Effect of adding a CLT storey on the seismic vulnerability of an existing reinforced concrete 10 storeys building

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SUMMARY This article presents results found when performing both a lateral forces analysis and a spectral modal analysis on a 10 storeys reinforced concrete building situated in a seismic zone that was upgraded by adding a light storey made of Cross Laminated Timber (CLT). The objective of the study is to quantify the effect of such upgrade on the seismic vulnerability of the structure. To achieve that, the fundamental frequencies and periods of the existing and modified building were compared in addition to the distribution of forces in the different floors, the shear, normal force and moment at the base of the structure. Furthermore, lateral displacements of the different floors were quantified in order to assess the impact that a light floor addition could have on earthquake induced pounding between adjacent buildings.

Key words seismic vulnerability, adding floors, multimaterials

I. INTRODUCTION

High rise buildings were developed as an attempt from engineers to create more space in highly dense cities where there is a lack of space. To overcome this lack of urban space, more and more engineers and architects are intending to add floors to existing buildings. Such solution can be seen as convenient and appears to be less costly than demolishing and rebuilding entire buildings. It also presents the advantage of preserving historic buildings as part of rehabilitation programs. Such rehabilitation involves performing a preliminary in-depth diagnosis in order to determine the material characteristics of the old buildings to be upgraded using either destructive or nondestructive methods [(Gentile et al); (Azenha et al., 2010); (Ozcelik et al., 2022); (Ranaweera et al., 2021)] ., 2007. Existing buildings could not be initially designed to receive additional floors and current design codes do not give detailed guidelines on how to design added floors in a way not to alter greatly the mechanical behavior of the existing building. Another question arises regarding the impact of such upgrade on the seismic behavior of the structure. Regarding that, few requirements are given by Eurocode 8 (Standard, B. (2005)) and AFPS guidelines (Balgiu et al., 2014). Among given recommendations, we can find the idea that the added floor should have a mass less than 10 % of the mass of the top floor to not increase the seismic vulnerability of the structure which is pretty restrictive when the addition of a floor is considered. Another recommendation proposes a criterion which is more suited to elevation (Balgiu et al., 2014) . It consists in stating that the increase in seismic vulnerability will be considered acceptable if the difference before and after the construction works remains below 10 % for the fundamental period, the solicitations at the base and the displacements at each floor. It should also be pointed out that no precise requirements are given in the design codes regarding the effect of using added floors made of different materials than the existing structure.

For buildings showing stiffness changes with height, the definition of a global behavior coefficient is for instance proposed (Corvez et al., 2016). However, the value that needs to be assigned in the case of multistorey buildings made of different materials is not clearly defined. It is also still unclear how the different parts of the building made of different materials interact with each other. In fact, such interaction may reduce the effective ductility of the structure and prevent the theoretical behavior coefficient from accurately accounting for the real behavior of the structure. To overcome this lack of knowledge, many research projects are undergoing to try to understand the effect of adding floors of different materials on the mechanical behavior and seismic vulnerability of structures. In some pioneer research projects found in the literature, researchers have tried to discuss the possibility for the addition of floors to decrease the seismic vulnerability of structures if the choice of material used in the added floor is made wisely [(Jančar et al., 2016), (Zafirov et al., 2021)].

The present article presents preliminary results found when studying the effect of adding a CLT storey to an existing 10 storeys reinforced concrete building. First, the geometry and material properties of the existing building are presented. Then, a comparison is made between results obtained when performing a lateral forces analysis on the existing building and on the upgraded one. The two building configurations were also studied using a modal spectral analysis with specific assumptions on material properties.

II. CASE OF STUDY

A. Project presentation

The study concerns a residential building located near Chambéry (Savoie, France). This construction was built in 1975. The frame (walls and floors) is made of reinforced concrete. The building has 10 storeys and a ground floor. Each storey has a clear height of 2,60 m and the floor thickness is equal to 20 cm. The total height is equal to 31,46 m when the acroteria are included. Each floor has the same repartition of walls and openings and the floor surface is equal to 370 m². The mass of each storey is considered to be applied at the middle height of each floor. For each intermediate floor, a surface mass of 1200 kg/m² was considered even if a lesser value of 1000 kg/m² was recommended (Balgiu et al., 2014). This choice was justified by a high density of walls on each level. On the other hand, a surface mass of 1000 kg/m² was assessed for the roof. Each floor has an equivalent mass of 444 tons, except for the roof that has a mass of 370 tons. The arrangement of walls is roughly symmetric, so that torsional effects can be neglected. As a consequence, the flexural behaviour can be considered independent in the two X and Y main directions. The flexural stiffness is almost twice in the Y direction, compared to the X direction (Table 1). Both directions were considered in the study in order to assess the possible effect of stiffness variation.

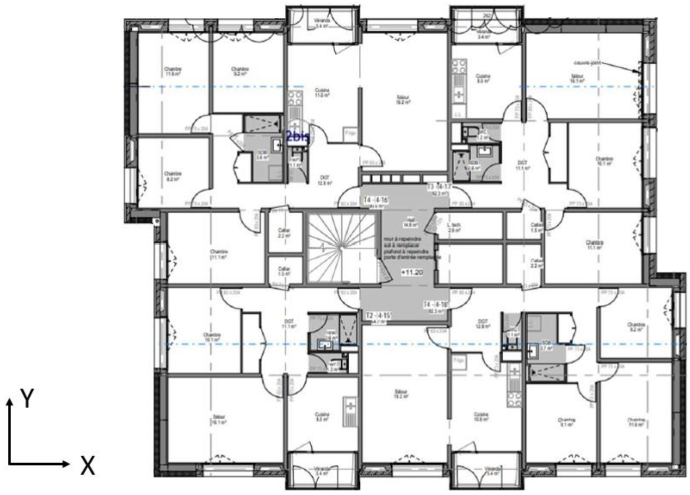

FIGURE 1. Floor plan of the existing building

The storey added on top of the existing building is made of cross laminated wood. For the sake of simplicity, the same thickness and arrangement of walls found in the existing building were applied to the added floor (Meynadier et al., 2023). Therefore, the flexural inertia of the added storey is considered to be identical to the one of the existing storeys (Table 1). The surface mass of the added storey is set equal to 300 kg/m², as proposed in (Balgiu et al., 2014) . It is assumed that the mass of the former roof is not modified by the presence of the added storey. As a consequence, the mass of the new roof is equal to 111 tons. The corresponding mass – spring models for both cases are presented in Figure 2.

TABLE 1. Flexural inertia in X and Y directions for each storey

Flexural inertia (m^4)	X direction	Y direction
Existing storey	11,36	21,47
Added storey	11,36	21,47

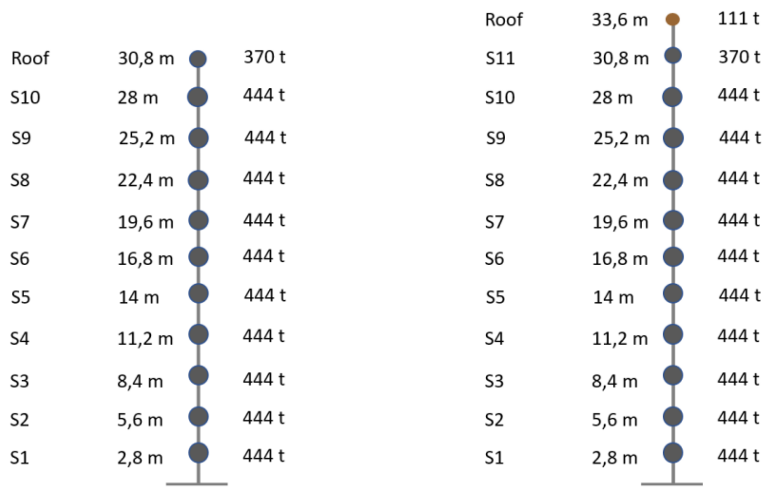

FIGURE 2. Spring – mass model for the existing building (left) and for the modified building (right)

B. Application of the equivalent lateral forces method

The building is regular in elevation. Thus, the equivalent lateral force method can be applied. Since the height of both the existing and modified buildings is higher than 28 m, the two structures belong to the importance category of high risk, which is denoted as category III (Standard, B. (2005)). The project is located in zone 4 of the seismic zoning map. The zoning and importance category of the building imply the obligation of performing a complete seismic analysis following CT AFPS 35 (Balgiu et al., 2014) and Eurocode 8 (Standard, B. (2005)) requirements. For simplicity, a behaviour factor q equal to 1,5 was considered, which corresponds to the category of moderate ductility.

The ground soil is made of non-cohesive soil, which corresponds to category D. Following the Eurocode 8 approach for an existing building located in seismic zone IV, with an importance class of III, a horizontal acceleration of 1,15 m/s² was considered (Standard, B. (2005)). Since the modified building is made of two materials, its fundamental period T_1 was computed using the Rayleigh's method. This method consists in applying an artificial horizontal gravity of 1g to each floor and to measure the horizontal displacement d of the roof floor. Then, the fundamental period is computed as :

$$T_1 = 2\sqrt{d} \tag{1}$$

TABLE 2 . horizontal displacement of the roof floor for the existing and modified building

	X direction		Y direction	
	Existing	Modified	Existing	Modified
d (m)	0,538	0,643	0,285	0,341
T_1 (s)	1,467	1,604	1,068	1,168

The fundamental period T_1 of the modified structure increased in both directions in comparison to that of the initial building. Fundamental periods for the existing and modified project in both X and

Y directions are denoted as $T_{1\,exi}^{X}$, $T_{1\,exi}^{Y}$, $T_{1\,mod}^{X}$ and $T_{1\,mod}^{Y}$, respectively. These four period.s are located in the descending part of the acceleration spectrum (Figure 3). As a consequence, the acceleration to consider decreases when the configuration switches between existing to modified building. Table 3 presents solicitation values computed from the equivalent lateral forces method at the basis of both building configurations. The moderate mass added resulted in a low rise of the normal force components in both directions (Figure 4). Moreover, the corresponding increase of 2,3% is widely lower than the 10% tolerated by (Balgiu et al., 2014). On the other hand, a reduction of the shear and moment values was noticed, with a ratio of – 6,4% and – 4,0% respectively. These values are still in the range of ± 10% accorded by (Balgiu et al., 2014). But they also mean that the seismic vulnerability of the building is reduced. The lateral force is reduced for each storey in the modified building configuration which globally compensates the additional lateral force generated by the wooden storey.

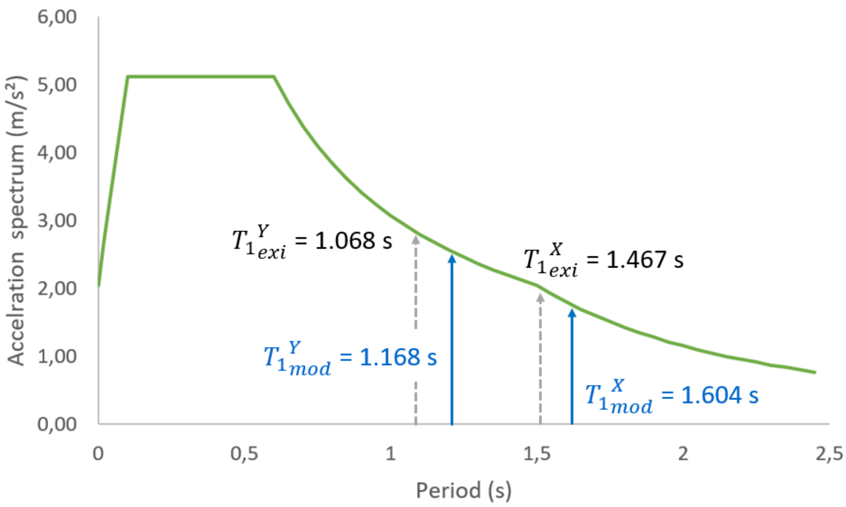

FIGURE 3. Acceleration spectrum and fundamental periods of the existing and modified building

TABLE 3. Solicitation at the basis for the existing and modified building

	X direction			Y direction		
	Existing	Modified	Difference (%)	Existing	Modified	Difference (%)
Normal Force N (kN)	48100	49210	+ 2,3	48100	49210	+ 2,3
Shear force V (kN)	5036	4712	- 6,4	6918	6471	- 6,4
Moment (kN.m)	106768	102512	- 4,0	146656	140779	- 4,0

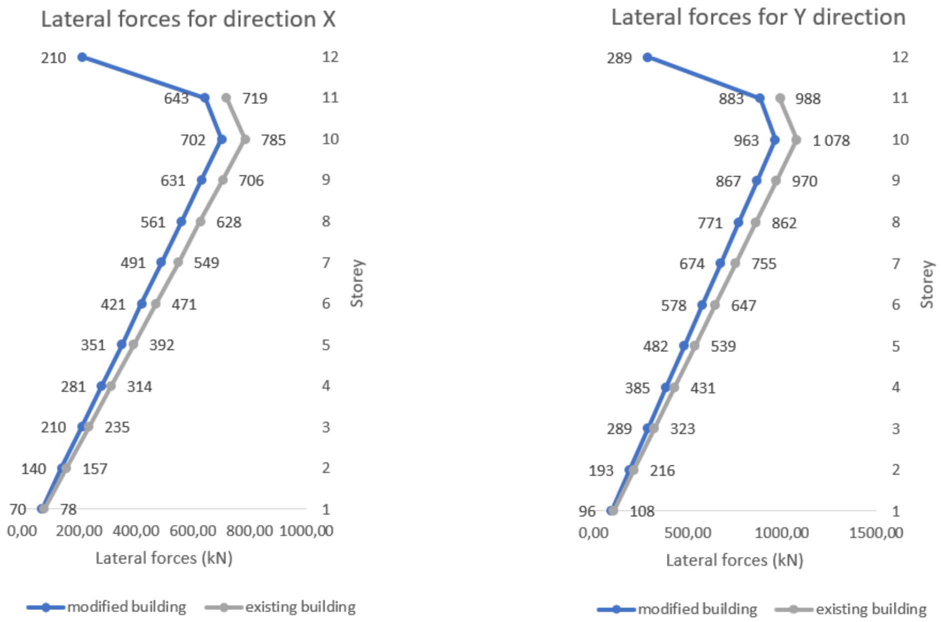

FIGURE 4. Lateral forces at each storey for the existing building and the modified building

Three aspects may explain this positive result: the added storey increases the height of the building as well as the fundamental period. As a consequence, the spectral acceleration decreases, which means that the shear force imposed to the basis of the building decreases also. It should be pointed out that the type of material used to construct the added storey has a direct impact on observed results. In fact, variations of both mass and Young modulus of the added storey plays a role on the vulnerability reduction. Further investigations are required to define which configurations can have a positive or moderate negative effect on the seismic vulnerability of the new structure due to the addition of floors (due to an adequate combination between the added part with the existing building).

C. Application of the modal response spectrum analysis

As in the previous analysis performed, the building was modelled using a mass and spring simplified model in order to perform a modal response spectrum analysis. For this type of studies, the Young modulus of concrete is usually reduced, in order to take cracks into consideration (Lestuzzi, P., & Smith, I. F. (2017)). However, a value of 30 GPa was considered here, in order to facilitate the comparison between the current and the previous method. The modal response spectrum analysis was carried out following the methodology given in Lestuzzi (Lestuzzi, 2017). Tables 4 and 5 give the natural frequencies of the initial and the modified building in both X and Y directions for the 3 first modes that are the most predominant. As shown using the lateral force method, there is a decrease of the natural frequencies due to the addition of a storey. The effective modal mass of each mode is given in Tables 4 and 5. It can be seen that the three first frequencies are sufficient to mobilize more than 90% of the total mass.

TABLE 4. **Frequencies and corresponding modal masses for the existing building**

	X direction				Y direction			
Mode	Frequency (Hz)	Modal mass (t)	Modal mass (%)	Cumulative modal mass (%)	Frequency (Hz)	Modal mass (t)	Modal mass (%)	Cumulative modal mass (%)
1	0,81	3082	64,1	64,3	1,12	3082	64,1	64,3
2	5,09	948	19,7	83,8	7,00	948	19,7	83,8
3	14,23	326	6,8	94,0	19,57	326	6,8	94,0

TABLE 5. **Frequencies and corresponding modal masses for the modified building**

	X direction				Y direction			
Mode	Frequency (Hz)	Modal mass (t)	Modal mass (%)	Cumulative modal mass (%)	Frequency (Hz)	Modal mass (t)	Modal mass (%)	Cumulative modal mass (%)
1	0,77	3136	63,7	63,7	1,07	3136	63,7	63,7
2	4,78	970	19,7	83,4	6,57	970	19,7	83,4
3	13,2	333	6,8	90,2	18,14	333	6,8	90,2

Table 6 presents the solicitation values at the basis of both the existing and modified building. An increase of +2,3% is observed for the normal component, which is consistent with the mass added by the new storey. The shear component and the moment exhibit an increase from 6,8 % to almost 10%. This result is quite different from the one obtained with the lateral forces method, as an increase of vulnerability is noticed here. The use of a standard Young modulus for concrete may explain partially this increase, but cannot be considered as the main cause. Figures 5 presents the values of the horizontal forces generated at each storey for the first mode. In both directions, the horizontal forces are quite similar for each storey. Thus, the forces mitigation observed with the lateral method does not apply here, and the shear force and moment provided by the added storey cannot be compensated.

TABLE 6. **Solicitation at the basis for the existing and modified building**

	X direction			Y direction		
	Existing	Modified	Difference (%)	Existing	Modified	Difference (%)
Normal Force N (kN)	48100	49210	+ 2,3	48100	49210	+ 2,3
Shear force V (kN)	11637	12434	+ 6,8	8464	9044	+ 6,8
Moment (kN.m)	268529	294764	+ 9.7	195328	214412	+ 9,7

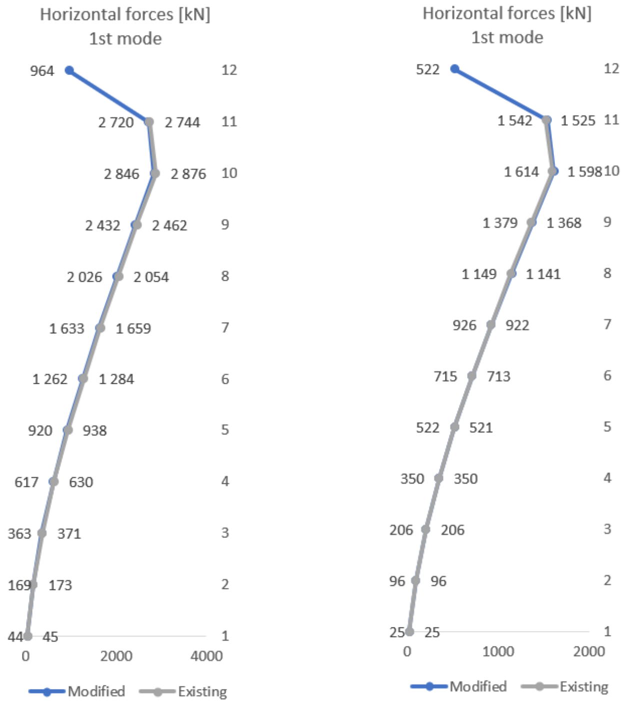

FIGURE 5. Horizontal forces for the first frequency in directions X (left) and Y (right)

This increase of solicitations may be explained by the systematic higher values of the fundamental periods, obtained using the modal analysis compared to the one computed with the lateral forces method. In the present study such periods are still located in the descending part of the acceleration spectrum. As a consequence, the slope of the curve is smoother. Moreover, the variations between the values of ${T_1}_{exi}^{x,y}$ and ${T_1}_{mod}^{x,y}$ are significantly reduced, compared to that of the previous method. This variation of fundamental period was already noticed previously (Davidovici, 2019) and shows that results provided by one method should be considered carefully for the assessment of the non-aggravation of the seismic vulnerability.

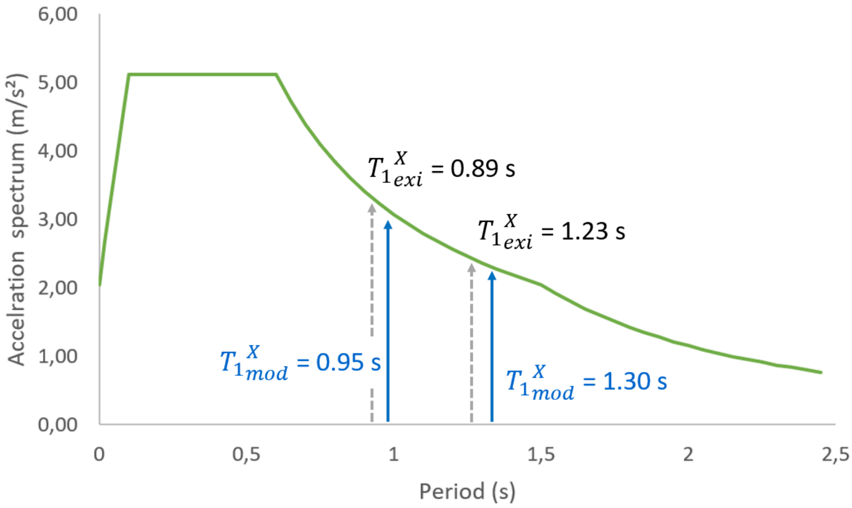

FIGURE 6. **Acceleration spectrum and fundamental periods for the existing and the modified building**

Finally, the modal shapes were drawn (Figure 7) Each of the two first mode shapes in direction X exhibits an increase of the roof displacement, that can be attributed to the height gain as well as the flexibility of the last storey. This figure illustrates also the issue that can be caused by this flexibility. This type of project cannot be considered in case of adjacent buildings, because of the risk of collisions induced by an increase of horizontal displacements due to the addition of the considered floor.

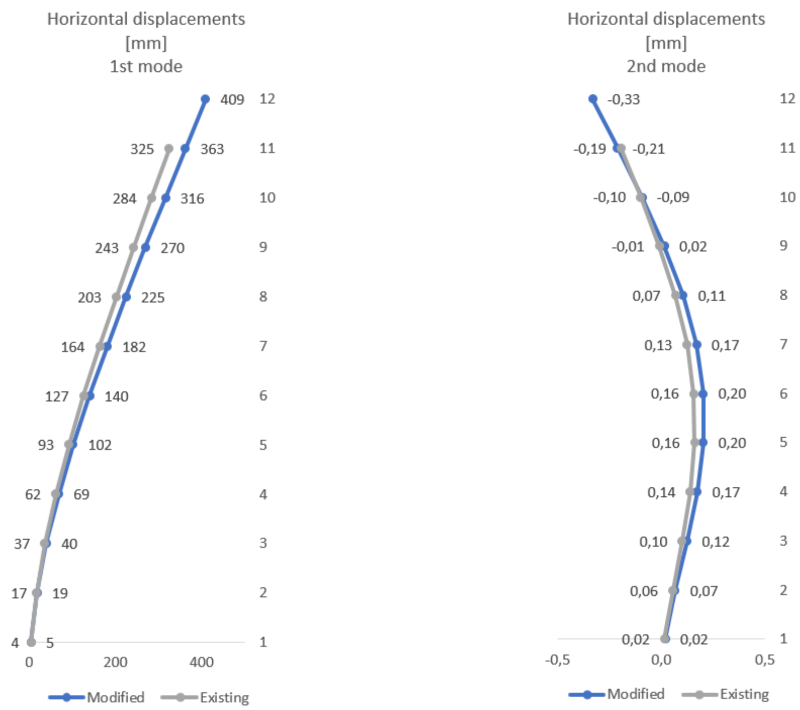

FIGURE 7. **Horizontal displacement for the three first modes in direction X**

III. CONCLUSION AND PERSPECTIVES

This case of study allowed showing the effect of adding a light floor made of CLT to an existing 10 storeys concrete building on the seismic vulnerability of the structure located in a zone of high seismic risk in France (zone 4). Results obtained using the lateral force method (the fundamental period being calculated using the Rayleigh method) are quite positive as they show that such addition not only do not increase the seismic vulnerability of the new structure but also decreases the seismic forces applied to the structure (a decrease of 6.4 % of the base shear as well as a decrease of 4 % of the moment at the basis of the structure were observed). Such decrease can be explained by the increase of the fundamental period of the structure. In fact, since the structure has a period located in the decreasing part of the acceleration spectrum, an increase of fundamental period induces a decrease of the spectral acceleration imposed to the structure. A spectral modal analysis was then performed on the structure using a simplified mass/spring approach. This time, results were less thrilling. Indeed, since the increase of fundamental period due to the added floor was not significant, an increase of base shear of 6.8 % was observed between the initial and modified building in addition to an increase of 9.7 % of the moment at the basis. The addition of the timber floor also induced an important increase in the lateral displacements of the different floors of the modified structure. Such increase can be really problematic in the case of adjacent buildings since it can induce pounding. Results observed using the modal spectral analysis should be reevaluated in future studies by considering for instance a more important behavior factor q rather than the 1.5 used to account for the ductility of timber.

This study is a starting point as it showed that adding floors to existing buildings even in seismic zones is possible. Such addition, if done using adequate materials do not necessarily increase much the seismic vulnerability of the structure. Reflections are in progress regarding the possibility for such addition to allow a decrease, or, at least a moderate increase in the seismic vulnerability of the structure for added floors of specific height and made of specific materials.

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