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SEISMIC RETROFIT OF MASONRY INFILLED FRAMES BY USING TIMBER PANELS

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Abstract

The study presented herein proposes a retrofit method aimed at reducing the seismic vulnerability of reinforced concrete (RC) frame structures. The method consists in the replacement of the existing masonry infills with timber structural panels made of Cross Laminated Timber (CLT) fixed to the concrete frame by using a timber subframe and dissipative metal dowel-type fasteners. The first part of the research was carried out by performing nonlinear static analyses of finite-element (FE) models of bare, masonry infilled and retrofitted single-storey single-bay frames. A large number of configurations was analysed considering different original conditions (e.g. in terms of geometrical characteristics, mechanical properties and loading) and several retrofit implementation approaches. Special attention was paid to the improvement of the seismic response of the beam-column joints, that represent a well-known structural vulnerability of existing concrete frame-buildings. The analysis results permitted to define a set of “general rules” to guide the implementation of the retrofit method depending on the characteristics of the original structure. Using these design rules, the proposed solution was then applied to the FE models of three case-study buildings, located in Italy and built in the period from 1950 to 1990. By comparing the seismic response of the pre- and post-intervention structures, it was observed that the proposed system could significantly improve the structural behaviour of the buildings, favouring the development of ductile mechanisms and reducing the vulnerability of the beam-column joints.

Keywords: Structural rehabilitation; Seismic engineering; Concrete structures; Timber panels; Nonlinear analyses

1. Introduction

Since the mid of the twentieth century, reinforced concrete (RC) frame structures with masonry infills have become more and more common all over the world. However, most of these structures have been designed neglecting or poorly considering the seismic actions. Furthermore, although nowadays is well-known that the presence of masonry infills significantly affects the seismic response of the RC frame structures [1,2], in most cases their presence has been completely neglected in the design phase, considering only the vertical loads due to their weight. Consequently, during the earthquakes it is not infrequent to observe unexpected damage and collapses of both the structural and non-structural elements. The main critical issues of this kind of structures regard the detachment and the collapse of the infills and the failure of the concrete elements due to the interaction with the infills [3]. Furthermore, in the built heritage the beam-column joints usually present reinforcements, anchorages and, in general, details characterised by designs that did not consider the modern capacity design principles [4], resulting in a significant vulnerability under the seismic loading [5,6]. In addition, because the plan and elevation disposition of the infills play a major role in determining the overall behaviour of the structure [7], it can lead to the activation of torsional motions and to the concentration of the lateral deformation in a single storey. The combination of these factors can also induce disastrous soft-storey mechanisms.

In order to reduce the seismic vulnerability of existing RC structures infilled with masonry, a retrofit intervention is being developed at the University of Trento (Italy). The intervention consists in the replacement of the existing masonry infills with timber structural panels made of cross laminated timber (CLT). This intervention, which results in a reduction of the wall thickness and the seismic mass, leads to a significant improvement in the seismic behaviour of the structures without altering their original structural system. The work presented herein, focus on the optimization of the proposed intervention via nonlinear static analysis of numerical models reproducing isolated single-storey single-bay frames that are representative of the existing building stock of many Countries. In particular, the intervention was optimized with the aim of preventing both the collapse of the beam-column joints and the shear failure of the concrete elements during the seismic events, thus favouring the development of ductile collapse mechanisms.

2. Retrofit Intervention

In the proposed intervention, the existing masonry infills are replaced with timber structural panels made of CLT, without modifying the existing structural elements. The main goal of the intervention is to enhance the seismic behaviour of the frames under in plane-lateral loading. It involves besides a reduction in the thickness of the walls and in the seismic mass. In addition, because timber panels of structural grade are used, they can contribute to resisting vertical actions in case of severe damage of the concrete-load bearing elements.

Considering an isolated single-storey single-bay frame (Fig. 1a), the intervention procedure consists in the removal of the masonry infill (Fig. 1b), followed by the installation of a sub-frame made of glued laminated timber (GLT) (Fig. 1c), to which a timber panel is fixed by using screw fasteners (Fig. 1d).

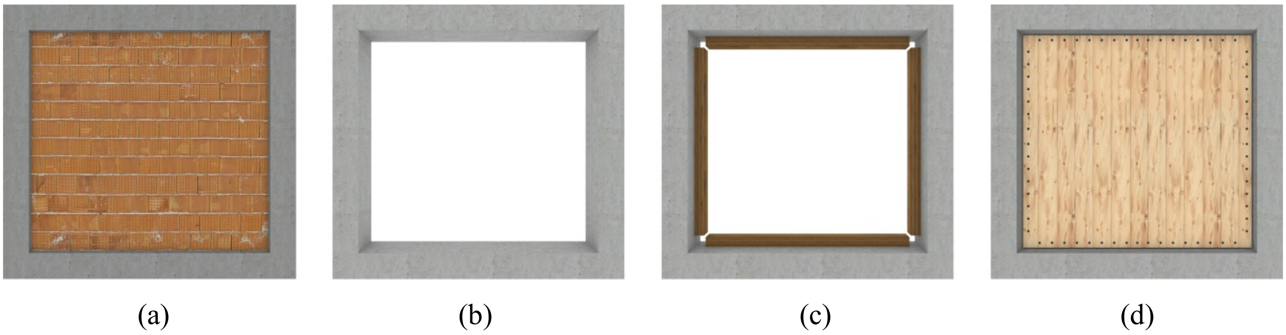

(a) (b) (c) (d)

Fig. 1 – Intervention procedure

The connection between the concrete frame and the timber subframe (Fig. 2a) and the connection between the timber subframe and the timber panel (Fig. 2b), are both realized by using screws. These connections form a system that can dissipate seismic energy by engaging both the timber bearing strength and the post-elastic behaviour of the metal fasteners.

(a) (b)

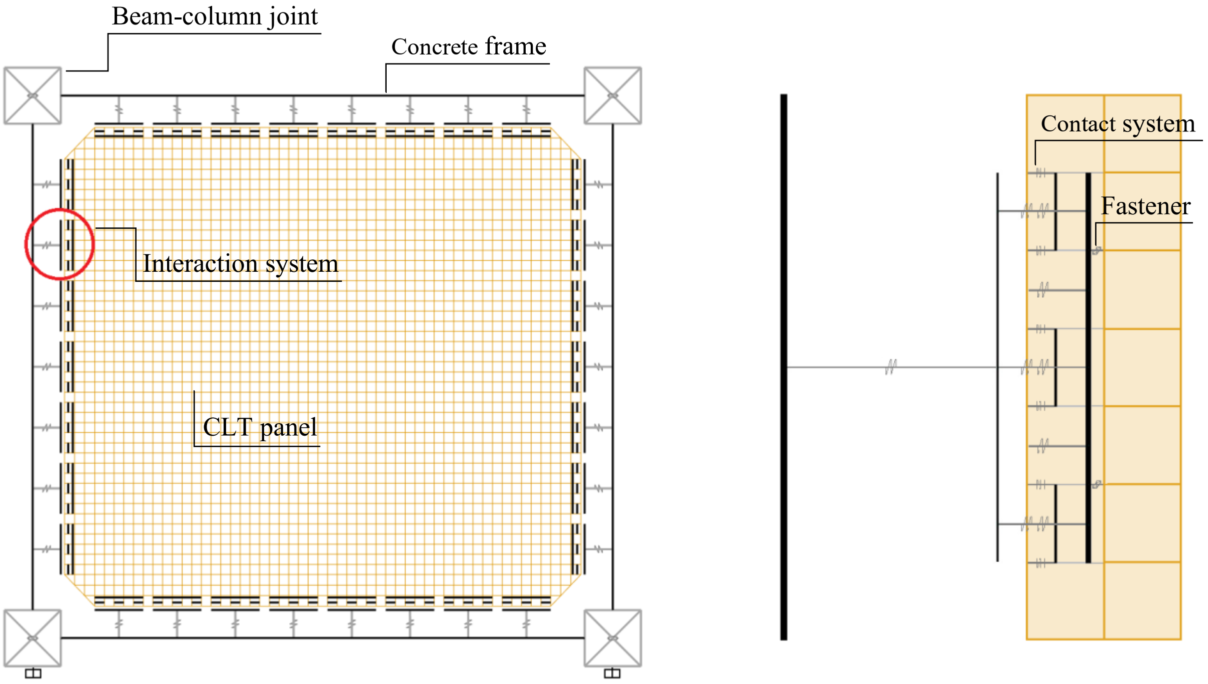
Fig. 2 – Connection systems

A gap that runs around the perimeter of the timber panel (Fig. 2b), eliminates any direct contact between the panel edges and the concrete frame. The gap is beneficial to the insertion of the panel inside the frame and also governs the transfer of load between the concrete frame and the panel. Due to the presence of the gap, in the first phase of the lateral loading there is no direct contact between the frame and the panel and the load is transferred from the frame to the panel solely through the screw fasteners. This load mechanism prevents the panel from acting as a compressed diagonal strut and, as a consequence, it eliminates stress concentrations that can lead to the dangerous shear failure of the columns, which is typical of the masonry infilled frames. Because of the shear force being transferred by the screws, the system can dissipate energy through the deformation of the connection system. In particular, the fasteners along the perimeter of the panel are arranged so that the stresses are transferred from the frame and panel mainly by the beams. Indeed, by transferring forces from the upper beam to the lower beam through the timber panel, it is possible to limit the shear that is transferred to the columns. In the existing buildings in fact, which usually have not been designed considering the horizontal seismic action, large shear stress on the columns can lead to brittle collapse modes in shear. Consequently, because the system avoids the shear failure of the concrete elements, it can develop a ductile behavior through the activation of the plastic hinges at the extremities of the beams and the columns. Furthermore, in case the lateral loading is continued even after the hinges have been activated, the gap is calibrated to go to zero when the concrete system has exhausted its plastic resources and it is on the verge of collapsing. This involves a direct contact between concrete frame and timber panel, and a consequent increase in capacity and stiffness.

Additionally, due to the presence of the gap and to the disposition of the fasteners, the proposed intervention reduces the stresses acting on the beam-column joints, preventing or delaying their collapse in most of the analysed cases. However, in case of joints particularly weak, characterized by poor rebar detailing and flat beams, the sole implementation of the proposed intervention could not prevent the joints from collapsing prior to the other structural elements. In these cases, it is necessary to intervene on the joints in order to guarantee their overstrength. Therefore, fiber reinforced polymer (FRP) strengthening of those joints that showed inadequate behaviour even after the installation of the timber panel, was assumed.

3. Numerical Model

The proposed intervention was studied through FE modelling by performing over 300 nonlinear static analyses of isolated single-storey single-bay frames using the software SAP2000 [8] (Fig. 3). In the FE models, the concrete elements are represented using *frame* elements and a concentrated-plasticity approach where specific hinges simulate both bending and shear post-elastic behaviour. The CLT panel is modelled using *shell thick* elements, with an orthotropic behavior based on the suggestions from Bogensperger et al. [9], Bogensperger et al. [10] and Brandner et al. [11]. The interaction between the panel and the frame, outlined in red in Fig. 3a, is composed of the screw fasteners and of a "contact system". Both the fasteners and the contact system are modelled using *link* elements (Fig. 3b). The fastener-links reproduce the elastic and post-elastic behavior of the connections, which was defined based on evidence available in literature (Gavric et al. [12], Rinaldin et al. [13], Schiro et al. [14], Eurocode 5 [15] and CNR [16]). The "contact system" simulates instead the contact forces that the concrete frame transfers to the timber panel when the gap is closed. With the aim of investigating the possible failure of the beam-column joints, the simplified model proposed by Sung et al. [17] was applied to a representative selection of the analysed frames. In this model, the post-elastic behaviour of the joint is simulated by two cross links placed at the intersection between the column and the beam (Fig. 3a).



(a) (b)

Fig. 3 – Finite element model

The analyses addressed alternative configurations of both the original and the retrofitted conditions. As regards the original as-built condition, the alternative configurations concerned different geometrical and mechanical properties of the frames and different load levels. In the retrofitted condition instead, alternative parameters were considered regarding the implementation of the intervention, such as the characteristics and the arrangement of the fasteners, the size of the gap and the thickness of the timber panel. Each frame was analysed with reference to the bare frame (i.e. without any infill), the as-built condition (i.e. with masonry infill) and the retrofitted condition (i.e. with timber panel infill). In the original as-built configuration, the masonry infills were modelled by using the equivalent-diagonal strut proposed by Al-Chaar (2002) [18].

The results achieved led to the optimization of the intervention system and to the definition of "design rules" that depend on the characteristics of the original not-retrofitted system. In particular, the analyses showed that, depending on the preexisting load level and on the ratio between the length of the beams and the height of the columns (l/h), two different configurations of the intervention should be used. The first configuration (C1) presents a gap equal to 10 millimeters and fasteners arranged both along the beams and the columns. This configuration proved to be the best one in case of frames with $l/h \leq 1$. The second configuration (C2) instead, presents a gap equal to 20 millimeters and fasteners arranged only along the beams. This configuration is optimal for frames with $l/h > 1$ and in case of heavy vertical loads, regardless of the l/h ratio.

4. Analysis of representative frames

In order to highlight the benefits of the proposed retrofit strategy, the seismic performance pre- and post-intervention of four representative single-storey single-bay frames is described in detail. These frames present characteristics that are representative of the existing building stock of many Counties in terms of geometry, mechanical properties and load levels. Table 1 shows the main characteristics of the selected frames.

Table 1: Main characteristics of the considered frames

Characteristics	**Frame 1**	**Frame 2**	**Frame 3**	**Frame 4**
Beam section (base for height): mm	300×500	300×500	800×200	800×200
Column section (base for height): mm	300×300	300×300	350×350	350×350
Length of the beam: mm	4680	2480	3430	2700
Height of the column: mm	3100	3100	2900	2900
Thickness of the original masonry infill: mm	200	200	200	200
Thickness of the CLT panel: mm	60	60	60	60
Configuration of the intervention	C2	C1	C2	C1
Weak joints	No	Yes	Yes	Yes
Additional retrofit on the joints	No	No	Yes	Yes

Although Frame 2, Frame 3 and Frame 4 presented preexisting weaknesses in the concrete beam-column joints, only Frame 3 and Frame 4 required additional interventions in order to avoid the collapse of the joints. Indeed, for Frame 2 the sole replacement of the masonry infill with the timber panel was enough to ensure that the collapse of the joints did not precede the collapse of the other structural elements. Two scenarios were therefore considered when analyzing Frame 3 and Frame 4 in the retrofitted configurations: a) the joints had not been reinforced (the model adopted was that of Sung et al. previously mentioned) and b) the joints had been reinforced and their behavior is assumed as rigid.

Fig. 4 shows the backbone curves obtained by analyzing each frame considering the bare-, the original masonry infilled- and the retrofitted conditions. In those cases where the additional FRP strengthening was assumed, both curves (with and without FRP) are reported.

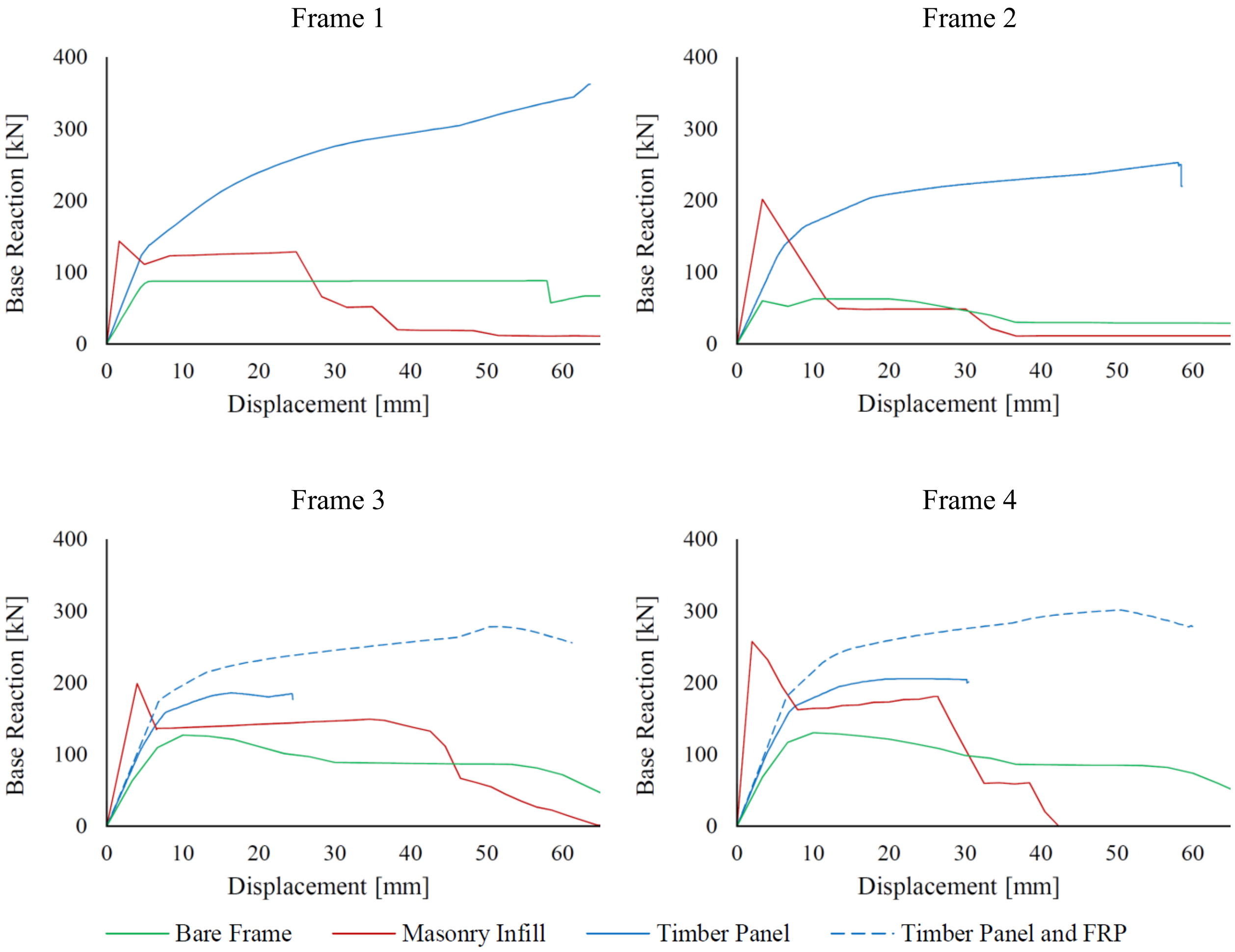


Fig. 4 – Representative frames – Backbone curves achieved for the bare frames, the original masonry infilled frames and the retrofitted configurations

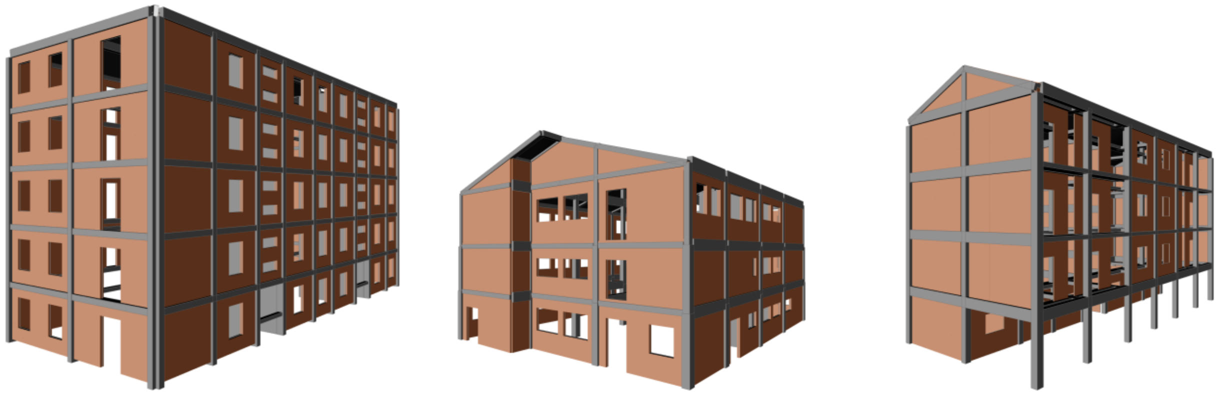
It can be observed that the proposed intervention can significantly enhance the seismic response of the frames. The as-built frames showed an initial rigid response due to the direct contact between the frame and the infill that led to the transfer of high additional shear stresses to the concrete columns. These stresses entailed the shear failure of the columns and consequent loss in load bearing capacity. As the lateral load increases, also the resistance of the masonry infills is reached, causing further decrease in the load bearing capacity. On the contrary, the retrofitted frames showed an overall ductile behavior and substantial increases in the maximum load bearing capacity. Such increases ranged from 15% to 250% in the best performing cases. It was also found that the higher the l/h ratio, the higher the improvement due to the intervention.

In general, in the initial elastic phase, the retrofitted frames showed a stiffness closer to that of the bare frames than to that of the masonry infilled frames. The reduced stiffness means higher fundamental periods that may results in a reduction of the seismic demand. Furthermore, although the retrofitted frames did collapse because of the shear failure of the columns as it was observed for the as-built masonry infilled frames, the collapse occurs at displacement levels approximately 20 times the displacement capacity of the masonry infilled frames. Such large enhancement in the deformation capacity is due to the formation of dissipative mechanisms. Because the transfer of stresses is governed by the metal fasteners, in the design phase it is possible to limit the shear actions transferred to the columns, favoring in this way the development of ductile bending mechanisms in both the beams and the columns. Additional energy dissipation can be obtained by having the metal fasteners engage their post-elastic behavior. The dissipative processes just described entailed the development of a ductile response, with a progressive reduction in stiffness without sudden capacity loss.

In the last phase, some retrofitted frames showed an increase in stiffness (see curve from Frame 3 and especially from Frame 1). This increase is due to the closing of the gap between the concrete frame and the timber panel. The direct contact between these elements, resulted in an increase in the load bearing capacity immediately prior to the system approaching the collapse condition.

4. Case study structures

The proposed intervention was implemented in three case-study structures (CS). These structures, shown in Fig. 5, are here named CS1, CS2 and CS3, and were built in Italy respectively in the 1950s, 1960s and 1980s.



CS1 CS2 CS3

Fig. 5 – Case study structures

Each structure was analysed by performing nonlinear static pushover analyses, considering the bare configuration (where the masonry infills are considered only as vertical loads), the original masonry infilled configuration (by using the simplified diagonal strut-model proposed by Al-Chaar 2002) and the retrofitted configuration (where it was supposed to strengthen weak beam-column joints by using FRPs). In order to reduce both the computational load and the duration of the analyses, a simplified model of the retrofit intervention was used. In the simplified model, the connection system is represented by only four equidistant fasteners per side of the panel. Each fastener replaces several screws and its resistance is increased consistently with the number of screws replaced. In addition, the contact system is represented by two links per side, located at the extremities of the panel and calibrated on the results obtained from the refined model. The simplified model is expected to simulate adequately the interaction between panel and concrete elements, but it does not give precise information on the stress level on the panels and on the single fastener.

The results of the analyses are shown in Fig. 6. For each structure, the backbone curve referring to the direction corresponding to the major building dimension is reported.

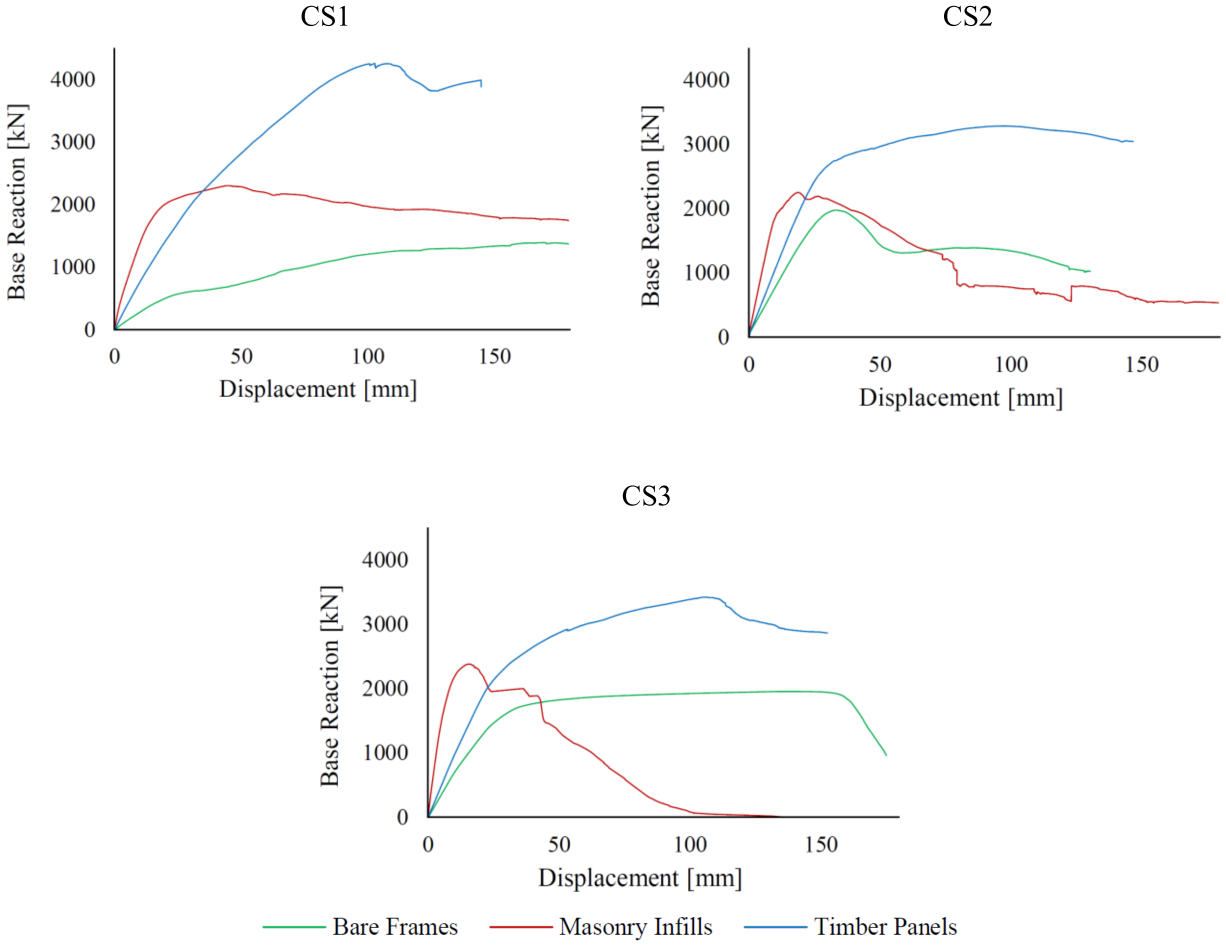


Fig. 6 – Case study structures – Backbone curves obtained for the bare frames, the original masonry infilled frames and the retrofitted configurations

Similarly to the isolated frames, the replacement of the masonry infills with CLT panels resulted in evident improvements in the seismic behaviour of the analysed structures. Considering the first phase of the response, the retrofitted structures showed an initial stiffness that was intermediate to that of the bare configurations and the masonry infilled ones. This means that retrofitted structures have higher fundamental periods than the original masonry infilled configurations which often translates into smaller seismic demands. Furthermore, the intervention involved the development of overall ductile behaviours, with improvements in both the load bearing and displacement capacity. As regards the load bearing capacity, increases of 85%, 46% and 44% were observed for CS1, CS2 and CS3, respectively. However, the major improvements were observed in the displacement capacity. The displacement peak capacity increased indeed respectively 2.3, 5.2 and 6.8 times for CS1, CS2 and CS3. This large improvement was due to the load-transfer mechanism enabled by the retrofit, that inhibited the brittle collapse of the structural elements and favored the activation of ductile mechanisms. In addition, also the dissipative capacity of the connections between the panels and the frames contributed to the development of a ductile failure mechanism that significantly reduced the seismic vulnerability of the case-study structures.

5. Conclusions

In the present research, a novel retrofit intervention for RC framed structures has been presented, that consists in the replacement of the existing masonry infills with timber structural panels. This intervention has the main goal of enhancing the seismic behaviour of the buildings under in-plane seismic actions. Furthermore, it does not modify the original structural system and involves a reduction in both the thickness of the infill walls and in the overall seismic mass. The intervention has been studied via FE modelling by performing nonlinear static analyses of over 400 isolated one-storey one-bay frames. In particular, the analyses focused on the effects of the intervention on the response of the beam-column joints under lateral actions. It was observed that the intervention can significantly enhance the seismic behaviour of the structures and can also improve the response of the beam-column joints. By using the results of the analyses performed on the isolated frames, it was possible to define some general design rules depending on the characteristics of the original systems. Using these rules, the retrofit intervention was applied to three case-study buildings. The seismic behaviour of the studied buildings showed that the proposed intervention can significantly enhance the response of RC framed structures by 1) improving both the deformation and the load bearing capacity, 2) reducing the vulnerability of the beam-column joints, and 3) favoring the development of ductile mechanisms of collapse.

6. Acknowledgements

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