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EXPERIMENTAL AND NUMERICAL ASSESSMENT OF AN IMPROVED PLYWOOD-BASED IN-PLANE RETROFITTING METHOD FOR TIMBER FLOORS IN HIGHLY SEISMIC AREAS

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Abstract

Wood-based retrofitting techniques for seismic upgrading and architectural conservation of existing buildings have found increasing application in the last decades. With reference to the in-plane seismic strengthening of existing timber floors, a particularly efficient solution consists of an overlay of plywood panels fastened to the sheathing. This technique allows a great improvement in strength, stiffness, and energy dissipation of the floors. Yet, when adopting this strengthening solution for existing floors in highly seismic regions, the target design loads could require large values of in-plane strength and stiffness for the retrofitted diaphragms, and this could cause their beneficial, dissipative potential to be reduced. Thus, in this work, a strengthening solution is presented, able to retrieve high strength and at the same time activate large energy dissipation in the floors. The proposed technique consists of the creation of two independent shear planes by means of two different superimposed overlays of plywood panels. Previously developed analytical and numerical models describing the in-plane response of floors retrofitted with a single plywood overlay were adapted for the present case with two overlays, validating the results against an experimental test conducted on a sample representing a floor portion. Very good agreement was obtained between experimental and analytical as well as numerical results, thus the proposed approaches enable an efficient design process and an accurate simulation of the proposed retrofitting technique.

Keywords: Timber floors, Plywood Panels, Seismic Retrofitting, Existing Buildings, Numerical modelling.

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1 INTRODUCTION

In several architectural contexts all over the world, unreinforced masonry (URM) structures featuring timber floors as horizontal elements, constitute a large part of the building stock. Numerous seismic events have highlighted the vulnerability of URM buildings to earthquakes, mainly due to poor-quality masonry, excessive in-plane flexibility of timber floors, and absence of effective connections among structural elements.

In this framework, several retrofitting methods for timber diaphragms [1]-[14] and timber-masonry connections [15]-[20] have been developed in the recent years, progressively focusing on more reversible techniques [21],[22]. With regard to the floors, the main proposed and tested retrofitting methods consisted of the traditional cast of a concrete slab on the existing sheathing, a widely adopted retrofitting in the last decades [1],[6]; the superposition of a second layer of planks arranged at 45° [1]-[4] or 90° [6],[7] with respect to the existing sheathing; the bracing of the floors with steel plates [1],[3],[4] or fibre reinforced polymer (FRP) laminae [1],[6]; the overlay of cross-laminated timber (CLT) [7],[8], oriented strand board (OSB) [8], or plywood panels [9]-[14]. Among these techniques, reversible ones are usually preferred because of their lower impact on existing buildings, especially when they are monumental or protected. In particular, the overlay of plywood panels on the existing sheathing has proved to be a valid and versatile strengthening method, as demonstrated by several investigations and applications in different contexts, e.g. in the United States [10],[12], New Zealand [9],[12],[13], the Netherlands [14],[23]-[27], and Italy [28],[29].

When considering highly seismic areas with more demanding requirements for the in-plane strength and stiffness of the plywood-retrofitted diaphragms, their beneficial dissipative effect, highlighted by several studies [12], [23]-[27], could be reduced. The in-plane strength and stiffness of the floors can be increased by means of e.g. lateral steel chords, thicker and more interlocked or blocked plywood panels, or fasteners in a larger number or with wider diameter. These design choices can strongly reduce the displacement capacity of the floor, and an excessive number of fasteners could also cause splitting of the existing wooden boards.

In this work, a simple method is proposed, allowing to achieve a large improvement in strength of the retrofitted diaphragms, while also keeping sufficient displacement capacity and, consequently, the possibility of activating large hysteretic energy dissipation. The proposed technique consists of the creation of two independent shear planes by means of two different superimposed overlays of plywood panels (Figure 1). The first layer, featuring smaller panels, is fastened directly to the existing sheathing; the second, with larger panels, is fixed to the sheathing through plywood boards surrounding each smaller panel. A small gap is left between the plywood boards and the smaller panel, enabling its free rotation and sliding.

With this strengthening method, the two overlays are not directly connected to each other, combining the strength of two plywood layers with an improved ductility linked to their independent movement. This solution of creating two separate shear planes proved to be very effective in the case of light timber shear walls [30], thus its application for the retrofitting of existing wooden floors was also investigated.

Previously developed analytical and numerical models describing the in-plane response of floors retrofitted with a single overlay of plywood panels proved to be accurate in predicting strength, stiffness and energy dissipation of such diaphragms [23],[25]. These models were adapted and used to simulate the present case with two overlays, validating the results against an experimental test conducted on a prototype sample representing a floor portion. Very good agreement was obtained between experimental and analytical/numerical results, and additional sensitivity analyses were also conducted, assessing the influence of fasteners diameter and plywood thickness.

2 MATERIALS AND METHODS

2.1 Materials

The principle for the execution of the proposed retrofitting method is shown in Figure 1. The plywood panels of the first overlay are fastened along their perimeter to the existing sheathing between two subsequent joists, with in-plane dimensions smaller than the joists' spacing. Most of the material resulting from the cut of these panels can then be used to create the interlayer between the existing sheathing and the second overlay (see Figure 1), leaving a small gap around the panels themselves, to enable their rotation during in-plane loading. The second overlay consists once more of plywood panels, fastened along their perimeter to the existing sheathing and the joists, through the previously placed interlayer made of plywood boards. Because of the modular structure of this retrofitting method, and accounting for its shear-related in-plane deflection, only a small, representative portion of the floor was selected for testing (Figure 1), resulting in the sample shown in Figure 2 along with its construction sequence.

As can be noticed, the prototype consisted of 100×18×500 mm planks, fastened to two 50×120×500 mm joists with two 3×65 mm nails at each end. The first, smaller plywood panel measured 380×380×18 mm, whereas the second had dimensions of 450×450×18 mm. For fastening the panels along their perimeter, 5×70 mm screws were used, in such a way that five screws for each side were present. With regard to material properties, the structural elements of the sample featured the following densities, referred to 12% moisture content:

- 530±58 kg/m^3 for the planks;
- 457±1 kg/m^3 for the joists;
- 511±10 kg/m^3 for the plywood panels.

Finally, the screws featured a characteristic yield moment $M_{y,k}$ = 8800 Nmm and a characteristic withdrawal-resistance parameter $f_{ax,k}$ = 15.5 MPa.

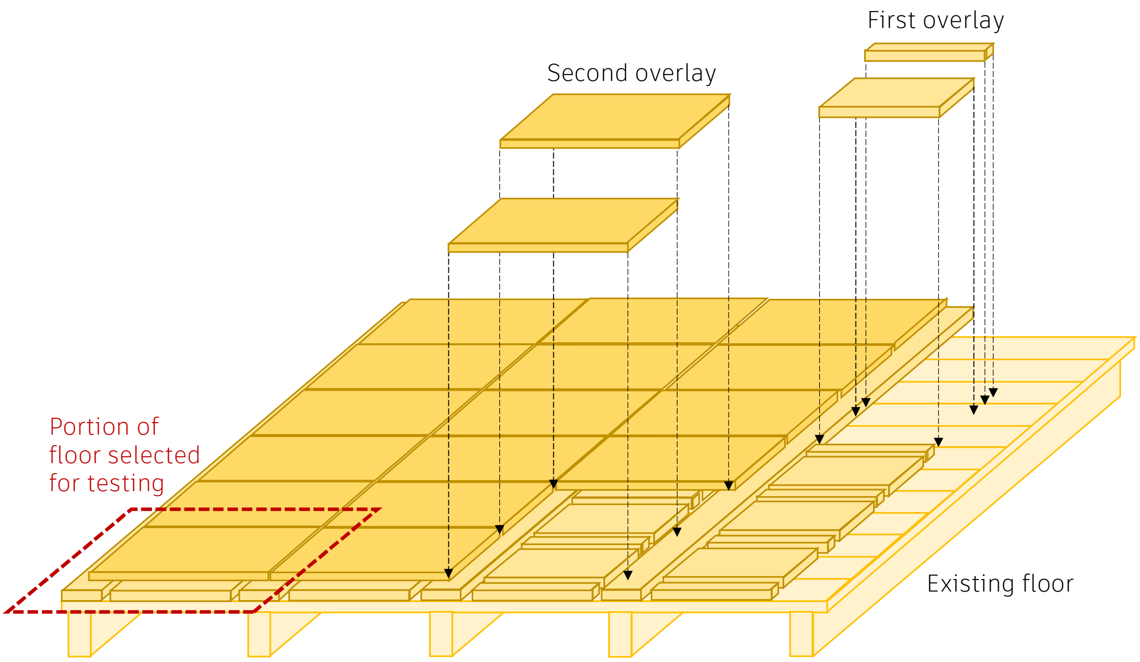

Figure 1: Principle for the execution of the double plywood panels overlay.

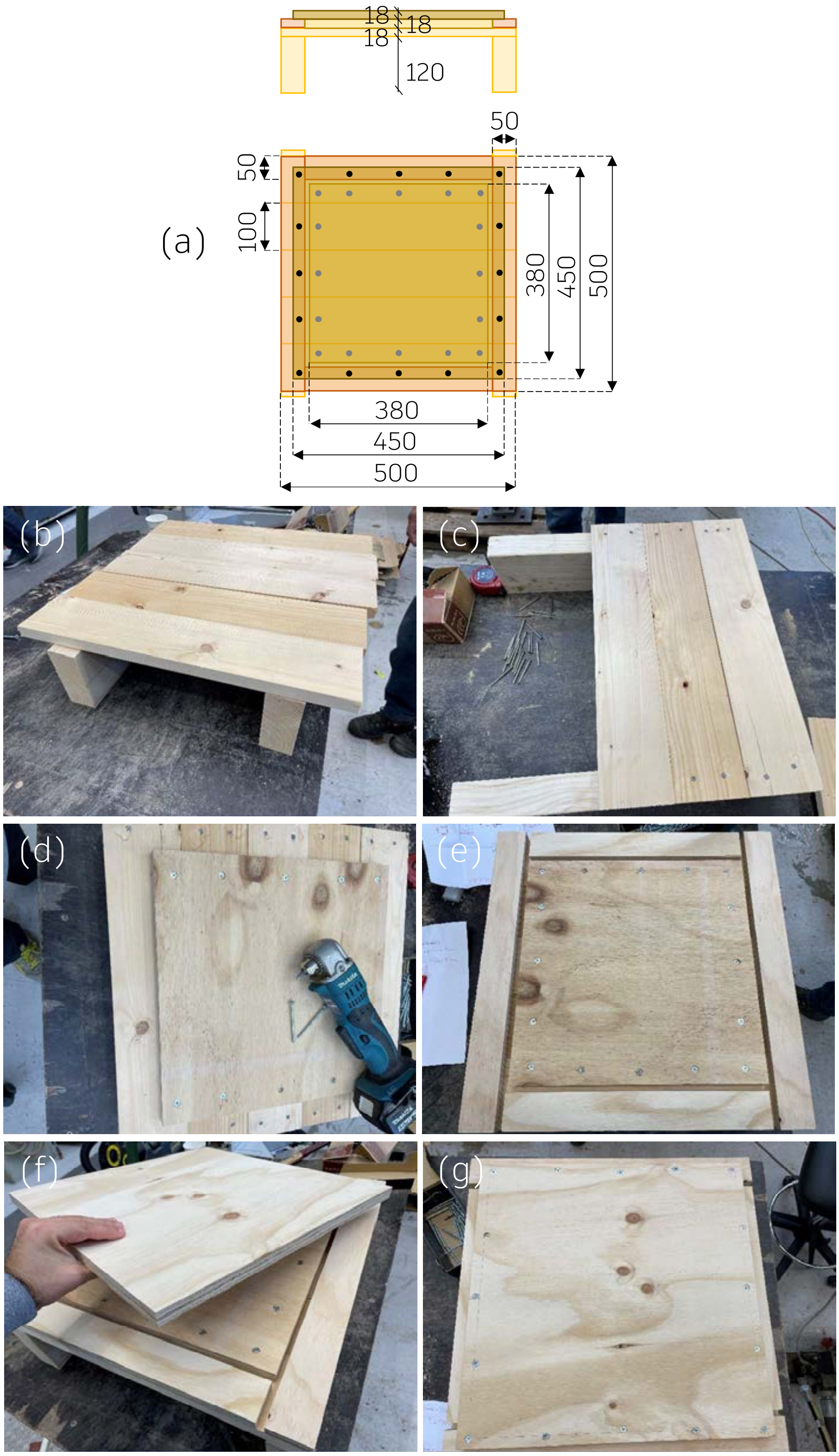

Figure 2: (a) Geometry and dimensions (in mm) of the tested prototype and construction sequence: (b) preparing joists and boards; (c) nailing the planks; (d) fastening the first plywood panel; (e) preparing the interlayer with plywood boards; (f) placing the second plywood panel; (g) fastening the second plywood panel.

2.2 Testing methods

The test setup adopted for the sample, shown in Figure 3, consisted of a compact steel frame to which the prototype and a hydraulic actuator (100 kN capacity, ±120 mm stroke) were fixed. To detect the in-plane displacements of the sample, two lasers and an additional sensor integrated in the actuator were placed. Additionally, digital image correlation (DIC) technique was adopted, thus the sample was provided with markers and a central reference pattern (Figure 3b). The DIC system consisted of two cameras, placed at 750 mm from the prototype, having a resolution of 4096×3000 pixels each. This allowed to detect the in-plane response of the sample in detail.

The specimen was subjected to displacement-based quasi-static cyclic tests following the loading protocol of ISO 16670 [31]. To this end, an ultimate displacement of 30 mm was assumed to derive the amplitude of each cycle, based on the analytical model presented in the following. The test was conducted at a constant displacement rate of 0.3 mm/s.

2.3 Analytical modelling

The adopted analytical model, also used for numerical implementation, was an extension of the formulation presented in [23],[25] to predict the in-plane response of the retrofitted diaphragms starting from the load-slip response of the single screws. This load-slip curve was modelled by means of a combination of a linear and a parabolic branch, representing the initial stiffness and the global behaviour, respectively [23]:

$$F_s = (F_0 + a\, d_s + b\, d_s^2)[1 - \exp(-K_0\, d_s/F_0)] \geq 0; \text{ with } a > 0,\ b < 0 \quad (1)$$

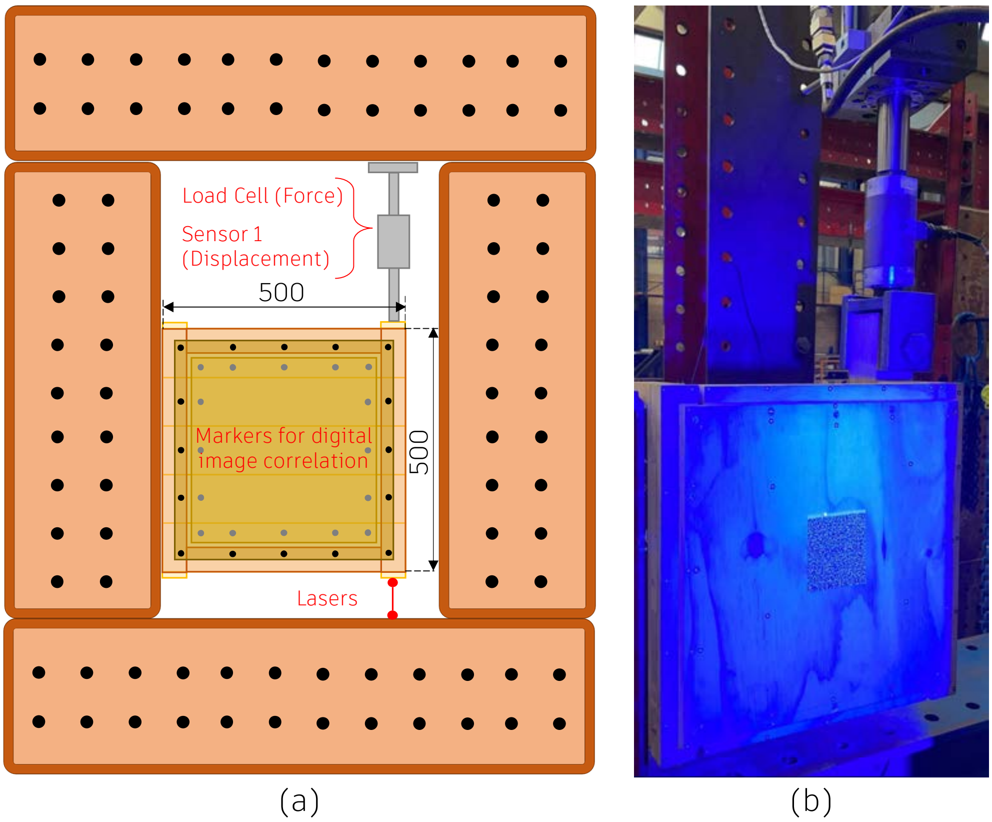

Figure 3: (a) Test setup used for the in-plane testing of the sample; (b) prototype in the setup while testing.

In Equation 1, F_s and d_s are the force and displacement of the screw, respectively; F_0, a and b are the coefficients of the parabola representing the global behaviour, while K_0 is the slope of the line representing the initial stiffness [23],[25]. As a failure criterion, in agreement with the provisions of ISO 16670 [31], the ultimate displacement was considered as the one for which the transferred load dropped below 80% of the peak strength during the softening phase.

All parameters of Equation 1 can be derived from tests on single screwed joints (see [23]), but can also be analytically determined. For the initial stiffness, the expression proposed in [32], i.e. $K_0 = 50\ d^{1.7}$, with d nominal diameter of the screw, can be adopted. F_0 can be predicted starting from the knowledge of the maximum force F_{max} determined according to EN 1995 [33] and Johansen's theory for timber-to-timber joints, and with a screw sufficiently slender to develop two plastic hinges. Then, F_0 can be estimated as $F_{max}/8$ [23],[25]. The remaining two parameters a and b, identifying the parabolic branch, have the following expressions: $a = 2(F_{max} - F_0)/d_{max}$ and $b = -(F_{max} - F_0)/(d_{max})^2$. In the former equations, d_{max} is the slip of the screw at F_{max}, estimated as $d_{max} = (b_1 + b_2)\tan(\alpha)$, with $(b_1 + b_2)$ distance between the two plastic hinges according to Johansen's theory [34], and α angle at which the yield moment of the screw is evaluated [35]. Based on the load-slip response of the single screw, the in-plane response of a whole retrofitted floor can be derived simply considering equilibrium relations [23],[25],[26].

This analytical model has shown very good agreement with previously reported experimental results on timber floors strengthened with a single overlay of plywood panels [14],[23],[25],[26]. The use of the presented formulation appeared thus to be promising for the prediction of the in-plane response of diaphragms retrofitted with the methodology proposed in this work. In fact, only one adjustment is needed, and namely in the expression for F_{max}. When the plywood panels are directly fastened to the sheathing (this is the case for the first overlay), the usual formulation from [33],[34] is adopted:

$$F_{max} = \sqrt{\frac{2\beta}{1+\beta}}\sqrt{2\ M_y f_{h,1}\ d} + \frac{F_{ax}}{4} \tag{2}$$

In Equation 2, M_y is the yield moment of the fastener, d its diameter, and F_{ax} its withdrawal strength; $f_{h,1}$ is the embedment strength of the sheathing, and $\beta = f_{h,2}/f_{h,1}$ is the ratio between the embedment strength of the plywood overlay and that of the sheathing.

When, instead, the second overlay is considered, the screws connecting the panels to the sheathing now also cross the interlayer made of plywood boards. This interlayer does not contribute to the shear strength, and constitutes in fact an interposed gap between the second overlay of plywood panels and the sheathing. This effect corresponds to a reduction of the distance b_1 of the plastic hinge in the sheathing from its interface with the interlayer. Thus, because of the presence of this interlayer (having thickness t), b_1 can now be expressed as [36]:

$$b_1 = \sqrt{\frac{2\beta}{1+\beta}}\sqrt{\frac{2\ M_y}{f_{h,1}\ d} + \frac{\beta}{1+\beta}\frac{t^2}{2}} - \frac{\beta}{1+\beta}t \tag{3}$$

Finally, the shear strength of a fastener in such configuration is $F_{max} = f_{h,1}\ b_1\ d + F_{ax}/4$, whereas $d_{max} = (b_1 + t + b_2)\tan(\alpha)$. With this adjustment it was possible to separately calculate the in-plane response of the first overlay (using F_{max} from Equation 2) and of the second one (using F_{max} from Equation 3), starting from the load-slip response of the single screws and considering the two different dimensions of the panels (Figure 4).

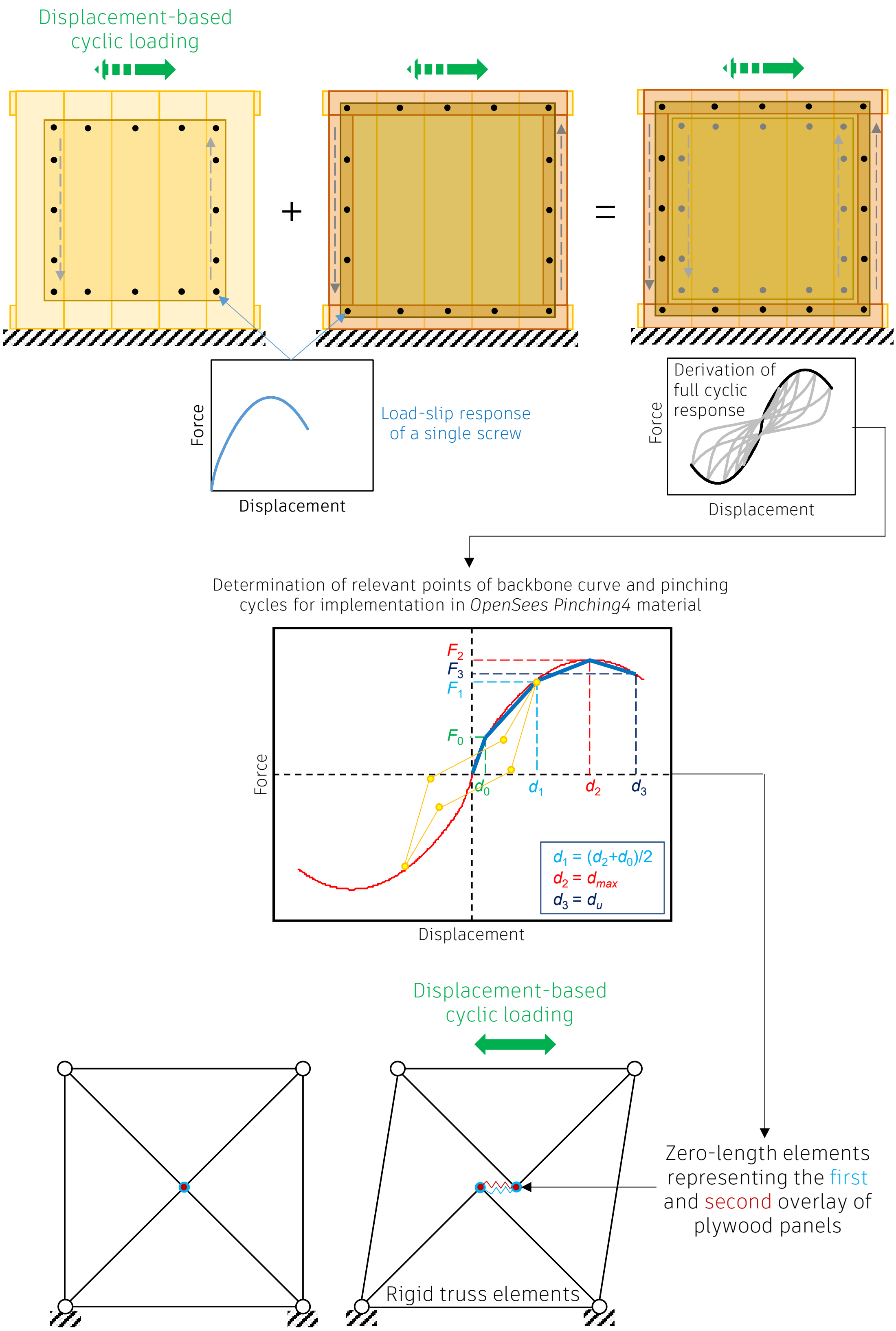

Figure 4: Adopted analytical formulation and its implementation in a macro-element modelling strategy for simulating the in-plane response of the tested sample.

2.4 Numerical modelling

Besides reproducing the conducted experimental test, sensitivity analyses were performed, in order to assess the influence of parameters such as the diameter of the screws and the plywood thickness. Thus, the aforementioned analytical formulation was implemented in the open-source software *OpenSees* [37], adopting a macro-element modelling strategy (Figure 4). The macro-element representing the prototype was composed of rigid truss elements forming an upper and a lower triangle connected to each other; in the middle of the macro-element, two *zero-length elements* [37] were present, representing the nonlinear, in-plane response of the first and second overlay of plywood panels. The two zero-length elements featured the *Pinching4* uniaxial material model [37], whose input parameters are the load-displacement points of the backbone curve and the internal pinching cycles. These quantities were derived directly from the analytically calculated backbone curve, following the approach presented in [23] and recalled in Figure 4.

3 RESULTS AND DISCUSSION

3.1 Experimental results

The tested sample exhibited large in-plane strength and stiffness, and considerable hysteretic energy dissipation (Figure 5). The presence of the double plywood panels overlay proved to be beneficial from this point of view, ensuring a stable softening phase after the peak load, and large strength with sufficient displacement capacity even for the limited dimensions of the prototype.

Diffused yielding of the fasteners was observed, responsible for the large dissipation: depending on the considered cycle, an equivalent hysteretic damping ratio of 13 to 17% was determined. The tested prototype reached a peak load of 13.7 kN, with a corresponding in-plane deflection of 38 mm. As will be shown in the next section, these values were in line with those expected from the analytical prediction.

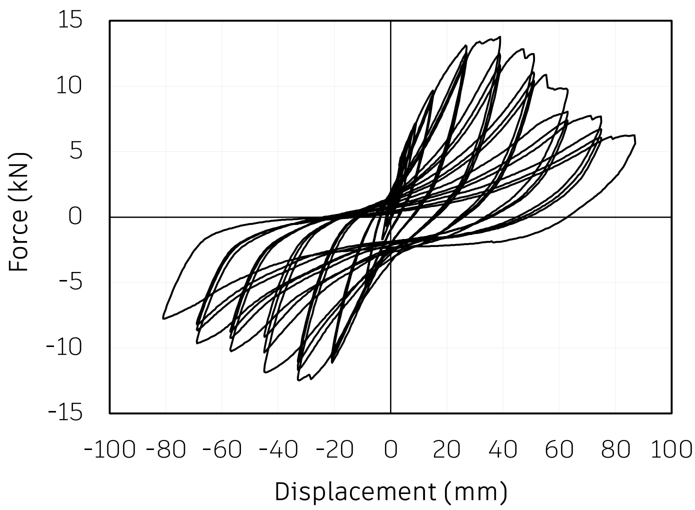

Figure 5: Experimental in-plane cyclic response of the tested specimen.

3.2 Comparison of the analytical and numerical models with the experiment

The analytical formulation presented in Section 2.3 allowed to construct two separate backbones for the two plywood overlays. Since the two panels ultimately contribute to the same in-plane deflection, the analytically determined backbone curves of the overlay were summed together, obtaining the graph shown in Figure 6b. The internal pinching cycles were derived from the resulting backbone curve (see once more Figure 4), following the geometrical procedure already presented in previous works [23],[25]. As can be noticed, a very good agreement between the analytical model and the experimental response of Figure 6a was obtained. In particular, from the performed calculations, based on the material properties reported in Section 2.1, values of F_{max} = 12.5 kN and d_{max} = 37 mm were determined. These values appear to be very close to those recorded from the experiment (see Section 3.1): F_{max} was underestimated by only 9% and d_{max} by only 3%. It should be noticed that, with respect to a single-panel overlay, the strength could be almost doubled, while still keeping the same displacement capacity.

Since the constitutive laws adopted for the zero-length elements of the numerical model were based on the previously reported analytical formulation (Figure 4), also the results of the simulations in *OpenSees* can accurately capture the in-plane response of the prototype (Figure 6c). The good agreement with the experiment is not only visible from the very similar shape of the numerical hysteretic response, but also when considering the energy dissipation per cycle: as can be noticed from Figure 7, the energy accumulation derived from the experiment is well described by the numerical model, with only minor discrepancies. In other words, the adopted modelling strategy and constitutive laws can reliably simulate not only the in-plane strength and stiffness of the proposed retrofitting method, but also its cyclic energy dissipation, confirming also for this strengthening configuration the results obtained for a single plywood overlay [23],[25].

3.3 Influence of diameter of screws and plywood thickness

Since the proposed analytical formulation and the performed numerical analyses showed good agreement with the experiment, these approaches were also used to assess the influence of different diameters of screws (4, 5, 7 mm) and plywood thicknesses (9, 12, 15, 18 mm) (Figure 8). Because the main failure mode of the prototype involves the development of two plastic hinges in the fasteners, the impact of screw diameter is, as expected, very relevant, with a great in-plane strength and stiffness increase for larger diameters. For the same reason, the influence of plywood thickness is lower, but can lead to a variation in strength of 2%/mm of panel thickness for the investigated range, similarly to past findings on floors retrofitted with a single plywood overlay [13].

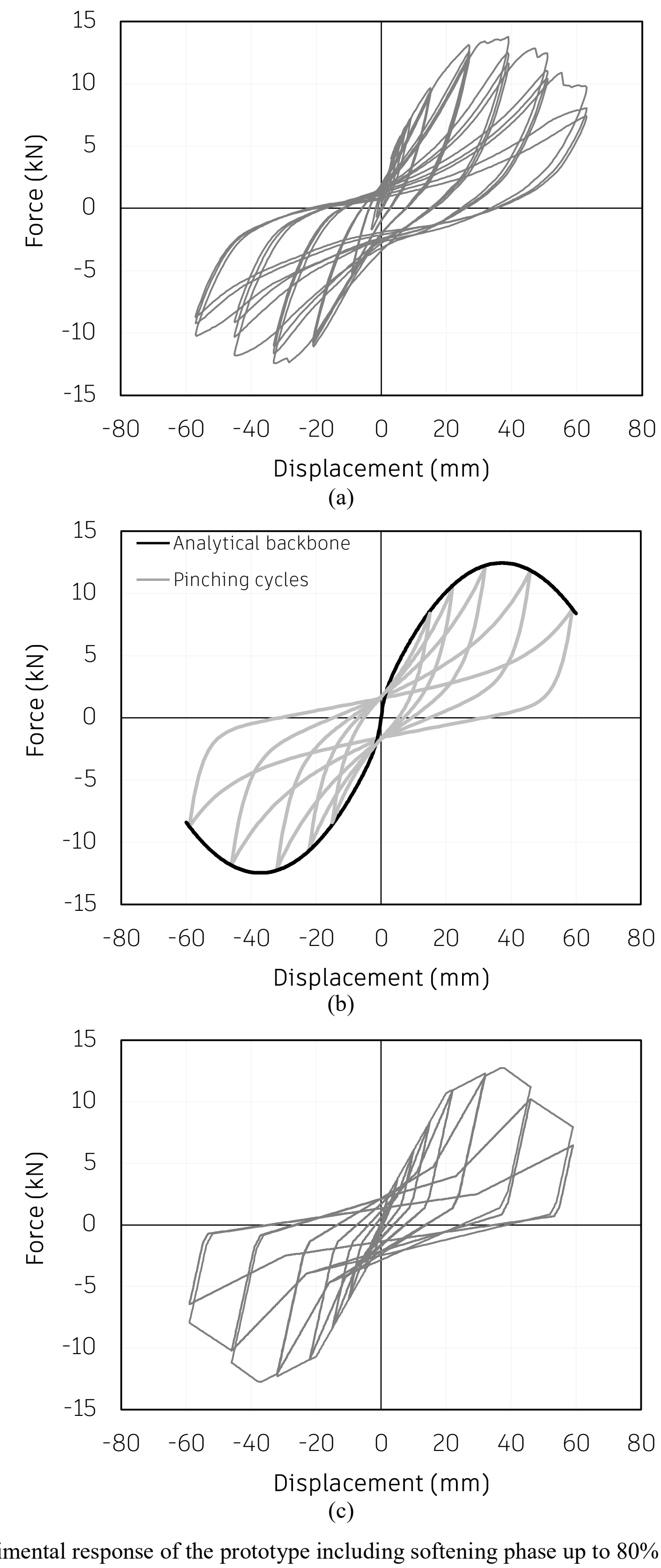

Figure 6: (a) Experimental response of the prototype including softening phase up to 80% of peak load; (b) prediction based on the presented analytical formulation; (c) cyclic response of the specimen simulated in *OpenSees*.

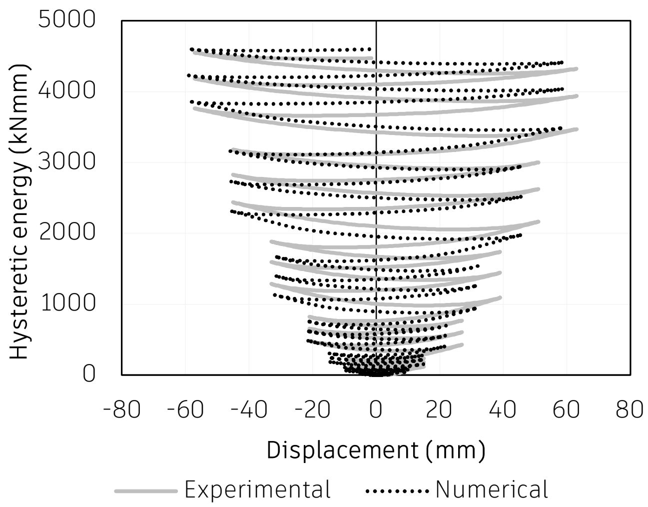

Figure 7: Comparison between the experimental and numerical hysteretic energy accumulation.

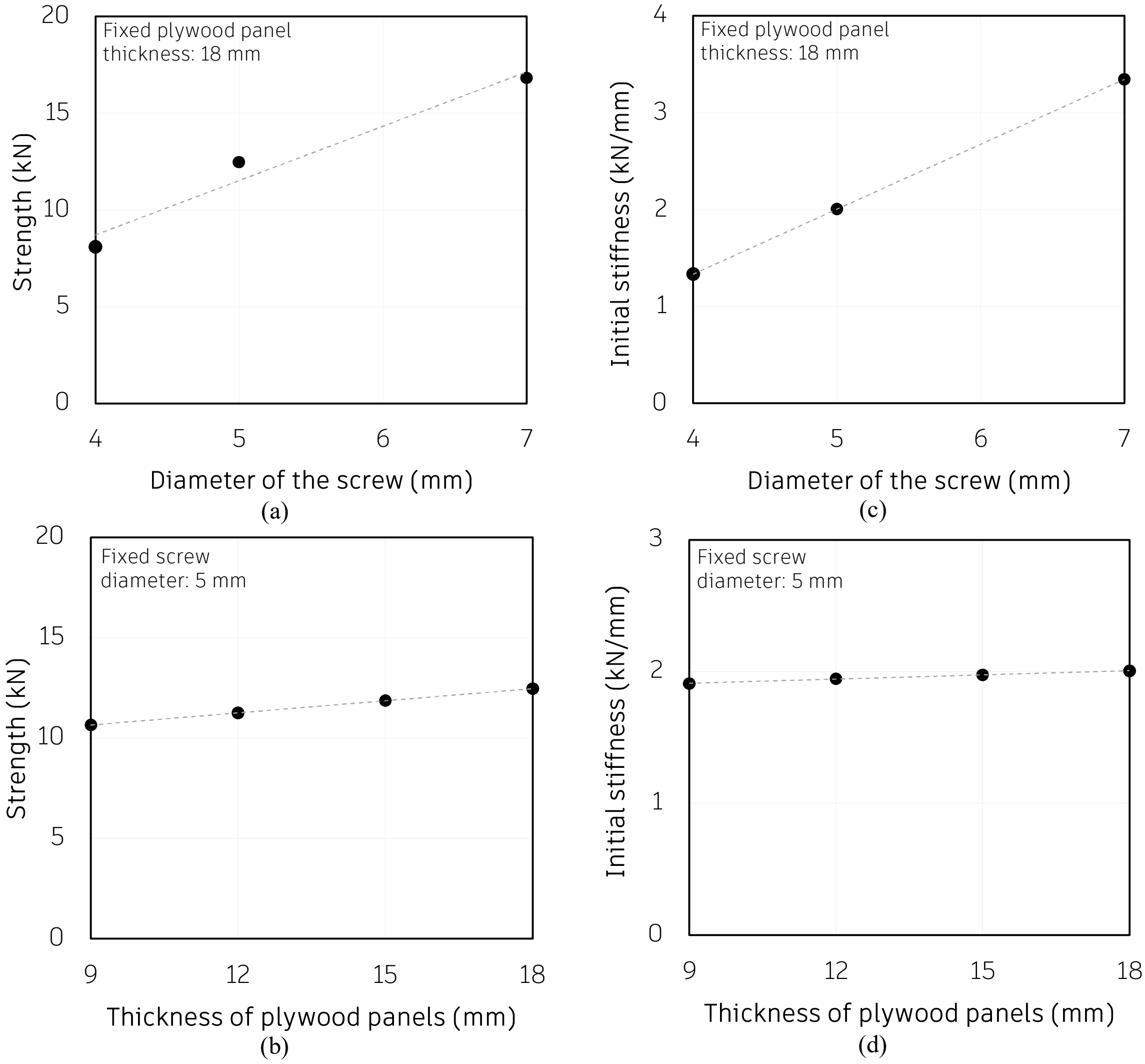

Figure 8: Influence of screw diameter and plywood thickness on strength (a, b) and initial stiffness (c, d) of the tested sample.

4 CONCLUSIONS

In this work, a plywood-based in-plane retrofitting for existing timber floors has been presented. The proposed strengthening method consists of the creation of two independent shear planes by means of two different superimposed overlays of plywood panels. The first layer is fastened directly to the existing sheathing, while the second is fixed to the sheathing through plywood boards surrounding each panel of the first overlay. A small gap is left between the boards and the panels, enabling free rotation and sliding. With this solution, the two overlays are not directly connected to each other, combining the strength of two plywood layers with an improved ductility linked to their independent movement.

Firstly, an experimental test was conducted on a prototype representing a 500×500 mm portion of a floor retrofitted with the aforementioned method. The results from this test were used to validate the analytical formulations and numerical modelling strategies previously developed for a single plywood overlay, and adapted in the present study for the case of the double overlay. Although the tested sample had relatively small dimensions, it exhibited an in-plane strength of 13.7 kN reached at 38 mm displacement, with large energy dissipation, corresponding to an equivalent hysteretic damping ratio of 13 to 17%, depending on the considered cycle.

The outcomes from the test were then compared with the analytical and numerical modelling approaches adapted for the case of two plywood panels overlay, showing an overall good agreement with the experiment. The influence of the variation of parameters such as screw diameter and plywood thickness was also evaluated. The developed modelling strategies can be adopted to design retrofitting interventions on existing timber floors with the proposed method, and to accurately simulate their in-plane response. Furthermore, these approaches can also be used for optimizing the layout of the two plywood overlays and their fasteners, in order to combine the target strength and stiffness of the floor with large energy dissipation, making the technique very adaptable and versatile.

The outcomes of this work can contribute to the research framework supporting the use of wood-based techniques for the seismic upgrading and architectural conservation of existing and historical structures.

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