,41E+06	1,69E+07	3807	3807
4	16	8132	9450	1,41E+06	2,25E+07	5077	5077
5	20	8119	9450	1,41E+06	2,81E+07	6340	6340
6	24	8119	9450	1,41E+06	3,38E+07	7608	7608
7	28	7926	9450	1,39E+06	3,88E+07	8752	8752
8	32	7914	9450	1,39E+06	4,43E+07	9994	9994
9	36	7831	9450	1,38E+06	4,96E+07	11174	11174
10	40	6866	1512	7,93E+05	3,17E+07	7148	7148
	∑ m	79349	86562	1,34E+07	2,83E+08	63715	63715

The resulting base shear using the Lateral Force Method was determined to be 49,000 kN.

The subsequent analysis was performed using a non-linear pushover analysis approach. For this approach, the SFRS incorporated the Tectonus resilient damper in braces and at the base of the rocking braced walls. The structure was tuned so that it would be self-centering and the load-deformation for the building in the y-direction is shown in Figure 4.

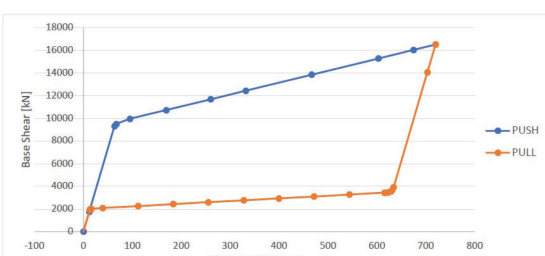

Figure 4. Hysteresys damping of the structure in the y direction using a non-linear push-over analysis, for the steel-CLT building..

The next analysis was a NLTHA using the earthquake records shown in Table 7.

Table 7. Earthquake records selected for the NLTHA for the steel-CLT building design.

Country	Region	Date	Mag.	PGA [m/s^2]	Link
Italy	Friuli	1976	6.5	0,887	https://esm-db.eu/#/waveform/IT/CDR/00/IT-1976-0002/HN
Italy	Campania	1980	6.5	0,457	https://esm-db.eu/#/waveform/IT/BVN/00/IT-1980-0012/HN
Italy	Lazio	1984	5.7	0,482	https://esm-db.eu/#/waveform/IT/TTP/00/IT-1984-0005/HN
Taiwan	Taiwan	1999	7.3	0,774	https://esm-db.eu/#/waveform/A/B065/00/INT-UT19990920_174715/HN
Italy	Sicily	2006	6.0	0,064	https://esm-db.eu/#/waveform/IT/LMZ/00/IT-2006-0272/HN
Greece	Peloponnese	2015	6.0	0,339	https://esm-db.eu/#/waveform/HI/MSL1//EMSC-20151117_0000025/HN
Italy	Lazio	2016	6.1	1,288	https://esm-db.eu/#/waveform/IT/CLF/00/EMSC-20160824_0000006/HG

The NLTHA analysis results confirmed the efficiency of the steel braces combined with the Tectonus resilient dampers but it was observed that the rocking steel frames were experiencing significant higher modes effects and needed to be modified in order to be structurally sound.

Ultimately, it was realised that very high rocking steel braced frames did not respond well and needed additional dampers along their height. It is thus better to address damping issues by using braces with dampers than to use a stiff brace frame and only provide damping at the rocking base. Nevertheless, using a steel frame with CLT panels as floor in combination with resilient dampers in braces can result in decreases in earthquake demands by up to 4 (factor q from EC 8).

One of the objective of looking at the steel frame with CLT floors combined with the Tectonus resilient dampers was to assess the reduction in seismic forces and as a consequence, the reduction in quantity of steel and concrete in the foundations.

The reduction in horizontal forces leads directly to a reduction in the size of the elements contributing to the stability of the building as might be expected. A reduction in cross-sections leads to a reduction in the mass and therefore the forces in the elements. It is therefore interesting to use resilient dampers as they allow material savings to be made. If we illustrate this with figures, we can see that there is a reduction in seismic demand of 32 % in the transverse direction (X) and 58 % in the longitudinal direction (Y). This demonstrates the effectiveness of the dampers and their impact on the design of the structure. This results in a reduction of the size and therefore the mass of the sections by an average of 51 %. This saves on the amount of steel needed for construction. In our case, with our design choices, we can reduce the weight by 155 tons which represents a reduction by a factor of 2.

The most significant savings are not in the visible part of the structure, but rather in the reduction of the foundations. The sub-structure part of the project will be significantly reduced because forces have a major influence on the design of the foundations. Installing dampers on our structures in seismic zone resulted in savings of approximately 55 % of concrete and 80 % of steel for the foundation only. In total, we can therefore reduce the amount of concrete by 961 m^3 and steel by 106 tons needed to build a 10 storey office building by using a CLT floor and dampers in the SFRS.

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6 – CONCLUSION

The design of 2 multi-story buildings located in Europe is carried within the contect of EC 8. Both solutions, an all-timber building and a hybrid steel-timber building are designed using low-damage seismic technology.

The study provides solutions for some part which is not well described in the Eurocode 8 such as the use of a damper in a structure. Furthermore, it is show that a more precise evaluation of the behaviour factor *q* could be done thanks to this study. It will allow the possibilities of taking a value greater than 3, which is the actual limit with the current research.

Finally, it is shown that an all-timber multi-story building solution is possible in an earthquake-prone zone and steel and concrete does not necessarily need to be used to resist lateral loads.

7 – REFERENCES

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