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MASONRY-INFILLED RC FRAMES STRENGTHENED WITH CROSS-LAMINATED TIMBER PANELS

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Abstract

Southern regions of Europe are characterized by presenting a large number of existing buildings with reinforced concrete (RC) structures with masonry infills. From a structural point of view, they are characterized by one-way RC frames, with poor structural details and masonry infills, contributing to the high seismic vulnerability of these constructions.
Current retrofitting technologies, such as reinforced concrete jacketing of columns, concrete shear walls or FRP wrapping, could be effective but require the occupants' relocation, available perimetral space and legislative constraints. The use of CLT panels, as an innovative retrofitting technique, seems to be a reasonable alternative for existing buildings given their easy and fast assembly, high performance and reversibility.
This paper presents a numerical analysis to evaluate the seismic behavior of masonry-infilled RC portal frames strengthened by an external CLT panel. The 20 cm thick masonry wall was represented by two nonlinear diagonal elements with a multi-linear plastic constitutive law, including a Pivot hysteresis type in the axial direction. On the other hand, the 100 mm thick CLT panel was modeled through an orthotropic elastic shell-element. The study comprises four different connections between the RC frame and CLT panels. These connections are modeled through nonlinear Pivot links in both uplift and lateral directions. Their cyclic response, including degradation parameters, effective stiffness and force-deformation envelope curve, was calibrated based on previous experimental results. Numerical results confirm that CLT panels can be an efficient strengthening solution to increase the initial stiffness, as well as energy dissipation, while decreasing the impact of strength degradation on the response of masonry-infilled RC frames against in-plane quasi-static cyclic loading.

Keywords: RC Frame; Masonry infills; Cross Laminated Timber; Quasi-static Analysis

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1 INTRODUCTION

Masonry-infilled reinforced concrete (RC) buildings constitute a significant part of the existing building stock across southern regions of Europe [1]. Consequently, many studies have been conducted to analyze the properties of infilled RC frames, in order to improve their weaknesses and prevent their failure under cyclic loading [2][3].

The presence of infill walls on the bare frame can induce unexpected force distributions that can lead to local failures during intense ground shaking [4]. The main failure modes in masonry-infilled RC frames that have been shown in experimental, analytical, and numerical research works are: corner crushing mode; sliding shear mode; diagonal cracking mode; diagonal compression mode; and the failure of the RC frame [5]. Furthermore, when subjected to seismic loads, RC frames are susceptible to non-ductile failure modes, particularly the frames built according to previous codes and standards [6]. Therefore, seismic retrofitting seems inevitable. Some of the available retrofitting techniques aim to directly strengthen the masonry infill, besides an improvement of the RC frame structure. Indeed, there is a wide range of retrofitting techniques that are divided into two general approaches: structure-level retrofit and member-level retrofit [7].

Cross-laminated timber (CLT) panels are a combination of several crosswise-stacked lumber boards that confer high in-plane stiffness. These panels allow fastening the construction work and can contribute to meet societal goals in terms of environmental sustainability, improving the energy performance of buildings, while reducing CO_2 emissions of construction. Sustersic et al. [8] introduced CLT as a seismic retrofitting method for infilled RC buildings by developing a three-step over strengthened connection. This study showed that longer CLT panels are more efficient than shorter segments under seismic forces for a better bending behavior.

On the other hand, Stazi et al. [9] showed that RC frames strengthened by CLT can reach higher lateral stiffness and peak load values than masonry-infilled RC frames. In both cases, the use of prefabricated timber panels improves the energy efficiency of the building by reducing global energy demand up to nearly 60% [10].

Experimental evaluations have shown that the connection used to connect panels and the main RC structures play a crucial role in the overall seismic response, given their nonlinear behavior that promotes energy dissipation [11][12]. Considering this fact, special attention should be given to their design and assessment.

The present work studies the response of strengthened RC frame under cyclic loadings with a special focus on strength degradation, stiffness deterioration, ductility and energy dissipation. A one-story one-bay infilled reinforced RC frame is used as a case study, where its seismic response is improved through a collaborative CLT panel. Four different connections between the CLT panel and RC frame, are evaluated by adopting distinct properties to nonlinear link connection elements. It is worth noting that these properties were defined based on tests results obtained through previous experimental campaigns [13][14][15]. The masonry infill is represented by an equivalent diagonal element, consisting on a macro-modeling procedure that exploits the multi-linear plastic link element with Pivot hysteresis law, available in SAP2000 NL software [16]. Moreover, the CLT panel is represented by the Homogenized-Orthotropic-plane stress-reduced cross-section (HOBS) approach [17].

2 DESCRIPTION OF THE INFILLED RC FRAME

The RC frame employed here, representing the actual building practice in Portugal, was built and tested at the University of Minho's laboratory in the 2/3 scale RC frame by Silva et al. [13]. Figure 1 shows the geometry and reinforcement scheme.

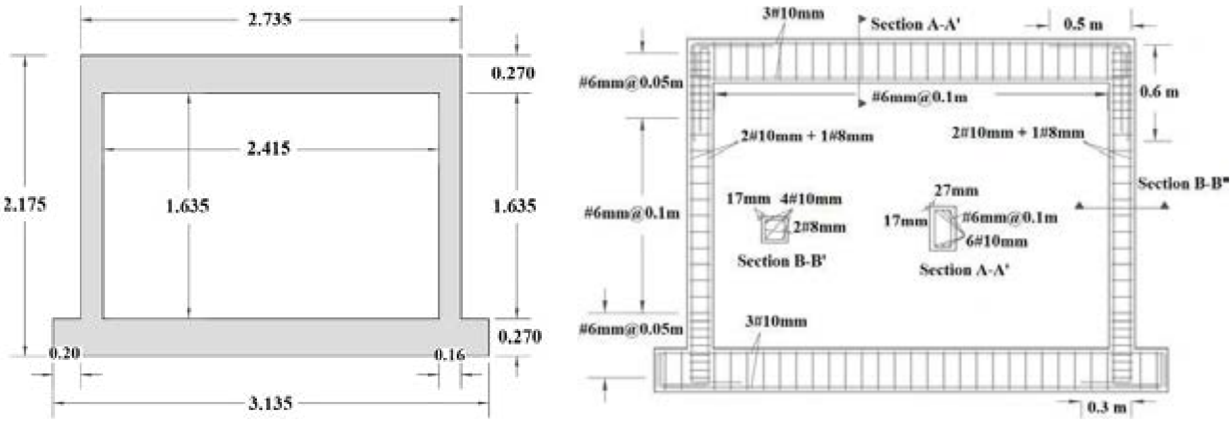


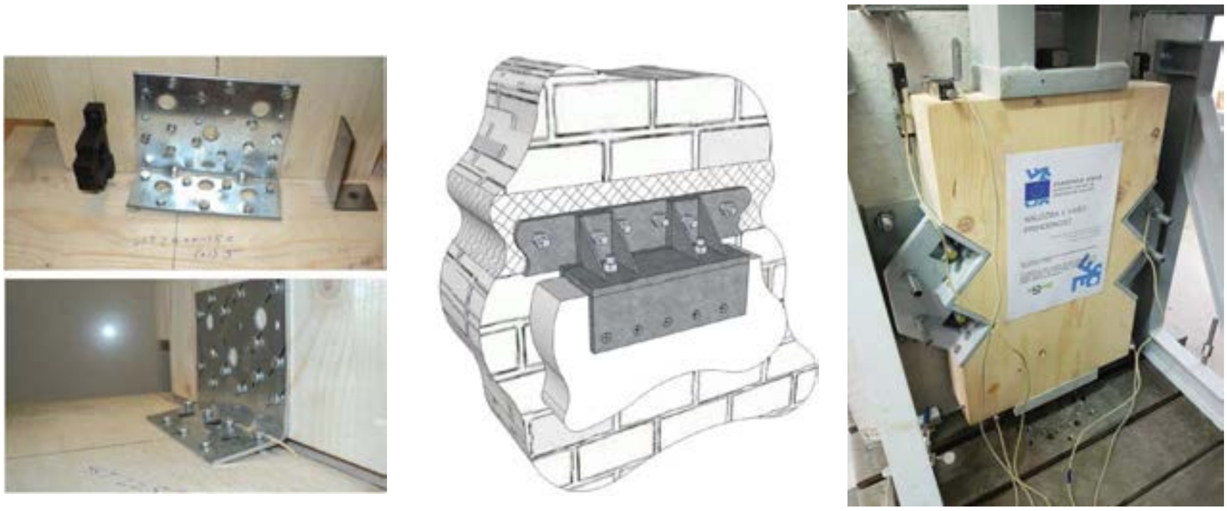
Figure 1: RC frame used in this study, Geometry, (b) Reinforcement scheme (Silva et al. [13])

The frame length and height are 2575 mm and 1770 mm, respectively. Beam and columns sections are 270×60 mm and 160×160 mm, respectively. The masonry infill was built with 294x187x140mm bricks with vertical perforation, using murfor RND 0.5 100 reinforcement in every two rows, and murfor L +100 anchors to connect the infill to the RC frame at the same level of reinforcements. The rebars used in the RC frame and masonry infill are an A400NR, and A500NR, respectively. The concrete of the RC elements is from the C55/67 class. For lying of masonry units, an M10 mortar is employed. The thickness of the horizontal joints is assumed to be 0.5 cm. More details can be found in Silva et al. [18].

3 CLT PANEL AND CONNECTIONS

The CLT panel has a thickness of 97 mm, comprising three layers with thicknesses 35, 27, and 35 mm. The panel’s mechanical properties, including moduli of elasticity and shear modulus, are determined according to standard EN 338 [19] and DIN 1052 [20], while the Poisson coefficients are obtained according to Bodig et al. [21].

Four different connections were considered in this study. The first (Figure 2 (a)) consists of a prefabricated mechanical connector, angle bracket AE116, widely used in the CLT structures [14]. The second one, Figure 2 (b), comprises three parts: a steel strap and steel threaded rods connecting to the beams, a steel bracket connected to the panel through self-tapping screws, and a steel plate connecting the steel strap with the steel bracket. The first two are designed to behave essentially elastic, whereas the last part is designed with a controlled failure, ductility and energy dissipation. This connection was developed and characterized by Sustersic [15]. The third and fourth connections, developed by Sustersic [15], adopt a newly designed angle bracket and two steel threaded rods with a length of 50 mm and grade rods of 4.6 and 8.8, respectively (Figure 2 (c)). The connections of Figure 2 (a) were selected because they represent a common in CLT buildings, while the remaining ones have presented an adequate response under cyclic loading both for sliding (shear) and uplift (tension) motions [15]. It important to mention that the availability of experimental tests [14][15] allows calibrating numerical models, increasing the reliability of their results.



(a) Connection I (b) Connection II (c) Connections III and IV

Figure 2: The CLT connections considered in this study. (a) Angle bracket AE116; (b) Steel strap & bracket; (c) Steel bracket & rods

4 MODELLING METHODOLOGY

4.1 Characteristics of RC plastic hinges

The RC frame is represented through linear elastic frame elements with plastic hinges at their ends that concentrate the nonlinear behavior of the beam-column joints. These plastic hinges whose properties are obtained according to Eurocode 8 (part 3) provisions [22] are governed by the Pivot hysteresis model, available in SAP2000 NL software [16]. The Pivot's coefficients are then adjusted in order to obtain an agreement between the numerical model and the test results from Silva et al. [13], in terms of the envelope curve, as shown in Figure 3.

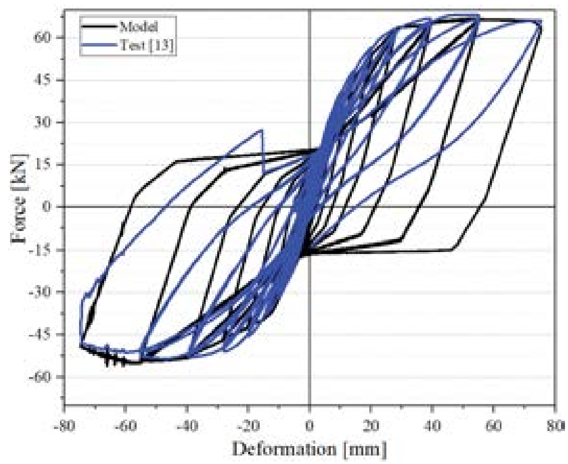


Figure 3: Experimental/analytical cyclic response of the selected RC frame from Silva et al. [13]

4.2 Characteristics of the masonry infill

The confined masonry infill is represented with two diagonal multi-linear link elements following the Pivot hysteresis law. The parameters of the links, including Pivot coefficients and Force-Deformation envelope definition, along with plastic hinges assigned to RC joints, are obtained after a calibration process based on the test data available in Silva et al. [10]. Figure 4 allows evaluating the response of the masonry infilled RC frame under cyclic loading and verifying the agreement between the numerical model and the experimental data in terms of force-displacement curves. The accuracy of the method is satisfactory in terms of the envelope curve, while the model is not accurate enough in terms of unloading stiffness.

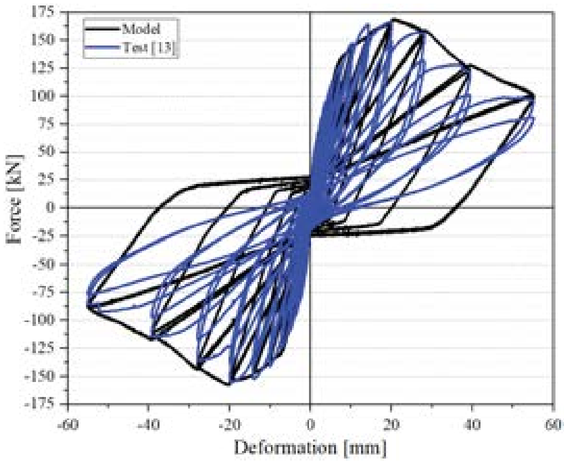
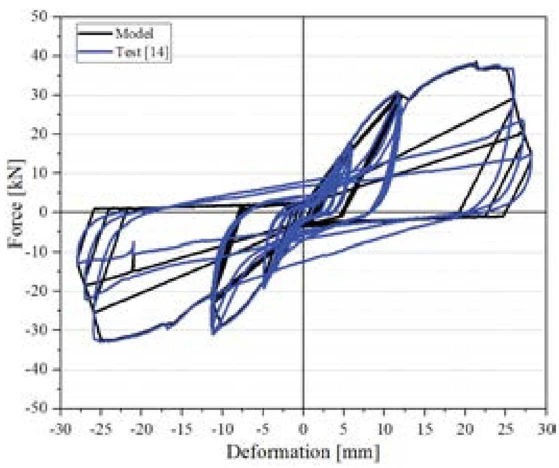


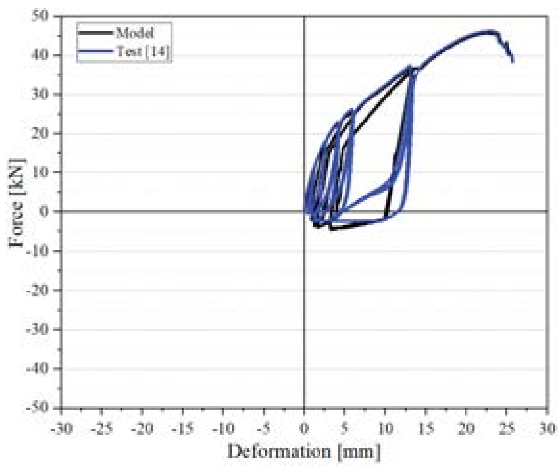
Figure 4: Experimental/analytical cyclic response of the selected infilled RC frame from Silva et al. [13]

4.3 Characteristics of connections between the CLT and frame

The connections between the CLT panel and the RC frame are represented by multi-linear plastic link elements that are governed by the Pivot hysteresis law. The force-deformation definition and Pivot's coefficients are obtained by a calibration process based on the experimental campaign developed by Matos et al. [14]. For connection I (angle bracket AE116), Figure 5 allows the numerical and experimental results of cyclic tests, for both lateral (a) and uplift (b) motions, in terms of force-deformation curves. In turn, Figure 6 presents the tension and shear response of an over strengthened connection (II), according to the experimental results obtained by Šušteršič [15]. The connections III and IV, presented in Figure 2 (c), were tested for loads applied in horizontal and vertical directions. In this regard, Figure 7 shows the behavior in shear for both numerical and experimental responses under cyclic loads for connections III (4.6 grade rods) and IV (8.8 grade rods).



(a) Lateral Loading



(b) Uplift Loading

Figure 5: Experimental/analytical cyclic response of the first connection I

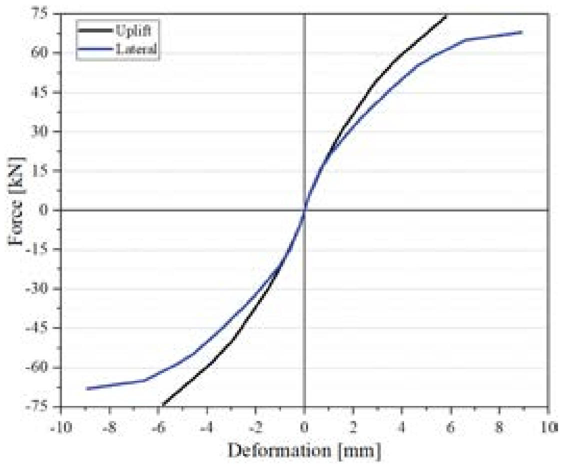


Figure 6: Uplift and Lateral force versus deformation in connection II [15]

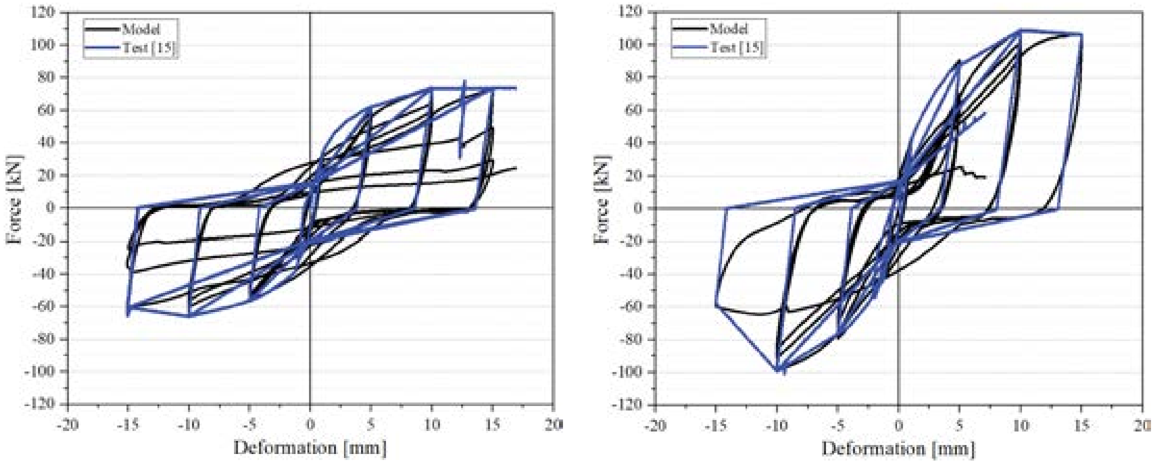


Figure 7: Experimental/analytical cyclic response, (a) Connection III, (b) Connection IV

4.4 Simulation of the infilled frame strengthened by CLT

The CLT panel and connections are simulated separately in this study. The panel is discretized according to the homogenized-orthotropic-plane stress-reduced cross-section method. The modeling approach adopted considered the three-layered panel as a single-layer shell element [17], based on reduction coefficients that result in a simplification, which requires less computational efforts, where most of the attention must be paid to connections modeling. Their correspondent links, divided into two sliding and uplift springs, can be distributed along panels' borders (beams and columns) or concentrated in four positions (corners). Considering the latter, in which the upper and lower beams corners are linked to the panel so that the end of connections is set to the end of beams, all springs are attributed by multi-linear plastic link elements.

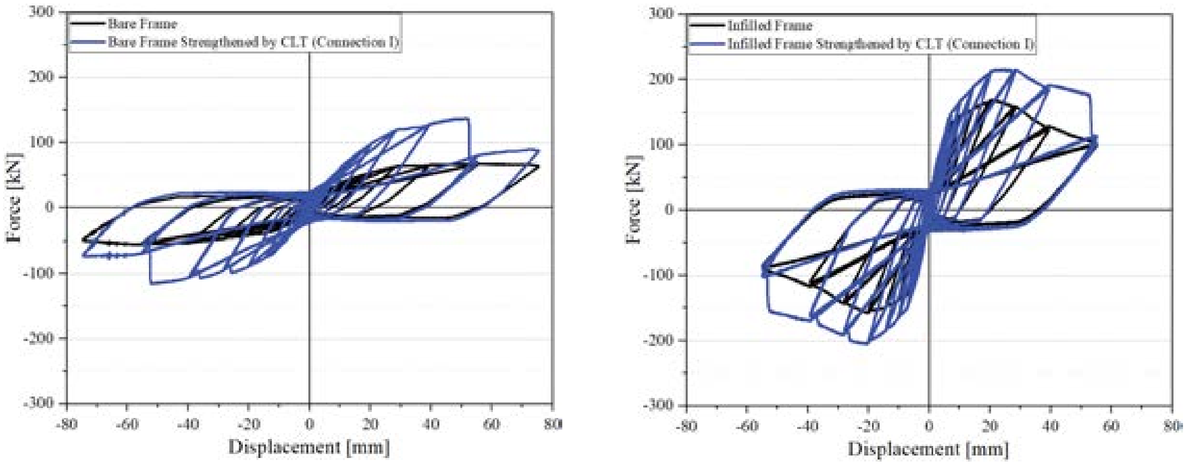
The loading pattern applied in the experimental campaign [10] followed FEMA 461 [14], in which the displacement is applied throughout 16 steps, starting from 0.5 mm, and ending in 75 mm. Each step is repeated two times except for the first one, which is repeated six times. The numerical study adopts the same loading pattern as the experimental work.

5 NUMERICAL RESULTS

In this section, one can evaluate the structural responses, under cyclic loading, obtained through the numerical modes used to represent the distinct connection schemes under study. The behavior is evaluated in terms of base shear versus top displacement, dissipated energy, and ductility factor.

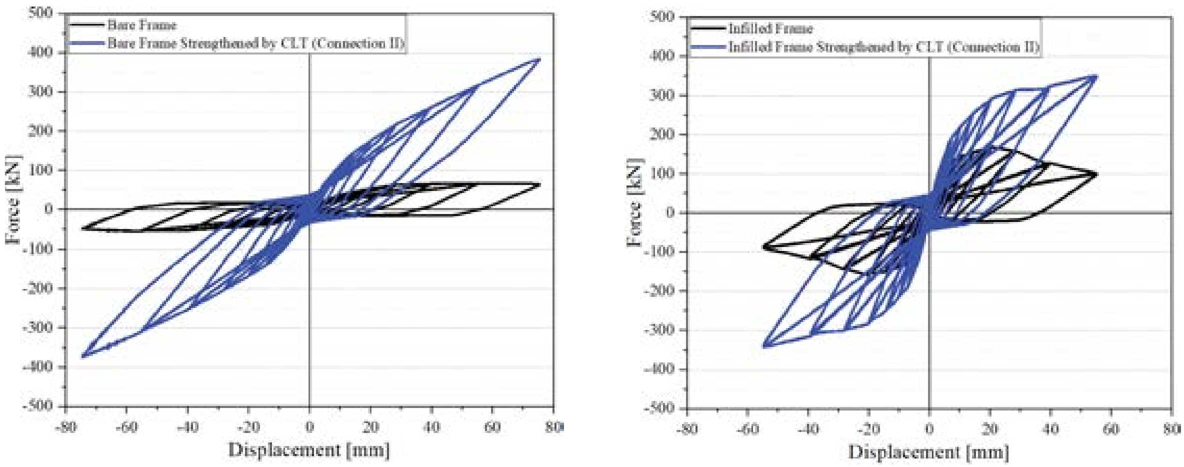
5.1 Force-displacement response of frames

Figures 8-11 present the force-displacement responses of the bare frame, the bare frame strengthened by CLT, infilled frame, and infilled frame strengthened by CLT, subjected to cyclic loading considering the four CLT connections.



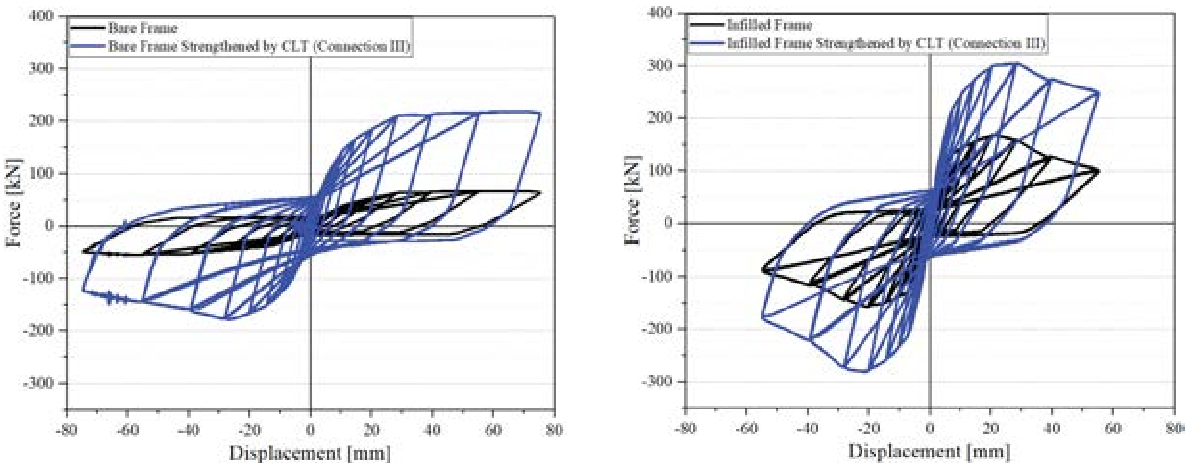
(a) (b)

Figure 8: Force-displacement response considering connection I: (a) Bare frame and bare frame strengthened by CLT; (b) Infilled frame and infilled frame strengthened by CLT



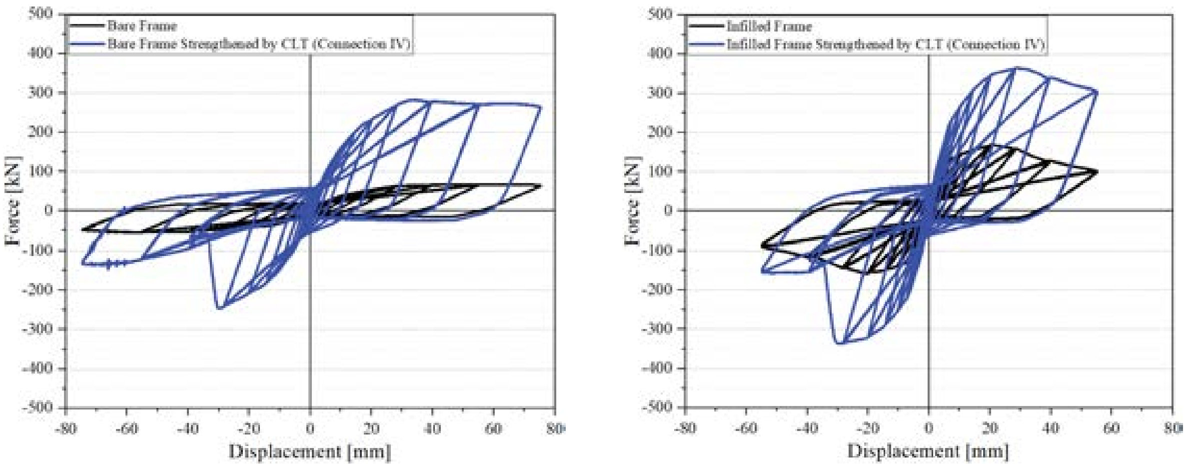
(a) (b)

Figure 9: Force-displacement response considering connection II: (a) Bare frame and bare frame strengthened by CLT; (b) Infilled frame and infilled frame strengthened by CLT



(a) (b)

Figure 10: Force-displacement response considering connection III: (a) Bare frame and bare frame strengthened by CLT; (b) Infilled frame and infilled frame strengthened by CLT



(a) (b)

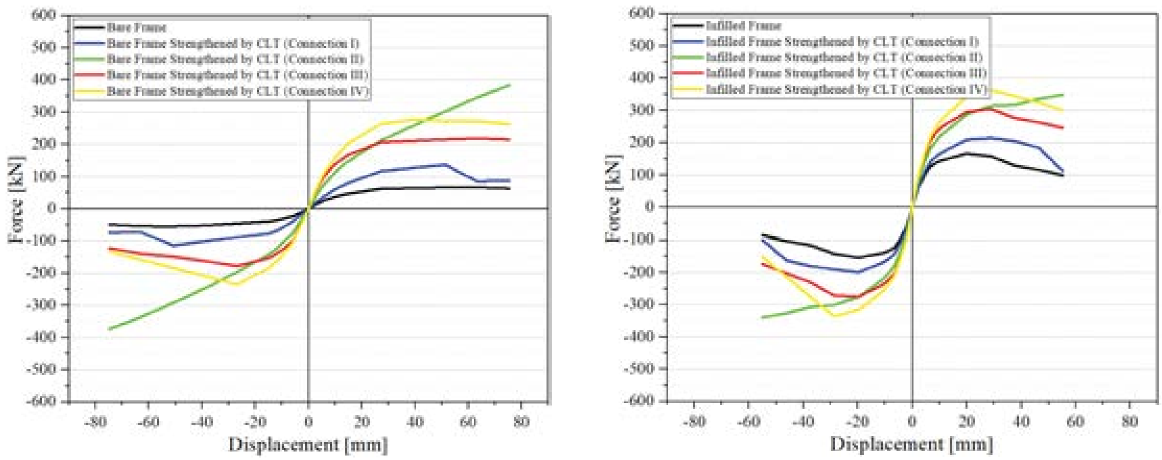
Figure 11: Force-displacement response considering connection IV: (a) Bare frame and bare frame strengthened by CLT; (b) Infilled frame and infilled frame strengthened by CLT

The overdesigned connection II makes 473% and 107% improvement in the maximum capacity of the bare frame and infilled frame, respectively. In this joint, unlike others, no strength degradation is observed for both bare and infilled frame strengthened. On the other hand, connection I has an increase of 104% and 27% in the strength capacity of the bare and infilled frame, respectively, which seems negligible compared to connection II, while the pinching effect as an index for evaluating energy dissipation is the same as previous. Figures 10 and 11 show the substantial ability of connections III and IV to dissipate energy, even more than connection II, although these connectors are simpler and then cheaper than three-part connection II, indicating that more efficient joints associating seismic reliability are possible at a lower cost. Connection IV shows about 30% and 15% improvement in strength capacity for bare and infilled frames, respectively, which is not satisfactory enough based on the differences in their rod strength. In other words, it proves that the geometry of connection, such as plate's thickness, number of rods and their size, makes a more contribution to modifying seismic properties of structures.

With regards to Figures 8-11, it is proved again that infills generally improve the post-elastic behavior of bare frames with increasing maximum strength and dissipating more seismic energy despite the fact that the ultimate strength stays almost unchanged. Comparing the results of the bare frame strengthened by CLT panel and those of infilled frame, a result is that the bare frame strengthened by CLT has higher seismic performance than the infilled frame due to the considerable potential shown to increase the energy dissipated, the initial stiffness, unloading and reloading stiffness, load carrying capacity, and decreasing strength/stiffness degradation.

It should be pointed out irregular responses in two opposite loading directions, as shown in Figure 11, due to unequal inelastic behavior in tension and compression.

In summary, Figure 12, through the backbone curves obtained from the cyclic analysis, compares the strengthening effect of the CLT panel connected to the RC frame considering four different connections. The comparisons are divided into two cases: bare frame (Figure 12 (a)) and masonry-infilled frame (Figure 12 (b)).



(a) (b)

Figure 12: Pushover curves considering all connections, (a) Bare frame and bare frame strengthened by CLT; (b) Infilled frame and infilled frame strengthened by CLT

Figure 12 shows that connection II, which presents a higher strength capacity than the remaining ones, did not achieve its post-peak strength, while other connections underwent that region. Furthermore, connection III presented higher peak strength per rod strength in comparison with connection IV; maybe referring to that strength itself is not a priority in the seismic design of connections. It should be stated that the CLT strengthening using connection I (AE116), which has a small contribution to the frame, has about the same peak capacity as the infilled frame (~160 kN).

5.2 Structural ductility

Having extracted the Pushover curves from the cyclic curves, the structural ductility factor (R), according to FEMA 2004 [23], is computed for all cases as:

$$R = \Delta_m / \Delta_y \tag{1}$$

In which, Δ_y and Δ_m indicate the yield displacement and the displacement associated with the structure's maximum shear capacity, respectively. These amounts are achieved by calculating the equivalent bilinear curve, which has the same area as the envelope curve, as shown below.

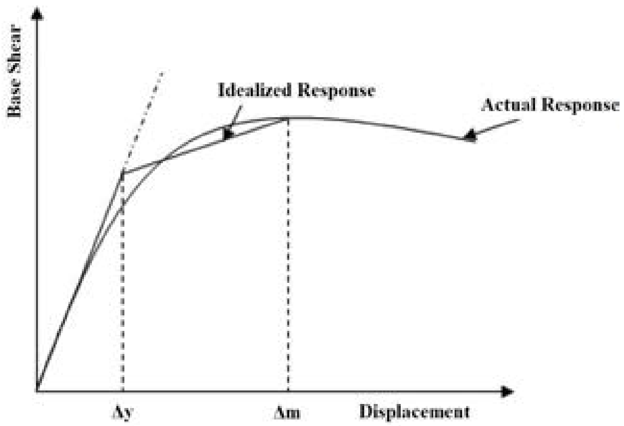


Figure 13: Definition of yield and maximum displacement

Therefore, all envelope curves in Figure 12 are transformed to equivalent bilinear curves, and then the ductility factor is calculated for the bare frame, infilled frame, and infilled frame strengthened by adding a CLT panel, considering the four selected connections (Table 1).

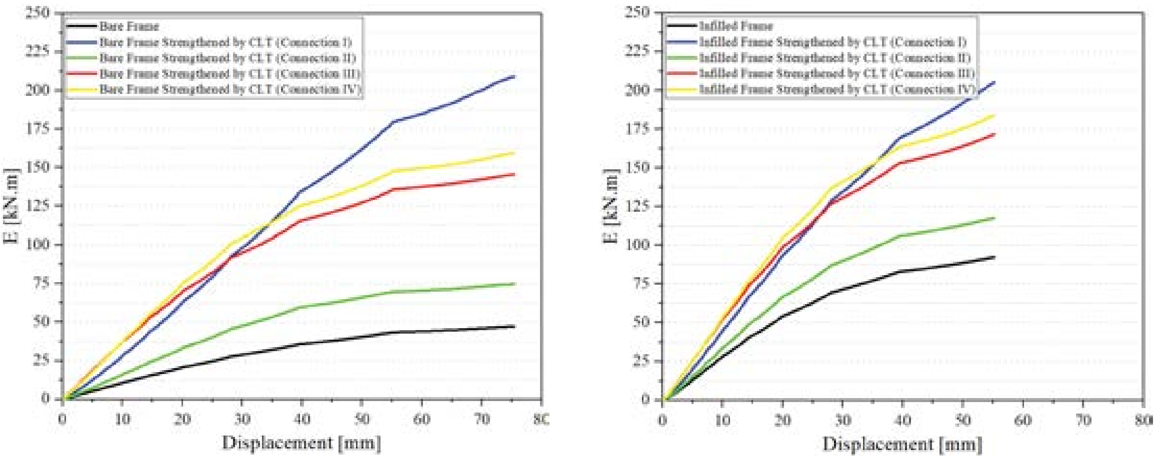
Table 1: Structural Ductility Factor

Bare Frame	Bare Frame Strengthened by CLT			
	Connection I	Connection II	Connection III	Connection IV
14.29	18.87	11.63	15.63	10.00
Infilled Frame	Infilled Frame Strengthened by CLT			
	Connection I	Connection II	Connection III	Connection IV
7.04	15.63	9.17	9.09	9.01

As shown in the above table, the infilled frame and infilled frame strengthened by CLT have mostly a lower ductility factor than the bare frame and bare frame strengthened by CLT, respectively, owing to failures of masonry that usually happens before the frame or connections. In addition, adding CLT led to an enhanced ductility in the infilled frame strengthened by CLT compared to the infilled frame due to transferring a part of loading from the masonry infill to the CLT panel. However, regarding the bare frame, adding CLT panels might not result in ductility increment, as shown in the case of the bare frame strengthened by CLT with connection II and IV. Nevertheless, there are other definitions for ductility that may be accompanied by increasing these amounts.

5.3 Energy dissipation

In order to have better comparisons between all frames under cyclic loading, in terms of energy dissipation, the accumulated energy versus displacement was calculated from base shear versus top displacement (Figure 8-11) and presented in Figure 14. According to Figure 14 (a), energy dissipation of the bare frame strengthened by CLT with connections I-IV is 1.6, 4.4, 3.1, and 3.4 times higher than that of the bare frame, respectively. In addition, Figure 14 (b) shows that energy dissipation of infilled frame strengthened by CLT with connections I-IV is respectively 1.3, 2.2, 1.9, and 2 times of infilled frame. The direct result is the seismic efficacy of CLT panels as a renovation of infilled RC frames. On the other hand, for comparing the effect of masonry infill in dissipation, energy dissipation of infilled frame and infilled frame strengthened with CLT with connections I-IV (Figure 14 (b)) are, respectively, 95%, 57%, 0%, 18%, and 15% larger than those of bare frame in Figure 14 (a). As a matter of fact, while masonry infills contribute to increasing energy dissipation of bare frames, there are not as efficient as adding CLT panels to bare frames.



(a) (b)

Figure 14: Accumulated dissipated energy considering all connections, (a) Bare frame and bare frame strengthened by CLT; (b) Infilled frame and infilled frame strengthened by CLT

6 CONCLUSIONS

In the present study, the seismic resistance of masonry-infilled RC frames retrofitted with CLT panels was evaluated. A collection of previous experimental tests on RC frame, masonry infills and connections was considered for calibrating finite element models that comprise four distinct connection techniques. The numerical simulations performed allowed to draw the following remarks:

- Adding a CLT panel increases the frame's load-carrying capacity, accompanied by an increment of the initial stiffness and post-yielding stiffness. However, in spite of the lessening pinching effect, stiffness and strength degradation, which is widely found in masonry-infilled frames, does not change considerably;
- Connections play a critical role in the post-yielding behavior of frames. An essential part of energy in cyclic loading is dissipated by these joints. The simulations showed a connection with lower load-carrying capacity and cheaper might result in better seismic behavior, mainly depending on joints' geometry;
- Regarding the ductility factor, defined by FEMA 2004, adding CLT panels does not always result in a ductility increment for bare frames, in opposition to what was expected. However, the ductility of infilled frames might be increased by adding CLT.
- Due to the first nonlinearity and failure observed in the structure by infill, along with the elastic behavior of CLT panels and high load-carrying capacity of connections in the post-elastic range, it can be concluded that CLT panels make much more contribution than masonry infills to energy dissipation under cyclic loadings.

Finally, it seems clear that CLT panels can be used as a strengthening measure that improves the seismic response of RC structures. However, it is crucial to develop connections able to ensure accurate performance, as the existing ones were not designed for this particular application.

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