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SEISMIC FRAGILITY ANALYSIS TO ASSESS THE IMPACT OF TIMBER VERTICAL ADDITIONS ON EXISTING RC BUILDINGS: A CASE STUDY

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Abstract

Construction of vertical expansions on top of existing structures can be considered as an economical and practical solution to contain urban sprawl. The use of timber, due to its lightness, suitability for modularity and prefabrication, and due to environmental benefits, emerges as an interesting option for the realisation of vertical additions in existing buildings. Unfortunately, in seismic-prone areas, the construction of vertical expansions clashes with seismic safety. Current standards require that the safety level of the existing structure after the expansion be that prescribed for new buildings. This requirement represents a major obstacle to vertical expansion because vintage buildings rarely comply with the provisions of the seismic standards even without any addition, making costly retrofit intervention necessary. In this paper, a case study is selected and analysed to try and understand how the vertical timber addition of existing buildings can impact their seismic behaviour. The selected case study is a 1980s four-story RC frame building with masonry infill walls. Following current design practices, a one-storey timber vertical expansion was designed by adopting a cross-laminated timber shear-wall system. The seismic response of the building with and without the timber expansion was then simulated via finite element modelling. The outcomes of the numerical simulations were then used to perform a seismic fragility analysis and assess the effect of vertical expansion on the seismic performance of the case study building. The results of the analysis showed how, in some cases, the vertical timber addition not only does not worsen the safety level of the building but can actually improve it. This outcome opens new paths for future research to further investigate the effect of vertical expansions and maximize their beneficial effect on the seismic response of existing buildings.

Keywords: Vertical Addition, Cross-laminated Timber, Fragility Analysis, Existing RC Buildings, Infilled RC Frames.

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1 INTRODUCTION

Urban sprawl, that is the rapid expansion of the geographic extent of cities and towns, is a hoary problem that threatens natural and rural environments and accelerates climate change due to an increase in greenhouse emissions. The gravity of the impact of unchecked urban sprawl has prompted the European Commission to take action and propose in the EU Environment Action Programme a specific plan that aims to achieve 'no net land take" by 2050 [1]. The consequence of this policy is that in the near future new housing volume can only be obtained by intervening on the existing building stock.

Within this scenario, there are many reasons why vertical building expansion, with one or more storeys built ex-novo on top of an existing structure, could be a valuable strategy to increase the housing volume with no land take. First, vertical expansion is efficient and economical: there is no need to allocate budget to purchase new land and new housing volume can be created where no land is available but where the extra-value of the expansion would be maximum (i.e., most prestigious neighbourhood in the city centres). In addition, the cost for services and supplies (e.g., power, water, gas) is lower because direct access is already available onsite. In case of buildings that have ageing roof structures in need of repair, adding one or more storeys can solve the roof problem while increasing the living space, and hence the building value with limited extra cost. Another strong point of vertical expansion is the speed of construction thanks to extensive adoption of prefabrication and modularity [2].

In earthquake-prone countries, seismic vulnerability of existing building stock is a critical issue that often discourages from intervening on existing structures and, as a consequence, it contributes to soil consumption. Historic, centuries old masonry buildings, as well as masonry infilled reinforced concrete (RC) frames built in the central decades of the 20th Century, constitute the largest part of the building stock of many cities and towns in Europe [3]. Such structures were not designed to resist lateral loading and therefore have been shown to be highly vulnerable to earthquakes [4][4]-[7]. Current standards such as NTC and ASCE 7 [8], [9], require for existing buildings, when significant modifications are made to their structure, as the case of vertical expansion, the same safety level prescribed for new buildings. This requirement represents a formidable obstacle to vertical expansion because existing structures may be far from complying with the provisions from seismic standards even without the inertial extra-load from the vertical addiction. This means that expensive retrofit interventions need to be designed in order for the building to be able to accommodate additional storeys. Adopting light building solutions such as those relying on timber walls or steel frames, that limit the extra weight due to the vertical expansion, is certainly positive, but it might not be sufficient to guarantee the viability of the intervention.

Sustainability is another key aspect to be considered [10] when selecting the optimal construction technology for the building expansion. In this regard, timber-based systems appear as the most promising option. "Environmental benefits" from using timber in construction have been proven by many studies that have provided numerous examples of life cycle assessment (LCA) evidencing advantages in terms of carbon sequestration, greenhouse emission and energy saving [11]-[14]. In addition, the large availability of wood on the entire EU territory (43% of EU land is covered by forests [15]) can be exploited to develop short and smart supply chains and foster local circular economies [16], [17].

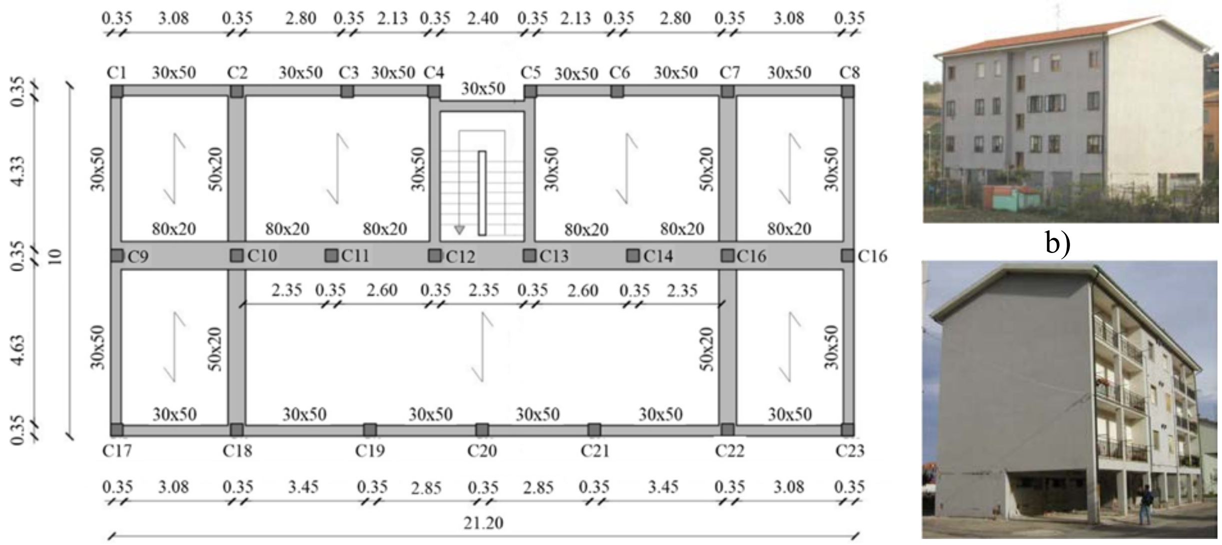
The scope of the present paper is to investigate the influence of vertical expansion on the seismic performance of existing buildings. Previous research has mainly focused on RC frames with vertical steel expansions. The findings indicated the ability of the addition to prolong the natural period of the structure usually resulting in lower seismic forces at the ground floor. However, the so-called whip effect, due to the lower stiffness of the steel superstructure, may cause an increase in interstorey drift at higher floors, such as to exceed deformation acceptance criteria and thus making the expansion unfeasible [18]. Recently, some authors [18]-[20] focused on timber vertical expansion using timber light frame as well as cross-laminated (CLT) shear wall systems. Also in this case, via modal analysis, a reduction in seismic force was found due to a shift in the natural period of the expanded building. In addition, this type of superstructure can be easily adjusted to fit a desired stiffness by changing the composition of the elements and using different fasteners with different arrangements [18], thus having a greater control over the period shift.

To analyse the effect of vertical timber expansion on the seismic safety of existing building, a case study was selected representing a typical example from the Italian mid-20th century residential building stock.

2 CASE STUDY BUILDING

The case study building selected for the present research is the one analysed by Manfredi et al. in [21]. It is a four-storey RC frame with masonry infill walls that was built in 1984 in the Molise region (South of Italy). It represents a typical multi-storey residential building for the period, with rectangular plan (circa 2:1 aspect ratio) and central staircase (Figure 1a). The openings are mainly distributed along the lengthwise direction. There is also a wide unobstructed space at the ground floor, due to the presence of the garages and the front porch (Figure 1b and Figure 1c).

The structure consists of parallel two-dimensional RC frames running in the longitudinal direction and having beams and columns with rectangular and square cross-sections, respectively. The columns are 35 cm wide on the ground floor and 30 cm on the upper storeys. The internal beams, and the external ones located in correspondence with the balconies, are wide-shallow beams with 80x20 cm cross-section geometry. The remaining external beams are characterized by a 30x50 cm cross-section. Transversal 50x20 cm beams are also present, connecting the longitudinal framing. A one-way hollow clay block slab (20 cm thick) constitutes the flooring system. The external infills are made of cavity walls with a hollow clay block wythe (8 cm thick) facing inwards and a solid clay brick wythe (12 cm thick) facing outward.



a) b) c)

Figure 1: a) Plan of the ground floor of the case study building. b) Back view and c) front view

2.1 Timber vertical addition

From an architectural point of view, the objective of the vertical expansion is to substitute the unused roof space of the case study building with a completely new floor (Figure 2b) thus increasing the habitable space by more than 25%. The vertical structure of the timber addition is constituted by a CLT shear-wall system. The timber panels are connected to the concrete beams using angle brackets (TCF200) and hold down connectors (WHT620) whose geometrical properties are summarised in Figure 4. In the case of CLT walls not directly supported by concrete beams, a supporting steel joist was inserted to transfer the panel forces to the RC frame (dashed lines in Figure 2b). The plan distribution of the CLT panels is shown in Figure 2c together with the arrangement of the steel connectors designed according to [22], taking into account the seismic action. To evaluate the seismic loads H and T (see Figure 3) acting on the angle brackets and hold down connectors, respectively, the horizontal seismic forces were calculated through an equivalent static analysis where the response spectrum for the region, corresponding to 475 years return period, was used [9]. The total shear force acting on the fourth floor of the expanded building was distributed among the CLT walls proportionally to their length thus obtaining the shear force H. Then, according to the scheme reported in Figure 3, the tension force T was also evaluated through simple equilibrium considerations.

To complete the vertical expansion, a new wooden roof and extension of the stairs were also designed.

Thanks to the lightness of the construction system based on timber panels, the total weight of the building after the expansion resulted to be approximately the same as the original case study building (Figure 2a).

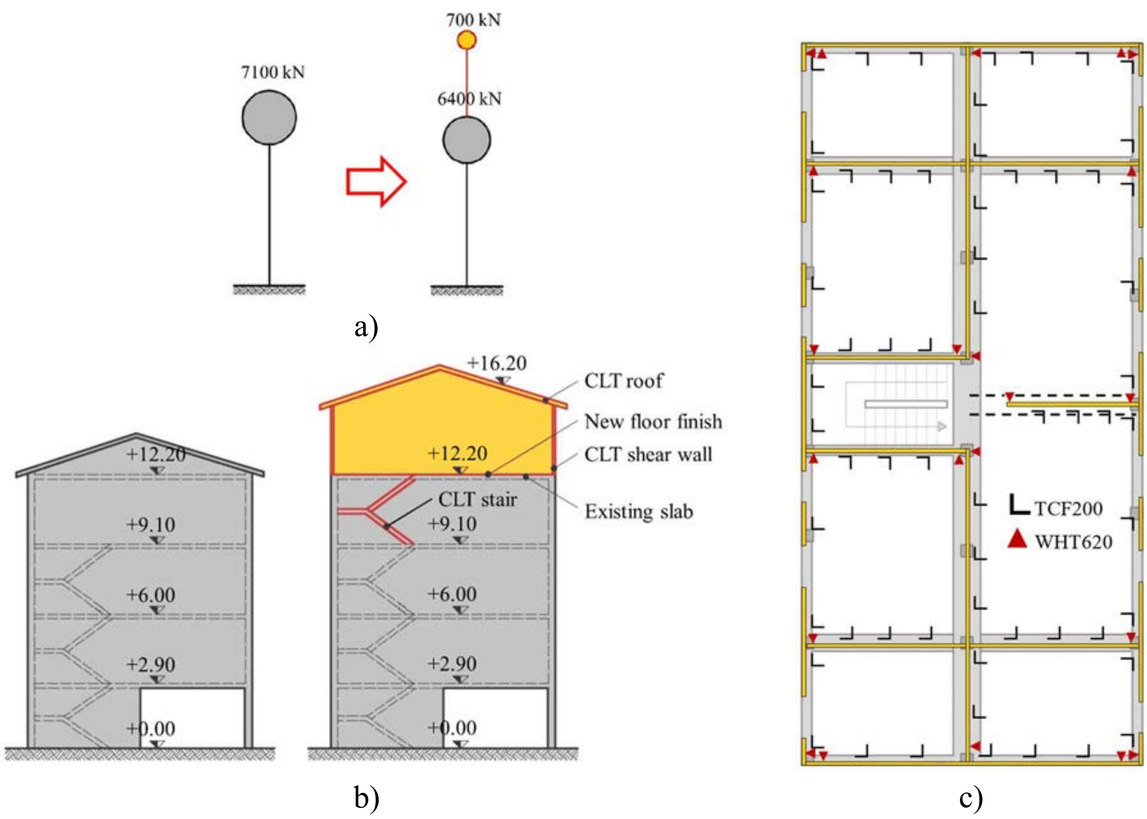


Figure 2: a) Total weight of the case study building before and after the timber vertical addition. b) Vertical expansion of the case study building. c) Plan of the CLT shear wall and of the steel connectors of the timber vertical expansion.

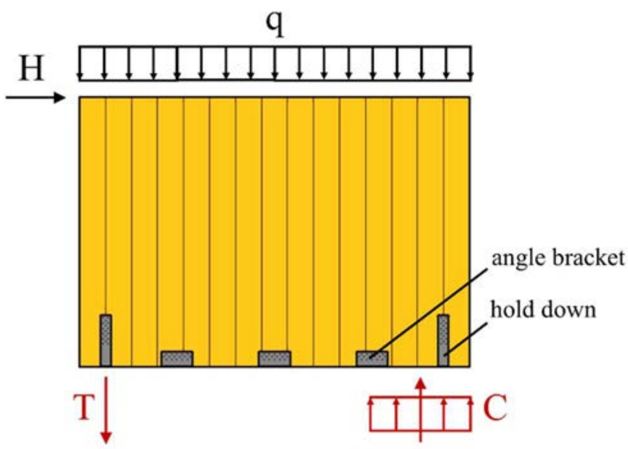


Figure 3: Scheme for the calculation of the seismic load of the shear wall connection system: q is the distributed load acting on the wall; H is the horizontal force acting on the panel equal to the shear load absorbed by the angle brackets; T is the tension force absorbed by the hold-down connector, which, together with the compression force C, generates the stabilising moment that opposes the one caused by the horizontal force H.

2.2 Finite element modelling

The structure of the building was modelled using the SAP2000 finite element software [23]. RC members are represented by frame elements and reinforcement detailing was defined in accordance with [21]. To account for the nonlinearities of the RC members a concentrated plasticity approach was used, and plastic hinges automatically defined by the software according to [24] were assigned to the frame elements.

The slab floor was not explicitly modelled by means of bi-dimensional elements, but a rigid diaphragm constraint was assigned to the nodes of each floor to enforce the same lateral displacements to any point laying on the floor area. A different approach was used for the sloped slabs of the existing pitched roof that were modelled through linear shell elements considering the out-of-plane stiffness.

The masonry infill walls were added to the model through nonlinear link elements by adopting the equivalent concentric strut macromodel proposed by Liberatore et al. [25]; hysteresis was described by using a pivot model [26] as suggested by [27].

The main material properties used in the model are reported in Table 1 and were assumed based on the information collected by Manfredi et al. [21] relying on test certificates from the construction period (compression tests on concrete cores and tension tests on steel rods) and the results of an in-situ testing campaign.

Table 1: Material properties assigned to the structural elements within the numerical model.

Concrete		Steel		Masonry infill wall	
Compressive strength (MPa):	16.7	Yield strength (MPa):	440	Compressive strength (MPa):	6.5
Modulus of elasticity (GPa):	25.7	Modulus of elasticity (GPa):	210	Shear strength (MPa):	0.13
				Diagonal cracking strength (MPa):	0.28
				Modulus of elasticity (GPa):	4.5

Concerning the timber expansion, the CLT shear wall system was modelled considering an elastic behaviour for the timber panels. Mechanical nonlinearities were only accounted for in the steel connectors, which were modelled through multilinear plastic link elements. The accuracy of this approach relies on the hypothesis that plastic deformation only occurs at the level of the connection system. The CLT walls were thus modelled through orthotropic linear shell elements whose elastic properties were derived from [28][29]. The multilinear backbone curves reported in Figure 4 (solid red line), representing the mechanical behaviour of the steel connectors (steel bracket TCF200 and WHT620 hold-down connector), were derived from the results of the experimental campaign conducted by Piazza and Sartori [30]. A pivot model suitably calibrated on the results of the aforementioned experimental campaign was adopted to describe the hysteretic behaviour of the steel connectors.

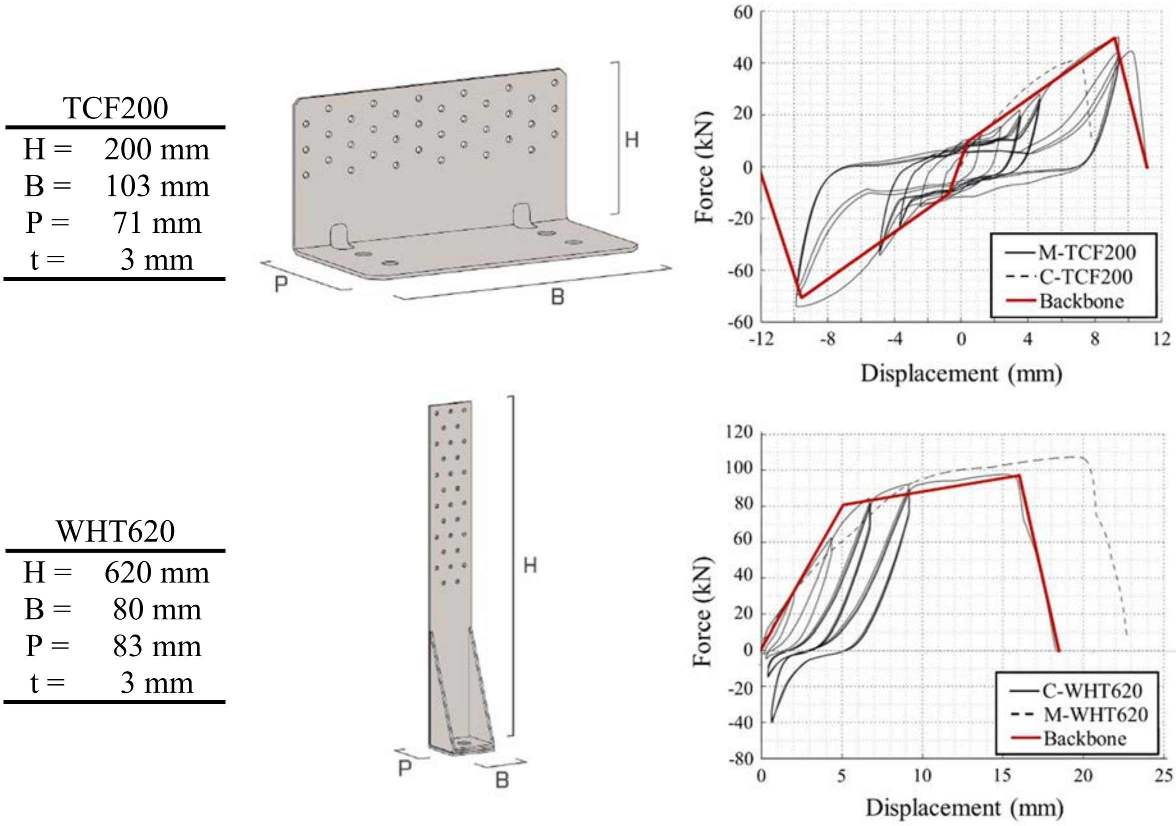


Figure 4: Geometrical and mechanical properties of the steel connectors.

3 COMPARATIVE FRAGILITY ANALYSIS

Fragility analysis is a valuable tool to assess the seismic vulnerability of structures. It has a long tradition in the nuclear industry and, since the late 1990s, it has been used also for ordinary buildings, fostering the development of new seismic standards [31]. Over the years, thanks to the improving computation power, fragility analysis has become, among researchers, the go-to tool for studying the seismic behaviour of a multitude of different structures [32].

The primary outcome of a fragility analysis is a set of curves that describe the probability of exceeding a specified limit state (e.g., collapse or life safety) given the intensity measure (IM) of earthquake ground motions [33]. Limit states are usually defined by damage thresholds expressed by suitable values of a selected damage measure (DM).

Among the various methods described in the literature [31], the one that relies on linear regression in log-space and incremental dynamic analysis (IDA) [34] was chosen to derive the fragility curves of the case study building, in both “as built” (AB) and vertically expanded (VE) configuration. Firstly, a set of seven ground-motion records (see Table 2) was selected from the

PEER Ground Motion Database [35], considering the spectral shape of the region and different earthquake mechanisms. For simplicity only the median capacity of the log-normal distribution was estimated by regression. The estimation of dispersion (β), which would have required a greater sample [31] was achieved by using tabulated values [36]. Peak ground acceleration (PGA) was adopted as IM and maximum interstory drift ratio was selected as DM. To define appropriate thresholds of the DM, reference was made to FEMA's Hazus program [36], and four damage levels were defined according to Table 3.

Table 2: Set of records selected from PEER to perform fragility analysis.

Earthquake name	Record number	Year	Mechanism	Magnitude
Christchurch	8119	2011	Reverse oblique	6.2
Coyote Lake	148	1979	Strike slip	5.74
Bam	4040	2003	Strike slip	6.6
Gazli	126	1976	Reverse	6.8
Managua	96	1972	Strike slip	5.2
San Fernando	77	1971	Reverse	6.61
Norcia	156	1979	Normal	5.9

Table 3: Damage thresholds defined within the FEMA's Hazus program and adopted to define limit state conditions in the present fragility analysis.

Damage level	Drift ratio threshold	β
Slight	0.0016	0.9
Moderate	0.0032	0.86
Extensive	0.008	0.9
Complete	0.0187	0.96

The results of the fragility analysis are summarised in

Figure 5. The regression curves (

Figure 5a) show that the VE building (black line) tends to exhibit lower drifts as the seismic intensity increase with respect to the AB configuration (red line). This behaviour becomes more and more evident as the PGA values exceed 0.2g corresponding to a damage threshold comparable to that defining the "extensive" damage level. This fact is reflected by the resulting fragility curves (

Figure 5b) of the VE configuration (dashed line) that show an appreciable reduction in the risk of exceedance respect to the AB configuration only when considering "extensive" and "complete" damage level. Specifically, the maximum reduction in the risk of exceedance between the AB and VE configurations moved from 1.9% and 4.3%, respectively for the "slight" and "moderate" damage level, to 8.7% and 13.5% for the "extensive" and "complete".

In the first place, the results indicate that the vertical timber addition did not worsen the seismic performance of the case study building, in addition, although it did not drastically improve it either, the seismic safety level of the RC frame building can still be enhanced through the vertical expansion.

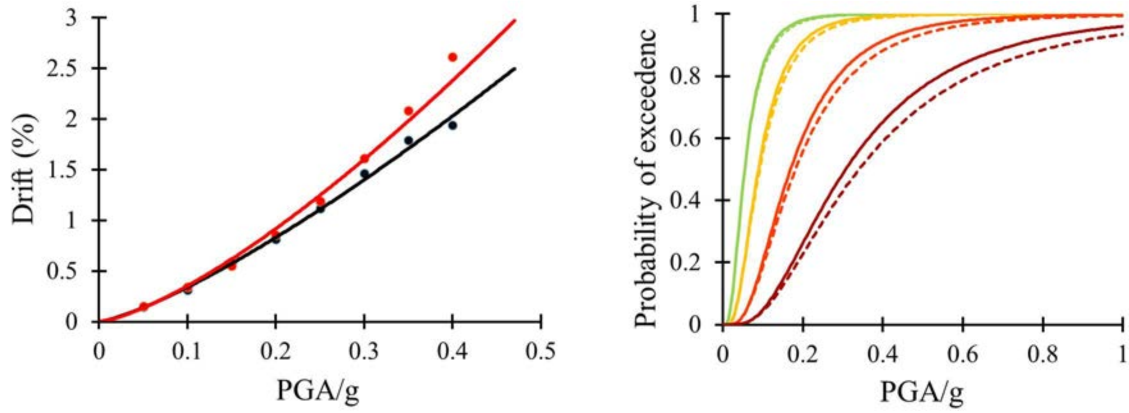


Figure 5: a) Regression curves (solid lines) that express the median DM as a function of IM for the AB (▬) and VE (▬) configurations; circle marks represent the median values used for the regression and obtained by the multi-IDA analysis. b) Fragility curves obtained for the AB (solid) and VE (dashed) configurations, and for the considered damage level: slight (▬) , moderate (▬), extensive (▬), complete (▬).

4 CONCLUSIONS

In this paper a RC frame case study building from the literature was subjected to a vertical timber addition with cross-laminated shear-wall structure. A comparative seismic fragility analysis was performed on the case study building before and after the expansion. The results provided a proof of concept of the following:

- the addition of vertical expansions on an existing RC frame building, when made of timber, does not necessarily produce a worsening of the seismic performance of the building;
- vertical timber additions can actually enhance the seismic safety of RC buildings;
- in this study, such a beneficial effect was more noticeable for higher seismic intensity and damage thresholds.

REFERENCES

[1] EEA, Urban Sprawl in Europe: The Ignored Challenge. Report No 10/2006. Office for Official Publications of the European Communities; Luxembourg, 2006.

[2] A. Jellen and A. Memari, Residential Vertical Expansion of Existing Commercial Buildings Using Modular Construction Methods. *2nd Residential Building Design & Construction Conference*, Penn State University Park, Pennsylvania, February 19-20, 2014.

[3] G. Tsionis, European building inventory framework. Report EUR 27603 EN, Publications Office of the European Union, Luxembourg, 2015.

[4] A. Penna, P. Morandi, M. Rota, C.F. Manzini, F. da Porto and G. Magenes, Performance of masonry buildings during the Emilia 2012 earthquake. *Bulletin of Earthquake Engineering*, **12(3)**, 2255-2273, 2013.

[5] J.M. Ingham, and C. Griffith, Performance of unreinforced masonry buildings during the 2010 Darfield (Christchurch, NZ) earthquake. *Australian Journal of Structural Engineering*, **11**, 207-224, 2016.

[6] K.M. Mosalam and S. Günay, Progressive Collapse Analysis of Reinforced Concrete Frames with Unreinforced Masonry Infill Walls Considering In-Plane/Out-of-Plane Interaction, *Earthquake Spectra*, **31(2)**, 921–943, 2015.

[7] F. Di Trapani and M. Malavisi, Seismic fragility assessment of infilled frames subject to mainshock/aftershock sequences using a double incremental dynamic analysis approach, *Bulletin of Earthquake Engineering*, **17(1)**, 211–235, 2019.

[8] ASCE (American Society of Civil Engineers), ASCE/SEI 7-16: Minimum Design Loads for Buildings and Other Structures. Reston, Virginia, 2016.

[9] Ministero delle Infrastrutture, Norme Tecniche per le Costruzioni (NTC). Aggiornamento delle «Norme tecniche per le costruzioni» Decreto Ministero delle Infrastrutture, 17 gennaio 2018, G.U. n. 42 del 20 febbraio 2018 - Suppl. Ordinario (in Italian).

[10] European Standards, CSN EN 15978: Sustainability of construction works - Assessment of environmental performance of buildings - Calculation method. Czech Republic, 2011.

[11] H.J. Darby, A. A. Elmualim and F. Kelly, A case study to investigate the life cycle carbon emissions and carbon storage capacity of a cross laminated timber, multi-storey residential building. *Sustainable Building Conference*, Munich, Germany, April 23-25, 2013.

[12] B. Grann, A comparative life cycle assessment of two multistory residential buildings: Cross-laminated timber vs. concrete slab and column with light gauge steel walls. *FPInnovations Report,* Vancouver, Canada. pp. 1-121, 2013.

[13] A. B. Robertson, F.C.F. Lam F. and R.J. Cole, A Comparative Cradle-to-Gate Life Cycle Assessment of Mid-Rise Office Building Construction Alternatives: Laminated Timber or Reinforced Concrete. *Buildings*, **2(3)**, 245-270, 2012.

[14] C.X. Chen, F. Pierobon, S. Jones, I. Maples, Y. Gong, Comparative life cycle assessment of mass timber and concrete residential buildings: a case study in China. *Sustainability*, **14(1)**, 144, 2022. https://doi.org/10.3390/su14010144

[15] Eurostat database. https://ec.europa.eu/eurostat/data/database

[16] M. Romagnoli, M. Fragiacomo, A. Brunori, M. Follesa, G. Scarascia Mugnozza, Solid Wood and Wood Based Composites: The Challenge of Sustainability Looking for a Short and Smart Supply Chain. *Digital Wood Design: Innovative Techniques of Representation in Architectural Design*; F. Bianconi, M. Filippucci, Eds., Springer International Publishing: Cham, Switzerland, 783-807, 2019.

[17] M. H. Ramage, et al., The wood from the trees: the use of timber in construction. *Renew Sustain Energy Rev*, **68**, 333-359, 2017.

[18] J. Jančar, T. Zafirov, M. Premrov and B. Dujič, Seismic resistance of existing buildings with added light timber structure storeys. *Gradevinar*, **74**, 403-4017, 2022.

[19] I. Šušteršič, B. Dujič, and S. Gostič, Timber upgrade of structures on seismically active areas. *World conference of timber engineering (WCTE)*, Riva del Garda, Italy, June 20-24, 2010.

[20] S. Calderón, S. Carcamo, C. Sandoval and F. Chateau Gannon, Structural feasibility of timber-structured vertical expansions for social housing buildings in Chile. *World conference of timber engineering (WCTE)*, Seoul, South Korea, August 20-23, 2018.

[21] G. Manfredi, A. Masi, R. Pinho, G. Verderame, M. Vona, Valutazione degli edifice esistenti in Cemento Armato. IUSS Press, Pavia, Italy; 2007 (in Italian).

[22] Swedish Wood, The CLT Handbook. Stockholm, Sweden; 2019.

[23] CSI, SAP2000 Integrated Software for Structural Analysis and Design, Computers and Structures Inc., Berkeley, California.

[24] FEMA-356: Prestandard and Commentary for the Seismic Rehabilitation of Buildings American Society of Civil Engineers, 2000.

[25] L. Liberatore, F. Noto, F. Mollaioli, P. Franchin. In-plane response of masonry infill walls: Comprehensive experimentally-based equivalent strut model for deterministic and probabilistic analysis. *Engineering Structures*, **167(7),** 533-548, 2018.

[26] O. Dowell, F. Seible, E.L. Wilson. Pivot hysteresis model for reinforced concrete members. *ACI structural journal*, **95**, 607-617, 1998.

[27] L. Cavaleri, F. Di Trapani. Cyclic response of masonry infilled RC frames: Experimental results and simplified modeling. *Soil Dynamics and Earthquake Engineering,* **65**, 224-242, 2014.

[28] T. Bogensperger, G. Silly. Two-axial load transfer of Cross-Laminated-Timber plates. *Bautechnik*, **91 (10),** 742-752, 2014.

[29] R. Brandner, P. Dietsch, J. Droscher, M. Schulte-Wrede, H. Kreuzinger, M. Sieder. Cross laminated timber (CLT) diaphragms under shear: Test configuration, properties and design. *Construction and Building Materials*, **147**, 312-27, 2017.

[30] M. Piazza, T. Sartori. Caratterizzazione meccanica attraverso prove monotone e cicliche dei principali dispositivi di connessione utilizzati negli edifci multipiano in legno. Test Report, Trento 2015.

[31] I. Zentner, M. Gündel, N. Bonfils. Fragility analysis methods: Review of existing approaches and application. *Nuclear Engineering and Design*, **323**, 245-258, 2017.

[32] S. Rajkumari, K. Thakkar, H. Goyal. Fragility analysis of structures subjected to seismic excitation: A state-of-the-art review. *Structures*, **40**, 303-016, 2022.

[33] K. Kiani, C. Camp, S. Pezeshk. On the application of machine learning techniques to derive seismic fragility curves. *Computers & Structures*, **218**, 108-122, 2019.

[34] D. Vamvatsikos, C.A. Cornell. Incremental dynamic analysis. *Earthquake Engineering & Structural Dynamics*, **31 (3)**, 491-514, 2002.

[35] Database. Pacific Earthquake Engineering Research Center, University of California, Berkeley. California (2006)

[36] Department of Homeland Security, FEMA. HAZUS-MH, Multi-hazard loss estimation methodology: earthquake model. Washington (DC), 2003.