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# IMPACT OF RETROFIT OF RC FRAMES BY CLT PANELS AND FRICTION DAMPERS

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**Abstract**

*In Italy, as well as in other earthquake-prone countries, most buildings have been erected without considering the effects of seismic excitation or according to obsolete seismic design provisions. Furthermore, they also suffer from significant structural deficiencies because of the low mechanical characteristics or the natural decay of the materials. The seismic vulnerability of the existing building stock is a serious economic and social concern and the need for retrofitting or rebuilding grows as time progresses. In this framework, this study investigates a newly developed retrofit technique for buildings with RC framed structure. The intervention is realized by means of Cross-Laminated Timber (CLT) panels placed over the exterior walls and connected to the RC structure by friction dampers. The CLT panels provide the existing structure with additional lateral stiffness and strength. The role of the friction dampers is twofold. On one hand they cap the internal forces of CLT panels, thus controlling the reaction forces transmitted to the existing structure and avoiding the failure of CLT panels themselves. On the other, friction dampers dissipate part of the input earthquake energy. The effect of these multiple features could reduce the storey drifts demanded by the earthquake to values compatible with the structure capacity.*
*This paper aims at sounding the impact of the proposed retrofit solution on the response of the RC framed structure to be upgraded. To this end, a one storey RC frame representative of existing RC framed structures designed considering only gravity loads is upgraded by a CLT panel and friction dampers of usual size. The impact of the retrofit intervention is investigated in terms of the achieved increase of stiffness, strength and energy dissipation capacity. The bare RC frame and the frame equipped with CLT panel and friction dampers are modelled in OpenSEES environment. Hence, the nonlinear responses of the two frames are assessed by monotonic and cyclic pushover analyses and the comparison between the results obtained for the bare and the upgraded frame quantifies the expected impact of the proposed retrofit intervention.*

**Keywords:** Existing buildings, RC framed structure, seismic retrofit, CLT, friction dampers.

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## 1 INTRODUCTION

In European seismic countries – such as Italy, Greece, Bulgaria, Turkey, Romania and the Balkan peninsula [1] – the building stock designed without anti-seismic criteria or according to old seismic standards is extremely wide, including mainly masonry or Reinforced Concrete (RC) framed buildings. For instance, in Italy, over 55% of the existing residential buildings was built before the 1970s [2], when seismic regulations were not in force and only gravity loads were considered at the design stage. Moreover, these buildings are over 50 years old, which means that they have reached their nominal service life, exhibiting structural deficiencies mainly due to the naturally decay of the materials originally used.

In this framework, seismic upgrading of the existing buildings is strongly needed, in order to ensure a higher level of safety for inhabitants, meanwhile to reduce the economic losses and environmental harm which could be caused by the damage or collapse of buildings in the event of earthquakes.

With reference to RC framed structures, the current seismic upgrading techniques are aimed at increasing the strength, stiffness, and ductility capacity of the structure and/or reducing the seismic demand. The most common techniques include the strengthening of the existing structural members by traditional materials (i.e. steel, concrete) or innovative ones (fibre-reinforced polymer, textile-reinforced mortar), as well as the addition of new RC shear walls or steel-braced frames. Other techniques include the installation of base isolators or energy dissipation devices. The main drawbacks that limit the wide applicability of these techniques are the excessive costs and time for implementation as well as the high occupants' disturbance. In fact, common strengthening techniques require the temporary downtime of the building and considerable demolition and reconstruction actions, which may affect up to 70-75% of the total construction costs in a new building [3]. Instead, the addition of a new seismic-resistant system requires relevant enlargements and reinforcement of the foundations and is not always possible if located externally to the building.

In order to overcome these drawbacks, newly seismic retrofit techniques need to be investigated, which can be able to meet the current needs of cost-effectiveness, quick installation and reduced users' disturbance. To this purpose, the use of Cross Laminated Timber (CLT) has been recently investigated as an alternative and sustainable solution to increase the seismic performance of the existing buildings, thanks to its high mechanical performance [4]. CLT is a plate-like engineered timber product, commonly composed of an uneven number of timber board layers, which are arranged crosswise to each other at an angle of 90° and quasi rigidly connected by adhesive bonding. The crosswise build-up provides the material high capacity of bearing loads both in-plane and out-of-plane, allowing its use for structural purpose [5].

Strengthening technique based on coupling the infill outer walls of the existing RC framed buildings by CLT panels has been investigated by Sustersic e Dujic [6-7], in view of an integrated retrofitting approach aimed also at increasing the energy efficiency of the buildings. Specifically, they proposed to realize the connection between the panels and the structure through special steel brackets, provided of ductility and energy dissipation capacity. The external application of CLT panels has been recently investigated also within the AdESA project [8], resulting in a real application on a case study characterized by a prefabricated RC structure. Stazi et al. [9] proposed CLT shear walls in replacement of the existing masonry infill walls. In particular, the results of preliminary numerical studies proved that CLT infills allows the RC frame to reach higher lateral stiffness and peak load values compared to common masonry infills. CLT infilled shear walls have been also analysed by Haba et al. [10], who investigated narrow CLT elements bonded to each other and onto the RC frame with epoxy resin, with potential results in terms of stiffness and ductility capacity according to the experimental activities conducted. Then, the use of post-tensioned, dissipative, and re-centering rocking CLT walls located in the external perimeter of the building has been investigated by Sandoli et al. [11]. In this work, nonlinear analyses on a case study showed the considerable effectiveness of this intervention in terms of seismic capacity increase, even using a small number of CLT walls with limited size.

The research on the topic of seismic upgrading of RC frame structures through strengthening CLT panels is still ongoing, and further studies are needed. Additional investigations on connection systems between the CLT panels and the existing structure are also required, in order to make this renovation solution concretely and widely applicable [12]. In this framework, this study investigates an innovative seismic retrofit technology (named e-CLT) for RC framed buildings based on the use of CLT panels placed over the exterior walls and connected to the structure by means of friction dampers [13]. This solution is currently under development within the ongoing multidisciplinary Horizon 2020 innovation project, called e-SAFE (energy and Seismic AFfordable rEnovation solutions), aimed at investigating innovative and combinable integrated retrofitting interventions. In this work, the impact of the e-CLT retrofit intervention on the response of the RC framed building structures is investigated, referring to existing structures designed considering only gravity loads. In the following sections, first the proposed retrofitting system is presented focusing on its components, mechanics, and installation. Hence, a RC frame is designed according to old building regulations and from this a set of single-storey frames with and without e-CLT is derived. The aim is to analyse the seismic response of RC frames upgraded by the e-CLT system, considering the number of CLT panels and friction dampers applied, as well as the contribution/presence of infill walls.

## 2 SEISMIC UPGRADING BY e-CLT SYSTEM

The e-CLT system is aimed at reducing the drifts demanded by earthquakes and improving the seismic performance of the building for the expected levels of seismic excitation. It consists in the application of CLT panels on the outer side of the existing walls, by connecting them to the RC structure through friction dampers (Figure 1a). The system is conceived so that in occurrence of moderate ground motions, the dampers rigidly connect CLT panels to the RC structure, thus making available additional lateral stiffness and strength that reduce drifts and may protect non-structural elements. Conversely, dampers activate in occurrence of stronger ground motions, thus dissipating part of the input seismic energy. This further resource of the system activated at this seismic excitation level, after cracking of non-structural elements, reduces the damage of structural components and protect the building from collapse. Furthermore, the activation of the dampers defines an upper bound to the force sustained by the CLT panels, thus preventing their failure even under strong ground motions. The installation of CLT panels from the outside of the building minimizes the occupants' disturbance, while maintaining the building operativity.

The mechanical characterization of the proposed friction damper is currently under investigation within the e-SAFE project [14]. The damper is basically made by two steel profiles, which connect the CLT panels of two consecutive floors to the existing interposed RC beam (Figure 1a). One profile (named "anchor profile") is connected to the RC beam by anchor bolts and to the other profile (named "free profile") by slotted holes and pretensioned high-strength bolts. Common timber screws connect both the steel profiles to the CLT panels. The shear force is transmitted from the free to the anchor profile by means of the friction exerted in the contact surface. During an earthquake, when the force transmitted by the damper attains the value of the friction force, the free profile slides on the anchor one and thus dissipates seismic energy (Figure 1b).

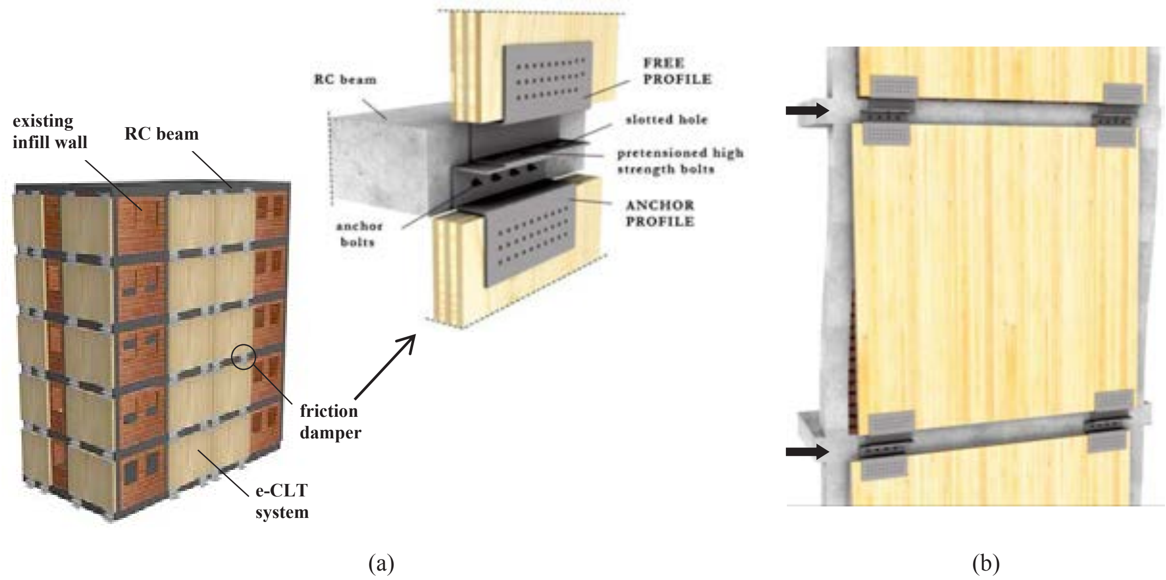



Figure 1: (a) e-CLT system and (b) behaviour of e-CLT system under seismic loads

The e-CLT system is designed also to allow a quick and easy external installation, which can be performed by means of a mobile lifting equipment (cranes, aerial platforms, etc.), proceeding to apply panels from the ground floor to the top of the building. In particular, the anchor profiles of each damper can be pre-assembled on the top of CLT panels off-site, in order to connect directly the panels to the existing RC beams through chemical anchors.
Moreover, the e-CLT system is designed to be combined with energy-efficient solutions, in view of an integrated (seismic and energy) approach to the buildings renovation. More details can be found in [15].

## 3 CASE STUDY

The case study is a one storey, three-bay RC frame having net height and net width of 3.2 m and 11.1 m, respectively. The columns have cross-section of 30x30 cm and are reinforced by four rebars with diameter of 14 mm, while the beams have cross-section of 30x50 cm and are reinforced by nine rebars with the 14 mm diameter. Both columns and beams have been designed according to the regulations in force in Italy during the 1970s, as well as the construction practices of that period. In particular, the cross-sections size and the steel reinforcements area of the frame members have been designed by means of the allowable stress method [16], considering gravity loads only. Columns have been designed to resist only to axial force, that was evaluated on the assumption of a 4-storey RC frame.

Steel grade Feb38K with a characteristic yield stress $f_{yk}$=375 MPa is assumed for rebars, while the characteristic compressive cubic strength $R_{ck}$ of concrete is assumed equal to 20 MPa (corresponding to cylinder strength $f_{ck}$ equal to 17 MPa).

The case study frame has been analysed considering both the bare and the infilled configuration. Specifically, the infill wall has been assumed made of two leaves of hollow clay bricks (8-cm and 12-cm thick, internally and externally respectively, with an intermediate air cavity), according to the construction techniques used in Southern Italy between the 1950s and 1980s.

Window openings in the infill walls have been considered according to two layouts. In the first and the second layout, openings are assumed in the two lateral bays and in the central one, respectively.

The impact of the e-CLT system on the seismic response of both bare and infilled case study frame has been investigated, considering two different configurations of the seismic retrofit system (configurations 1 and 2 in Figure 2). Specifically, configuration 1 (Figures 2a, c) involves the application of a single CLT panel to the central bay of the frame, while in configuration 2 (Figures 2b, d) the RC frame is retrofitted by 2 CLT panels applied to the lateral bays of the frame.

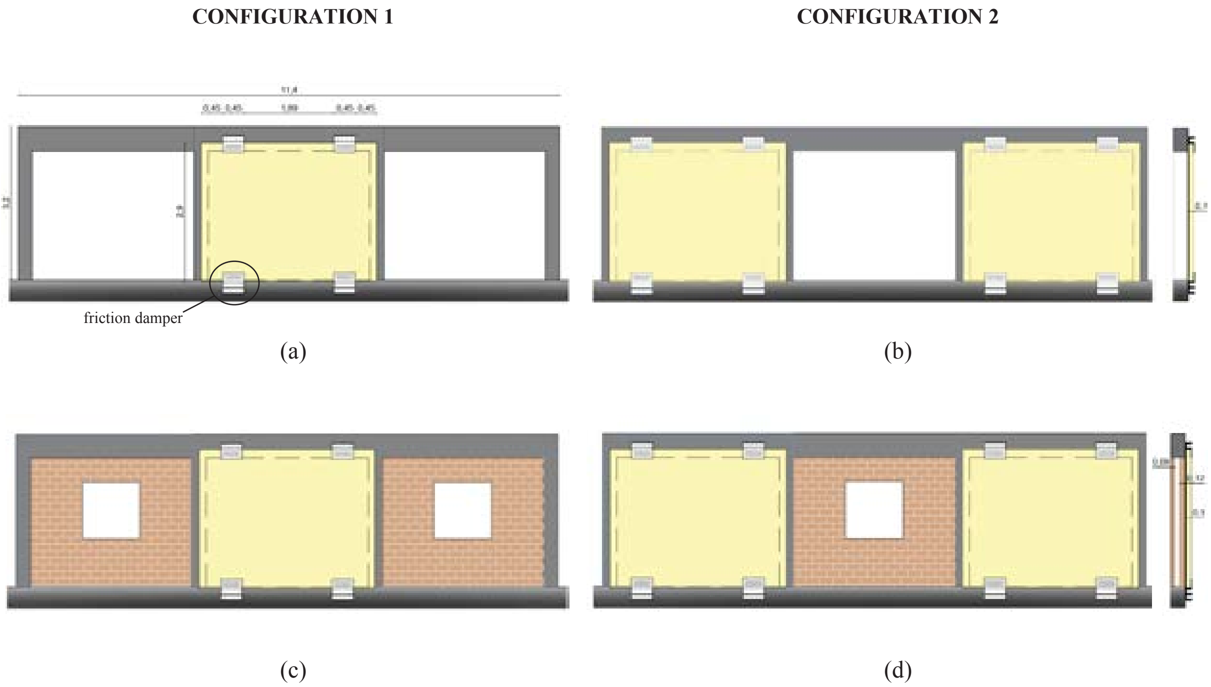



Figure 2: Investigated configurations of the e-CLT retrofitting intervention on the case study frame: (a) bare and (c) infilled frame with e-CLT in configuration 1; (b) bare and (d) infilled frame with e-CLT in configuration 2.

In both configurations, 10-cm thick, 3-ply CLT panels made of C24-class boards are assumed. Each CLT panel is 2.9-m high and 3.7-m wide and is connected to the RC beam by means of two anchor profiles arranged on its top. Two friction dampers connect the bottom of each CLT panel to the foundation of the RC frame. The friction dampers are 450-mm wide and 8-mm thick and are arranged symmetrically each other, at a distance of 0.45 m from the side edge of the panel.

## 4 NUMERICAL MODELLING

A numerical model has been implemented in OpenSees environment, in order to analyse the nonlinear response of the investigated RC frame at pre- and post-intervention state, considering the configurations described in Section 3.

Figure 3 shows the numerical model schema, referring to a single infilled bay of the case study frame, equipped with CLT panel and friction dampers. The detailed description of the parts the numerical model (RC frame, CLT panel, friction damper and infill) is reported in the following Sections.

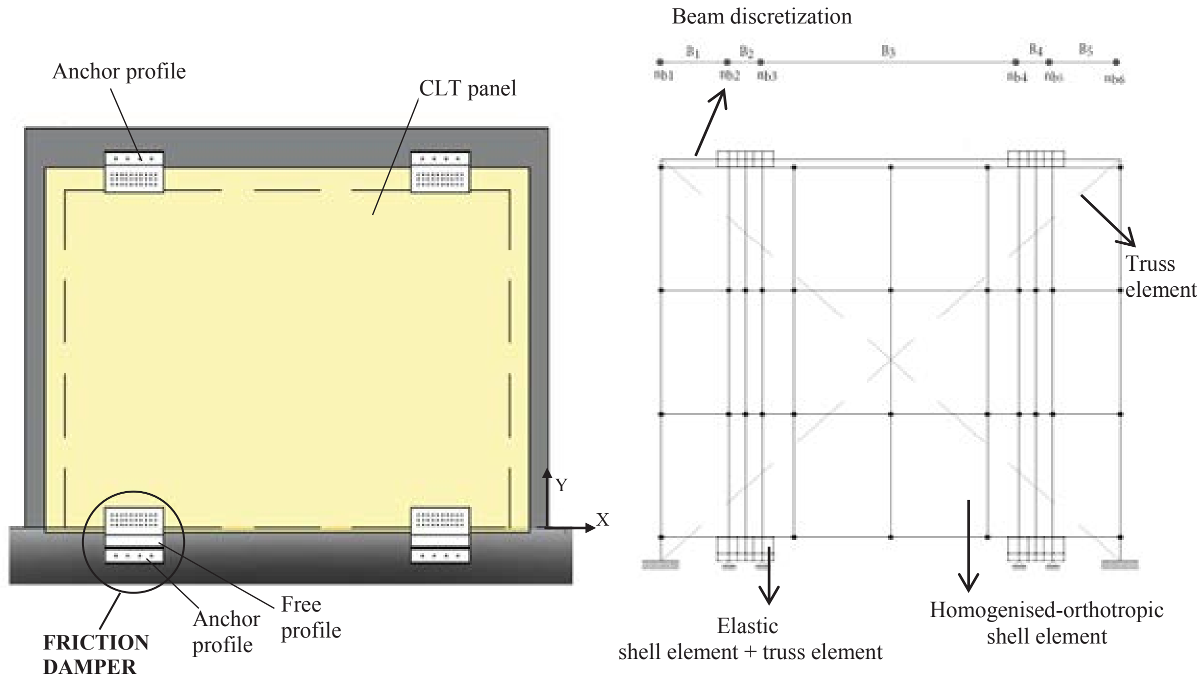



Figure 3: Numerical model schema, referring to a single infilled bay of the case study frame at post-intervention state.

## 4.1 RC frame

Beams and columns of the RC frame have been modelled differently. Specifically, the "beamWithHinges Element" is used for columns. This element consists in a member with a linear-elastic region in the middle and plastic hinges at its ends. The length of the plastic hinges is equal to the depth of the column cross section. Instead, beams where the CLT panels are fixed at post-intervention state are discretized in five elements (elements $B_1$-$B_5$ in Figure 3). The intent was to locate along each beam four intermediate nodes (nodes $n_{b2}$, $n_{b3}$, $n_{b4}$ and $n_{b5}$ in Figure 3) to connect the beam and the two anchor profiles. The two lateral beam portions (elements $B_1$ and $B_5$) and the central one (element $B_3$) are modelled by the "nonlinearBeamColumn Element", a nonlinear force-based beam-column element able to replicate the spread of plasticity along the member. Three and five Gauss integration points are assigned to the lateral and central portions of the beam, respectively. Whereas, the "elasticBeamColumn Element" is used to model the beam portions $B_2$ and $B_4$, assuming that plastic hinges form outside of the damper length. Instead, the beams belonging to the span without CLT panels are modelled by nonlinear force-based beam-column elements, with five Gauss integration points.

A fibre cross section is assigned to each plastic zones of nonlinear RC members, considering both the concrete part and steel rebars. The concrete part is dived into fibres having constant 5-mm depth, to which the Mander constitutive law ("Concrete 04" uniaxial material) is assigned. Instead, single fibres enclosed in the cross section are used to model the steel rebars. In particular, an elastic-plastic material with isotropic strain hardening ("Steel 02" uniaxial material) is assigned to steel rebars. The parameters used for the two materials are summarized in Table 1.

| Concrete | |
|---|---|
| Average compressive strength | 25 MPa |
| Strain at maximum strength | 0.002 |
| Strain at crashing strength | 0.0035 |
| Young's modulus | 31,500 MPa |
| **Rebars** | |
| Average yielding strength | 380 MPa |
| Young's modulus | 200,000 MPa |

Table 1: Material properties of RC frame members.

## 4.2 CLT panel

The 3-ply CLT panel (layers thickness: 30-40-30 mm) is modelled as an assembly of 10-cm thick "MITC4 Shell Elements", as shown in Figure 3. In order to model the multi-layer panel layout, an orthotropic and homogenized material is assigned to the cross section of each shell element, according to the reduced cross section method proposed in [17]. This method is based on the reduction of a multi-layer material into a single-layer one by means of specific composition factors, assuming a plane stress state of the timber panel. This assumption is widely adopted to define the material properties of CLT for the needs of seismic modelling, when building nonlinear behaviour is mostly localized in connections [6,18].

The material properties of the homogenized CLT material are reported in Table 2 and are based on the mechanical characteristics of C24-class spruce wood, according to EN 338 [19]. The value of shear modulus was reduced to 500 MPa since generally CLT panels are not glued on their narrow face. For the same reason, the value of Poisson's ratio has been set equal to 0.0 [20].

| CLT | |
|---|---|
| Perpendicular-to-grain Young's modulus ($E_{wx}$) | 4622 MPa |
| Parallel-to-grain Young's modulus ($E_{wy}$) | 6748 MPa |
| Perpendicular-to-grain Young's modulus ($E_{wz}$) | 370 MPa |
| Shear modulus | 500 MPa |
| Poissont's ratios | 0.0 |
| Density | 420 kg $m^{-3}$ |

Table 2: Material properties of CLT panel.

## 4.3 Friction damper and connection elements

As shown in Figure 1a, the proposed friction damper is made by two steel profiles (i.e. anchor and free profile), which mainly consist of a middle web and two side flanges. The "ShellMITC4 Element" and the "Truss Element" are used to model both these components. Specifically, the web of each profile is modelled by five 8-mm thick shell elements (Figure 3), while the flanges are modelled by truss elements (8-mm thick and 100-mm depth) which connect the edge nodes of the above-mentioned shell elements. An elastic material is assigned to web and flanges of the steel profiles, assuming that they do not yield. The Young modulus of steel ($E_s$=210.000 MPa) is considered for the assigned material.

A "zeroLength Element" is used to connect the adjacent nodes of the anchor profile and "free profile" of each friction damper. In the X direction, an elasto-plastic material with strain kinematic hardening constitutive law ("Steel01" uniaxial material) is assigned to each element, in order to model the sliding movement of the upper profile when the shear force attains the value of 30 kN. In the Y direction, two of these elements are characterized by a large stiffness, in order to simulate the pretensioned high strength bolts that connect the two steel profiles.

Then, "Two Node Link Elements" are used to model the connection between the friction damper and CLT panel by means of timber screws. An elastic material is assigned to each element, whose stiffness is calculated in accordance with the Eurocode 5 [21] assuming the use of 30 screws for each damper.

The same modeling is used for the anchor profiles on the top of each CLT panel, using "zeroLength Elements" with large stiffness to connect the web to the RC beams, in order to simulate the connection by means of chemical anchors.

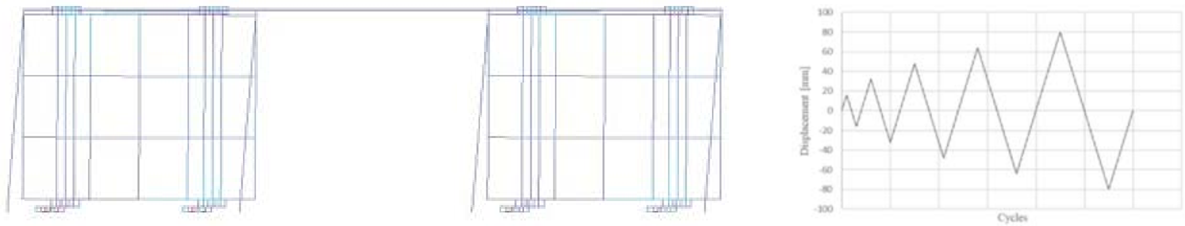
### 4.4 Infill wall

The infill walls are modelled by a pair of diagonal "Truss Elements", which connect the top of each column with the bottom of the subsequent one (Figure 3). These elements are supposed to have no tension resistance and their force-displacement relationship is calibrated to replicate the shear force-drift relationship of the infill panel, as proposed by Panagiotakos and Fardis [22] and Celarec et al. [23]. This relationship consists of four branches: a first elastic branch up to the first cracking of panel, a second branch with a lower stiffness up to the complete cracking of panel, a degrading branch and a last branch with a residual resistance. The stiffness and the value of the maximum force of each branch are determined according to the equations proposed in [23]. The multi-linear force-displacement relationship thus obtained is then converted into an equivalent stress-strain relationship. The values of stress and strain corresponding to the three corners of the envelope are assigned to the truss member by means of the "Hysteretic" uniaxial material implemented in OpenSees. The force-displacement relationship is first determined for the infill without openings assuming that it is 20-cm thick, as reported in Section 3, the shear cracking strength is equal to 0.28 MPa, while Young modulus and shear modulus are equal to 4130 and 1240 MPa, respectively. The ordinates of this force-displacement relationship have been reduced to 50% for the infill with openings. These relationships define a layout of infills with high mechanical properties. Other two infill layouts are defined reducing the ordinates of the force-displacement relationships of the first layout to 80% and 60%, in order to represent infills with lower mechanical properties and/or window openings having larger size.

## 5 ANALYSES AND RESULTS

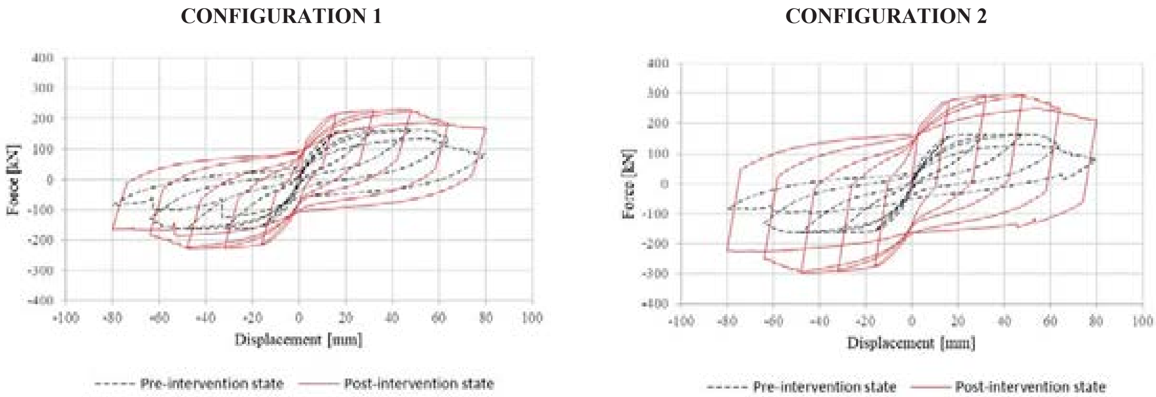
Monotonic and cyclic pushover analyses in displacement control have been carried out both on bare and infilled RC frame at pre- and post-intervention state (Figure 4a). First, a vertical load of 292.5 kN has been applied at the top of the two central columns, a vertical load of 146.25 kN at the top of the two lateral ones, and a uniformly distributed load of 26 kN has been applied on each beam. These loads are consistent with those used to design the frame.

The top horizontal displacement corresponding to the near collapse limit state of the bare RC frame is determined by monotonic pushover analysis. In this case, the top horizontal displacement is increased until in one column the chord rotation has attained its ultimate value determined according to Eurocode 8 – part 1-3 [24]. The cyclic pushover analysis is performed for all the considered frames. The applied top horizontal displacement is cycled according to the loading protocol reported in Figure 4b, where the maximum amplitude is equal to the top displacement corresponding to the near collapse limit state of the bare RC frame. The hysteretic responses of bare and infilled frame are shown in Figures 5 and 6, respectively. Specifically, the seismic response of the masonry infilled frame has been investigated assuming the three different levels of quality of masonry infill, i.e. mechanical properties equal to 100%, 80% and 60% of the reference infill defined in Section 4.4.




(a) (b)

Figure 4: (a) Cyclic pushover analysis on bare RC frame equipped with e-CLT in configuration 2 and (b) cycling loading protocol.




(a) (b)

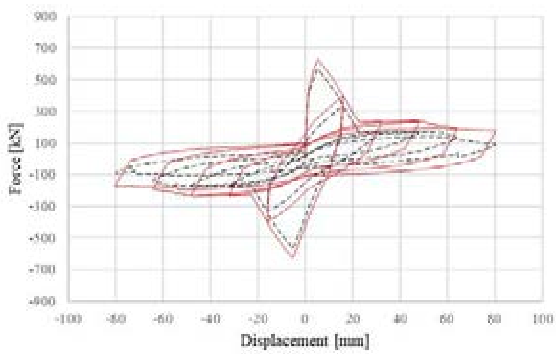
Figure 5: Hysteretic responses of the investigated bare frame at pre- and post-intervention state, with e-CLT system in (a) configuration 1 and (b) configuration 2.

The impact of the retrofit by e-CLT system on the seismic capacity of the case study frames has been investigated in terms of the achieved increase of lateral strength, stiffness, and energy dissipation capacity. The lateral strength is assumed equal to the maximum horizontal force sustained by the system during cyclic loading. The lateral stiffness is calculated as the ratio of the lateral strength to the corresponding displacement. Finally, energy dissipation capacity is quantified as the energy dissipated during cyclic loading, which is calculated as the area enclosed by the hysteresis loops.

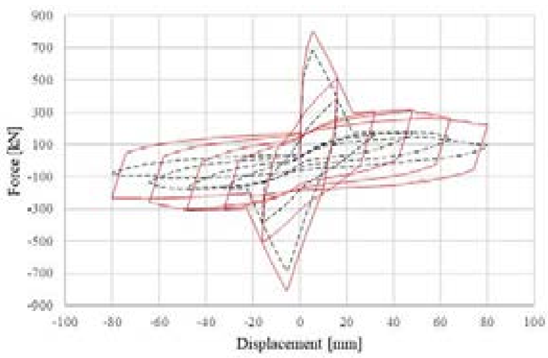
The hysteretic responses of the bare frame at pre- and post-intervention state (Figures 5a, b) show a considerable increase of the seismic capacity after the application of the e-CLT system. In particular, the lateral resistance of the structure upgraded by the e-CLT in configurations 1 and 2 reaches the values of 231 kN and 300 kN. Compared to the lateral strength of 165 kN at pre-intervention state, the achieved percentage increase is 40% and 82% for configurations 1 and 2, respectively. Furthermore, the application of a single CLT panel equipped with two friction dampers (configuration 1) provides the RC frame with an increase of lateral stiffness and energy dissipation capacity of 93% and 128%, respectively. Instead, by adding two CLT panels and four friction dampers (configuration 2) the stiffness of the structure increases of 165%, while the energy dissipation capacity of 275%.

**CONFIGURATION 1** **CONFIGURATION 2**

Values of masonry infill at 100%, high mechanical properties

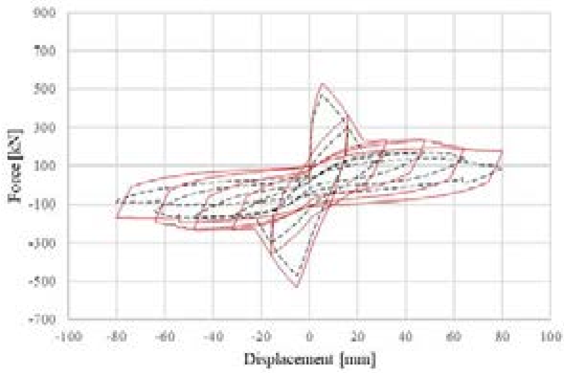



(a)

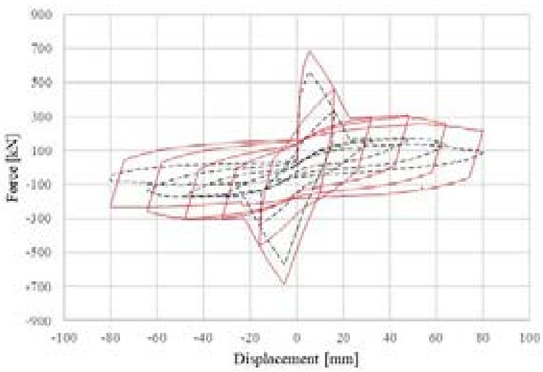



(b)

Values of masonry infill at 80%, intermediate mechanical properties

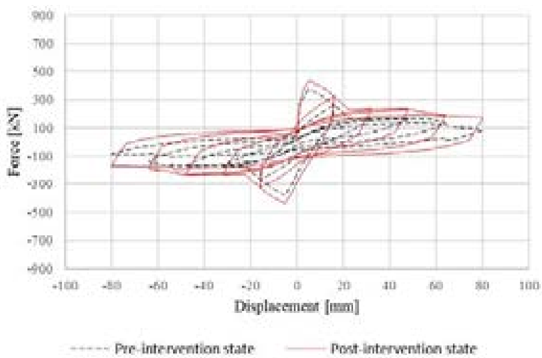



(c)

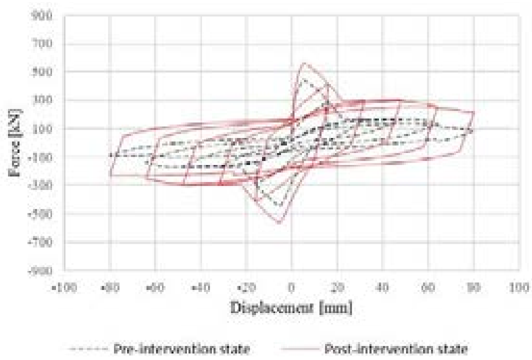



(d)

Values of masonry infill at 60%, low mechanical properties




(e)




(f)

Figure 6: Hysteretic responses of the investigated infilled frame at pre- and post-intervention state, with e-CLT system in (a-c-e) configuration 1 and (b-d-f) configuration 2, assuming the mechanical characteristic values of the masonry infill at: (a,b) 100%; (c,d) 80%; (c,d) 60%.

The impact of the e-CLT system on the capacity of infilled frames (Figure 6) is less remarkable, because the infills make the frame stiffer and stronger, and significantly depends on the capacity parameter. As showed by the comparison of the hysteretic responses of the infilled frame at pre- and post- intervention state, the application of CLT panels determines a negligible increase of the lateral stiffness, regardless of the mechanical properties of infills.

The increase of lateral strength is also low, with higher percentage increase for infills with low mechanical properties (increase of 16% and 26.3% in configuration 1 and 2, respectively). However, the introduction of the e-CLT still leads to a significant increase of the lateral residual strength of the RC frame after the infill failure and even a more remarkable increase of energy dissipation capacity. The percentage increase of lateral residual strength achieved by the retrofit with e-CLT in configuration 1 and 2 is about 38% and 77%, respectively. Finally, the percentage increase of energy dissipation capacity achieved for infills with high, intermediate and low mechanical properties is 82%, 89.5% and 98.5% after the application of the e-CLT in configuration 1 and 146%, 162.7% and 182.6% in configuration 2.

## 6 CONCLUSIONS

This paper investigates the potential impact of an innovative seismic retrofit technology on the response of RC framed structures. This technology, named e-CLT system, consists in the application of CLT panels on the outer side of the existing walls, by connecting them to the RC structure through innovative friction dampers. The friction damper is still under development and here it is idealised with a connection with rigid-plastic cyclic behaviour. The results reported in this work evidence the potential of the e-CLT system in enhancing the seismic performance of existing RC framed buildings considering different features of the buildings to be upgraded (with and without infill walls) and different importance of the retrofit solution (one or two CLT panels with dampers for the one storey, three-bay RC frame considered as case study).

Even the configuration with the single CLT panel, if applied to the bare RC frame, leads to a significant improvement of all the seismically relevant features of the building: lateral strength, stiffness and energy dissipation capacity. In this case, the largest impact is on energy dissipation capacity. Significant is also the impact on lateral stiffness. However, when the e-CLT system is applied to infilled frames, even considering the solution with two CLT panels, the impact on the lateral stiffness is minor. Instead, the improvement achieved in terms of increase of energy dissipation capacity remains significant: for instance, even in the case of the stiffest and strongest considered infill, it was found equal to 82% and 146% for the configurations with one or two CLT panels, respectively. The increase of lateral strength of the infilled frame provided by the e-CLT system is fair.

Based on these results, the e-CLT system appears to be a promising tool for seismic upgrading of RC framed buildings. Its effectiveness is expected to be great in fulfilling the Near Collapse performance objective, which relies mostly on energy dissipation capacity of the structure. Instead, when the improvement of seismic performance is mainly related to the increase of lateral stiffness, as in the case of damage limitation performance objective, the effectiveness of the-CLT system could be limited when it is applied to infilled frames. In the future, more comprehensive investigation will be performed, based on the experimental mechanical characterization of the proposed friction damper. Furthermore, the effectiveness of the e-CLT system will be also investigated by multi-storey numerical models.

## ACKNOWLEDGEMENTS

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