World Conference on
Timber Engineering
Oslo 2023

PRELIMINARY TEST RESULTS ON THE IN-PLANE STRENGTHENING OF TIMBER FLOORS WITH THE DOUBLE PLANKING TECHNIQUE

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ABSTRACT: The seismic retrofit of existing masonry buildings often needs global interventions to guarantee the box-structural behaviour to inhibit the onset of local mechanisms. However, the so called box structural system requires a correct organization of the diaphragm, as well as its adequate connection to the masonry walls. The use of a new crosswise single layer of wooden planks is here proposed for the in-plane strengthening of existing timber floors. According to this solution, the new layer made with wooden planks has an inclination of 45° with respect to the existing ones that are arranged orthogonally to the wooden beams. The wall-to-floor connection is made of studs fixed to perimeter chord, which is in turn nailed to the wooden planks. The aim of this work is to highlight the role of the type and arrangement of the connections between the wooden planks and the steel plate on the shear behaviour of the diaphragm, as well as on the transmission of the actions from the perimeter chords to the diaphragm inner web-panel by means of an analytical model. The test results on in-plane cyclic shear behaviour of the diaphragm shows a linear trend of shear stresses along the plates, contrary to the usual design practice that assumes a uniform distribution.

KEYWORDS: diaphragm, seismic upgrade, double-planks, nailed connections, in plane shear behaviour

1 INTRODUCTION

The high seismic vulnerability of historical masonry buildings is mainly due to onset of local collapse mechanisms, which involve the detachment of the perimeter walls perpendicular to the inertial actions [1]. In the worst-case scenario, the detachment is followed by the rigid out-of-plane overturning of the masonry blocks or of the whole wall, thus causing also the floors' collapse. Widely used techniques for the retrofitting of masonry buildings rely on the adoption of roof and floor diaphragms. When efficiently connected to the perimeter walls, the diaphragm can collect the inertial forces of the floor and of the wall loaded out-of-plane and transfer them to the shear resistant walls, thus preventing the onset of local mechanism and guaranteeing a box-like behaviour of the whole building [2-5].

Traditional techniques for the construction of a rigid diaphragm entail the use of reinforced concrete slabs. Such a solution was also recommended by past national codes: for example, before the enacting of the Italian building Code (D.M. 2008 [6]), earlier Italian codes recommended replacing the existing timber floor with a new heavy concrete slab, with the exception of historical and monumental buildings for which the conservation of the existing materials was a mandatory requirement for the preservation of the cultural heritage.

Recent Italian earthquakes (2016, 2017) showed the ineffectiveness of the concrete slabs to provide the box-behaviour of stone-masonry buildings, since the walls were not able to withstand significant seismic actions generated mainly by the high mass of this type of diaphragm.

Several techniques were proposed in the past for the construction of in-plane floor diaphragm. Initially, the same techniques proposed for the flexural strengthening of existing wooden floors, fully compliant with the conservation principles of heritage buildings, were further engineered as to also activate a diaphragm action. They rely on the replacement of the non-structural existing screed placed between the wooden planks and the floor, with a structural overlay, stud-connected to the wooden joists, thus generating a composite cross section. The collaborating structural overlay may consist of ordinary [7-8], or natural hydraulic lime mortar [9]. Alternatively, the extrados retrofit may be obtained with a very thin steel plate [10], or of Fiber Reinforced Polymers (FRP) [11]. Recently, efficient dry composite sections were also proposed by using single or double-crossed timber planks [12] or Cross Laminated Timber panels (CLT) [13-16], connected to the existing joists by steel dowels or screws. More recently, specific solutions for wooden floor diaphragms were proposed. The in-plane behaviour under shear loading of strengthened wooden floors was experimentally and numerically investigated by considering: i) composite materials [13, 17-19] ii) single and double diagonal wooden boards, having different thicknesses and orientation of the planks, for varying the connection type and the arrangement between the adjacent boards [13, 17-19]; iii) CLT panels [14, 16]. Other experimental studies investigated retrofitted wooden diaphragms with a different test set-up allowing the development of both the in-plane flexural and shear deformation of diaphragms like in a real building. Several stiffened configurations were considered: i) a single layer of plywood panels or flooring boards connected with

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stapled metal sheets [5, 20]; ii) a single overlay of nailed plywood panels [21, 22]; iii) a second diagonal layer of wooden planks, nailed on the existing planks; iv) diagonal bracing consisting of screwed steel plates or epoxy-resin glued FRP strips; v) multi-layers of plywood panels glued on the existing floor; vi) traditional thin reinforced concrete slab connected by means of steel stud to timber joists [23, 24]; vii) a steel truss fixed to the joists' intrados [21].

The experimental results showed that the several proposed configurations can efficiently enhance the in-plane capacity and stiffness of the strengthened timber floor. Furthermore, the experimental results may be considered as an effective benchmark for the validation of numerical and analytical models aiming at shedding light on the capability of flexible diaphragms to affect the global response of the whole buildings, by controlling the out-plane detachment of masonry walls and by contributing to dissipate energy during a seismic event [16; 25].

Among all the cited techniques for the retrofitting of the existing timber floors, it is worth acknowledging that the application of an extrados double crossed planks or timber panels (either plywood or CLT panels) has been widely accepted in the field of architectural restoration as less invasive, with a high degree of reversibility and without the risk of moisture and water percolation. Furthermore, these dry wood-based techniques are very light and the seismic retrofitting of the whole building can benefit from reduced seismic actions with respect to the use of the concrete overlay.

The effectiveness of the retrofit interventions, based on the adoption of either floor or roof diaphragms, is governed by the correct detailing of the connections between the diaphragm and the perimeter walls transferring both the out-of-plane inertial forces of the walls to the floor diaphragm, and the seismic floor actions to the seismic resistant walls. Specific technological, experimental and analytical studies can be found in literature focusing on the local behaviour of steel studs connecting the perimeter diaphragm chords to the masonry walls [26, 27]. This technique has been widely accepted and adopted in the construction practice for the retrofit of many historical monuments since it minimally invasive as opposed, for example, to dovetail joints, and it improves reversibility of intervention.

The literature survey shows that, despite many experimental results on the in-plane strengthening of existing wooden floors, there is a lack of scientific studies focusing on the correct detailing of the connections between the floor diaphragm web panel and the perimeter chords, commonly realized by steel plates. Such a detailing is critical since it governs the distribution of the shear forces/stresses along the diaphragm edges during a seismic event. This paper focuses on the fundamental role of these connections and it aims at presenting design criteria and rules for a correct design of the boundary elements in a wooden diaphragm with double planks.

2 AIMS OF THE RESEARCH

The present research deals with light-dry-wooden diaphragms with double crossed floorboards because this technology complies with the conservation principles of historical buildings, such as compatibility with existing materials, high-reversibility and low-invasiveness. Furthermore, the use of overlaying double planks allows the floor to be breathable while wood panels, like plywood, laminated veneer lumber (LVL) and CLT, can entail vapour barrier due to the presence of adhesive layers which may produce water condensation, thus favouring the degradation of the existing materials.

In the case of the double crossed planks technique, the diaphragm is obtained with the application of new planks overlaying the existing floorboards. the new layer of planks can be placed either perpendicularly (α=90°) or with an inclination of α=±45° to the existing ones. It should be pointed out that the two solutions differ in the capability of transferring the shear actions within the diaphragm. While in the former configuration the resisting shear flow depends both on the width of the overlaid planks and on the number of nails placed at the intersection of the planks, in the latter configuration the resisting shear flow mainly depends on the number of nails placed along the diaphragm boundaries [28]. Furthermore, it can be easily proved that the arrangement with perpendicular planks requires a total amount of nails ten times greater than the configuration with diagonal planks since each intersection between the overlaying timber boards needs at least four nails.

For these reasons, the research work was restricted to the case with diagonal planks only, for which nail connections can be limited, in principle, along the contour to guarantee equilibrium. The connection between the floor diaphragm and the perimeter walls is provided by the diaphragm perimeter chords, usually made with steel profiles (either L-shaped or rectangular section, Fig. 1). The chords are nailed to the double wooden boards and jointed to the seismic-resistant masonry wall by means of shear dowels and to the walls perpendicular to the earthquake direction by means of steel ties which transfer the inertial actions to the diaphragm.

The present work aims at investigating the transfer phenomenon of the shear actions from the boundary steel chords to the diaphragm web panel made of overlaid double planks. Experimental and theoretical studies are presented that focus on the role and the arrangement of the connections on the transmission of actions from the perimetral chords to the inner web of the diaphragm.

As a result, specific design detailing of the boundary connection, with the adoption of additional nails, is proposed to guarantee the effectiveness of the diaphragm. In the first part of the paper, the behaviour of the connections between the overlaying double crossed planks and the perimeter steel chords is analytically studied, whilst in the second part the experimental results of a full-scale test on the proposed wooden diaphragm are presented.

https://doi.org/10.52202/069179-0049

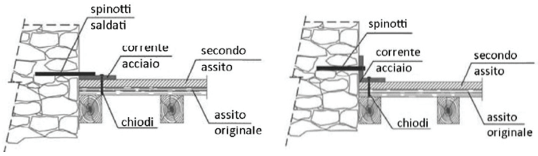

Figure 1: *Diaphragm perimeter chords made of steel plates (a) or L-shaped profiles (b) [29]*

3 DESIGN OF THE CONNECTION

3.1 EFFECT OF SHEAR FLOW DISTRIBUTION ON THE ACTIONS IN THE CONNECTIONS

A rectangular floor diaphragm is considered (Fig. 2). At a given storey, the seismic actions (f_0) produce a uniform distribution of shear flow $q = V / L_y$, being V the force transferred to the seismic-resistant walls and L_y the diaphragm depth. The shear flow (q) transferred from the perimeter steel chord to the diaphragm web panel depends on the orientation of the timber joists, which can either be perpendicular (case 1 in Fig. 3), or parallel to the diaphragm edge (case 2 in Fig. 3), respectively. In the diagonal configuration, the horizontal and vertical translational equilibriums of a floor length equal to the joist spacing (Δx) allow for the evaluation of the axial action (F_y) in the joist and in the diagonal wooden plank (f_{wd}), as follows:

$$q\,\Delta x = f_{wd}\,\Delta x\,cos^2\alpha \quad F_y = f_{wd}\,\Delta x\,cos\alpha\,sin\alpha \qquad (1)$$

where α is the inclination of the diagonal planks. If $\alpha = 45°$, the actions in the joists and in the diagonal planks are given by:

$$f_{wd} = 2\,q \qquad F_y = q\,\Delta x \qquad (2)$$

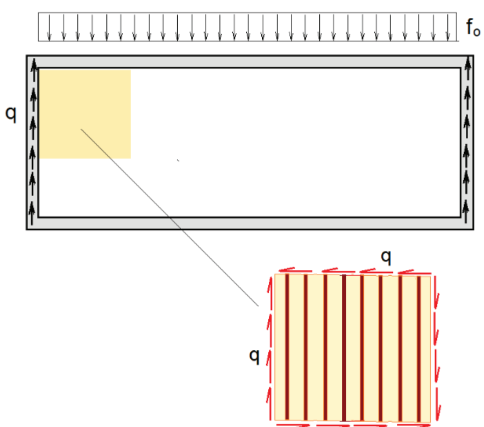

Figure 2: *Shear flow distribution in the diaphragm*

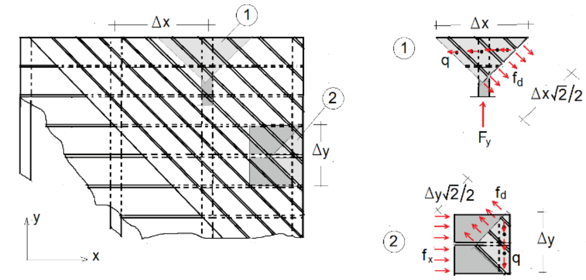

Figure 3*: equilibrium of timber planks along the diaphragm edge*

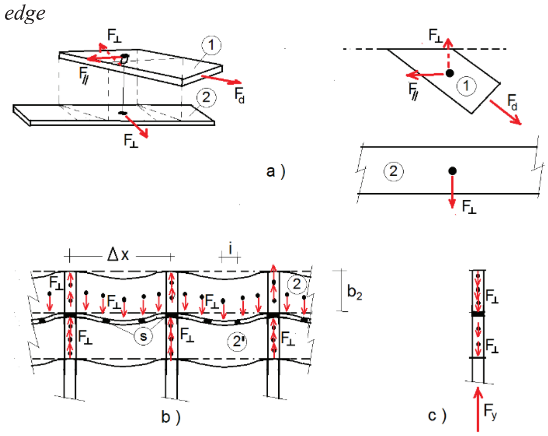

Figure 4: *Portion of the diaphragm with the joist perpendicular to the edge: actions in the nailed connection (a) in the lower existing plank (b) and in the joist (c)*

Furthermore, the shear flow along the diaphragm edge is transferred from the perimeter steel chord to the diaphragm's web panel made of the double-crossed planks through local forces acting in each nailed connection perpendicularly ($F_\perp$) or parallel ($F_{//}$) to the edge (Fig. 4a), as given by the following equation once it is assumed that the steel chord is nailed over the double-crossed planks with a given nail spacing (i) and with plank orientation of α=45°:

$$F_\perp = F_{//} = q\,i \qquad (3)$$

As shown in Figure 4b, the plank parallel and close to the edge is loaded by the bending action induced by the transverse forces $F_\perp$ of the nailed connections. Thus, the bending moment (M_2) in the perimeter planks is given by:

$$M_2 = \beta(F_\perp/i)\Delta x^2 \qquad (4)$$

where $\beta = \frac{1}{10} \div \frac{1}{12}$ if the outer plank is modelled as a continuous beam supported by timber joists. As a result, the reaction in the inner supports can be approximately assumed as equal to (Fig. 4c):

$$R = \frac{F_\perp}{i}\Delta x = F_y \qquad (5)$$

It should be noted that each joist has to be connected to the outer plank (labelled as 2 in Fig. 4) by the same number of nails ($n_{nails} = \Delta x / i$) placed along the edge length (Δx). Since in most cases all these nails cannot be placed within a single outer plank (b_2), it is necessary to

https://doi.org/10.52202/069179-0049

include also the inner planks in the connection. In the case of clearance between the existing floor boards, specific wooden or steel wedges have to place between them in order to engage the bending stiffness of the inner plank. Thus, the bending stress of the outer planks having the same width (b_2) (2 and 2' in Figure 4) is:

$$\sigma_2 = \sigma_{2'} = M_2(2t_2b_2^2/6) \qquad (6)$$

The number of nails to connect the steel chord to the double-crossed diaphragm within the joists spacing is:

$$n_{nails} = \mathrm{q}\Delta x/V_{Rd,n} \qquad (7)$$

where $V_{Rd,n}$ is the shear design strength of each nailed connection. The same number of nails connects the outer planks (2 and 2' in Fig. 4) to each joist.

Along the edge parallel to the joist (case 2 in Fig. 3), the connection does not produce any bending in the perimeter joist since the two layers of planks guarantee the translational equilibrium of the perimeter chord length (Δy). In other words, referring to Fig. 3, the horizontal component of the axial action in the diagonal planks is balanced by the action in the floorboards perpendicular to the joists, while the vertical component by the shear flow along the steel chord length (Δy).

Thus, the translational equilibrium of a diaphragm portion (2 in Fig. 3) along the two directions allows the evaluation of the forces per unit length in the double-planks, as shown by the following equations:

$$q\Delta y = f_{wd}\ \Delta y\ cos\alpha\ sen\alpha \qquad f_x\Delta y = f_{wd}\ \Delta y\ cos^2\alpha \quad (8)$$

By assuming an inclination of the diagonal planks α=45°, the actions in the planks are:

$$f_{wd} = 2q; \qquad f_x = q \qquad (9)$$

3.2 STRENGTH AND STIFFNESS OF THE NAILED CONNECTIONS

The bearing capacity of the nailed connections between the steel chord and the double-crossed planks depends on the steel grade of the nail, the nail diameter, and on the local bearing strength of wood (mainly affected by the density of the timber element), and by the angle of the action with respect to the wooden fibers. The nail needs a minimum embedded length of 50÷60 mm in order to connect the three overlaying elements (the existing plank, the new plank and the steel plate). It should be noted that considering the connection between the steel chord and the diagonal plank, the point load acts with an inclination of 45° with respect to the diagonal plank grain direction , while at the interface between the two timber boards the angle to the grain of the point load is equal to 45° in the upper diagonal plank and 90° or 0° in the lower existing plank for the portions 1 and 2, respectively (Fig. 4).

Preliminary tests [28] were carried out according to EN 383 [30] to evaluate the bearing strength and the stiffness of spruce timber for nails with a diameter (ϕ) of 4 mm, commonly used to fix the planks in existing floors. Some test results are presented in Figure 5.

The test results show that the bearing strength (f_{hw}) of spruce wood for ϕ=4 mm nails depends on the load angle with respect to the timber grain, differently from the equations of the main international Codes [31], for which the bearing strength is a function of the wood density and of the nail diameter only. The bearing strength (f_{hw}) is equal to 50, 42 and 37 MPa for an angle to the grain β of 0°, 45° and 90°, respectively, measured for a relative displacement of 4 mm. Furthermore, the local compressive stresses were substantially elastic up to a nail relative displacement of about 1 mm, as it is shown in Figure 5, where the bearing strength is plotted as a function of the nail-to-timber relative displacement. The average initial slope of the curves (Fig. 5) is the elastic stiffness of foundation soil which varied between $k_{w,0}$ = 80 N/mm³ and $k_{w,90}$= 30 N/mm³, depending on the action to wooden grain angle.

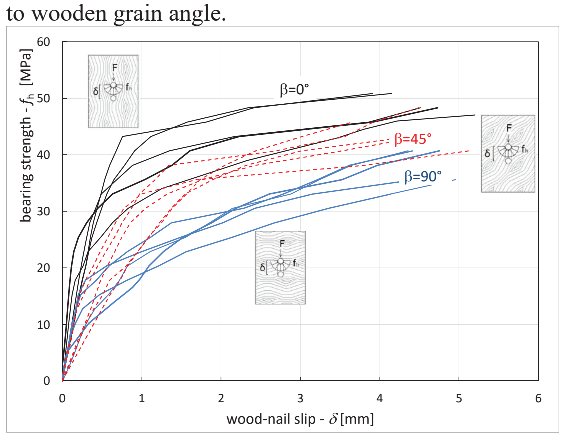

***Figure 5**: Experimental results on the local compressive behaviour of spruce timber (f_{hw}) with 4 mm nails for an action parallel (β=0°), with angle of 45° (b) and perpendicular to the grain (β=90°) (MC=12% during the tests).*

***Table 1**: Bearing strength ($f_{hw,\beta}$) and stiffness $k_{w,\beta}$ of spruce planks for varying direction (β) of the action with respect to wood fibers*

β =0°		β =45°		β =90°	
$f_{hw,0}$ (N/mm²)	$k_{w,0}$ (N/mm³)	$f_{hw,45}$ (N/mm²)	$k_{w,45}$ (N/mm³)	$f_{hw,90}$ (N/mm²)	$k_{w,90}$ (N/mm³)
50	80	40	50	37	30

it is possible to determine the shear stiffness of the nailed connections on the basis of the classical approach of the beam on elastic foundation [9]. Thus, the stiffness of the steel chord - to diagonal plank connection is expressed by the following equation:

$$K_{cp} = 2E_sJ\left(\frac{k_{w45}\phi}{4E_sJ}\right)^{3/4} \qquad (10)$$

while the stiffness of the connection between the existing and the new overlaying diagonal plank in the portion 1 and 2 of the diaphragm are given by the following equations, respectively:

https://doi.org/10.52202/069179-0049

$$K_{pp,1} = 2E_sJ\left[\frac{1}{\left(\sqrt[4]{\frac{k_{w45}\phi}{4E_sJ}}\right)^3} + \frac{1}{\left(\sqrt[4]{\frac{k_{w90}\phi}{4E_sJ}}\right)^3}\right]^{-1} \qquad (11)$$

$$K_{pp,2} = 2E_sJ\left[\frac{1}{\left(\sqrt[4]{\frac{k_{w45}\phi}{4E_sJ}}\right)^3} + \frac{1}{\left(\sqrt[4]{\frac{k_{w0}\phi}{4E_sJ}}\right)^3}\right]^{-1} \qquad (12)$$

where E_s is the steel modulus of elasticity and J the moment of inertia of the nail cross-section.

For relative displacements greater than 2 mm, the wood local compressive behavior approaches the plastic phase, up to the bearing strength. By assuming a homogeneous isotropic behaviour of the timber and that the bearing strength of the nailed connection does not depend on the ratio between the nail diameter and sapwood thickness, the bearing capacity of the nailed connections can be evaluated by considering the collapse mechanism with two plastic hinges in the nail shank having a fixed end in the steel plate [8]. The strength in the connection depends on the wooden bearing strength in the direction of the applied load, on the yield strength of steel and the nail diameter. The resistance of the steel chord-to-diagonal plank nailed connection is given by the following equation [8]:

$$V_{Rn} = f_h\,\phi\,L_w \qquad (14)$$

$$L_w = L'_w - t/2 \qquad (15)$$

$$L'_w = L\left\{-1 + \sqrt{2 + \frac{2}{3}\frac{f_y}{f_{hw,45}}\left(\frac{\phi}{L}\right)^2 + \frac{1}{2}\left(\frac{t}{L}\right)^2}\right\} \qquad (16)$$

where t and t_p are the thickness of steel plate and wooden plank, respectively, L_w is the effective length of the nail, f_y the nail yield strength, and $f_{hw,45}$ is the timber bearing strength for an inclination of the shear force of β=45° with respect to grains.

The shear strength of the existing-to-new diagonal timber plank connection depends on the timber bearing strength of the two overlaying planks, which are loaded with a different inclination of the shear action with respect to their grains [31]. The following equations express the shear strength of the existing-to-new plank nailed connection in the portion 1 (with the steel chord perpendicular to the timber joist, Fig. 3) and in the portion 2 of the diaphragm (with the steel chord parallel to the timber joist, Fig. 3), respectively:

$$V_{R,u} = f_{h,90}\Phi^2\sqrt{\frac{2}{3}\frac{f_y}{f_{hw,90}}\left(1+\frac{f_{h,90}}{f_{hw,45}}\right)}\frac{1}{1+\frac{f_{hw,90}}{f_{hw,45}}} \qquad (17)$$

$$V_{Rn} = f_{h,0}\Phi^2\sqrt{\frac{2}{3}\frac{f_y}{f_{hw,0}}\left(1+\frac{f_{h,0}}{f_{hw,45}}\right)}\frac{1}{1+\frac{f_{hw,0}}{f_{h,45}}} \qquad (18)$$

In Table 2, the connections stiffness and strength are listed considering a ϕ=4 mm nails, a steel yield strength of 1000 MPa, a thickness of the planks and of the steel chord equal to 22 mm and 3 mm, respectively, along with the bearing strength and the stiffness of the spruce found experimentally (Table 1).

***Table 2**. Stiffness K and strength V_{Rn} of the nailed connections (ϕ=4 mm; t=3 mm; t_p=22 mm)*

Type of connection	K [N/mm]	V_{Rn} [kN]
Steel chord-to timber diagonal plank	1516	1.93
Existing plank – diagonal plank (Portion 1)	614	1.81
Existing plank – diagonal plank (Portion 2)	890	1.95

4 TEST ON DOUBLE-PLANKING DIAPHRAGM

4.1 GEOMETRICAL AND MECHANICAL PROPERTIES OF THE SPECIMEN

A portion of a double planking diaphragm was tested at the University of Brescia with the aim to investigate its in-plane cyclic behaviour under a shear action. A square specimen having a side of 2.0 m was designed on the basis of the seismic actions in a reference two-storeys masonry building with timber floors [28] (Fig. 6). A design shear action V_{Ed}= 30kN was considered in the floor diaphragm during the seismic event. By assuming a design shear resistance $V_{rn,d}$=1.5 kN of the nailed connection, a minimum of 13 nails/m are needed to connect the perimeter steel chord to the wooden diaphragm.

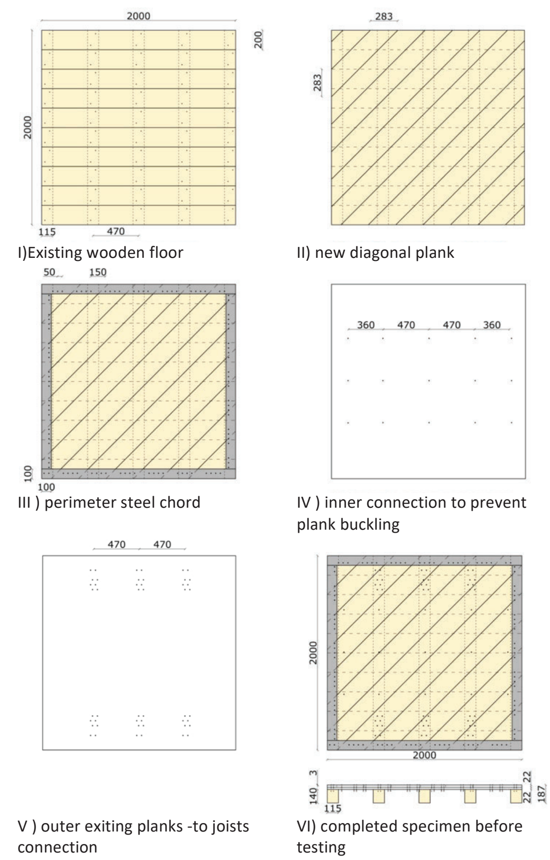

***Figure 6**: Scheme of the assembly stages of the tested specimen*

The specimen consists of spruce joists having a section of 130x110 mm^2 and a spacing of 0.50 m, over which perpendicular timber planks (190x22 mm^2), resembling the existing floorboards, are connected by means of two 4 mm nails at each joist-to-beam joint. Overlaying diagonal planks are arranged with an inclination of α=45° with respect to the horizontal ones (Fig. 6). Along the perimeter, 3x100 mm steel plates are connected to the double-crossing planks by means of groups of four 4 mm nails (L=70mm) hammered into calibrated holes, corresponding to 13 nails/m. Each group of nails has a spacing of 150 mm; they are inserted into calibrate holes along a single row with a distance of 25 mm to the inner edge of the steel chord (Fig. 6). To avoid the bucking of the diagonal planks, inner screws (d4x70 mm) are set in correspondence of each lower joist. A group of eight nails connects each joist end to the outer horizontal plank to balance the component of the diagonal plank force acting perpendicular to diaphragm edge (Fig. 6). It should be noted that these connections activate the flexural behaviour of the outer existing planks, as already discussed in the previous section.

4.2 TEST SET UP

The testing bench consists of a rigid reaction frame within which the diaphragm specimen is placed. The sample is placed inside the testing bench so that the joists are horizontal (Figure 7). The test was carried out by imposing cyclic displacements of increasing amplitude to the upper chord of the diaphragm using a hydraulic jack fixed to the reaction frame. A steel collector welded to the upper chord of the diaphragm allowed the applied horizontal forces to be distributed as a shear flow along the specimen side. The bottom steel chord of the diaphragm was welded to the supporting beam of the bench.

To measure the specimen deformations and displacements, Linear Variable Differential Transformers (LVDTs) and potentiometers were installed as shown in Figure 7. The horizontal displacement of the diaphragm is measured by a Linear Variable Differential Transformers (LVDTs) while the force acting on the specimen is measured by a load cell placed between the reaction frame and the collector. The deformations of the diagonal planks were measured by potentiometric transducers equipped with extensions, and arranged on the main diagonals of the specimen, one parallel and the other orthogonal to the axis of the plank (diagonal "a" and “b” in Fig. 7). Finally, several potentiometric transducers were placed along two orthogonal sides of the panel, for a continuous acquisition of relative slip between the perimeter steel chord and the diagonal planks. In particular, along two sides of the specimen, three pairs of transducers were arranged to record the relative in plane displacements (slip δ) between the perimeter steel chord and the diagonal planks (detail in Figure 7).

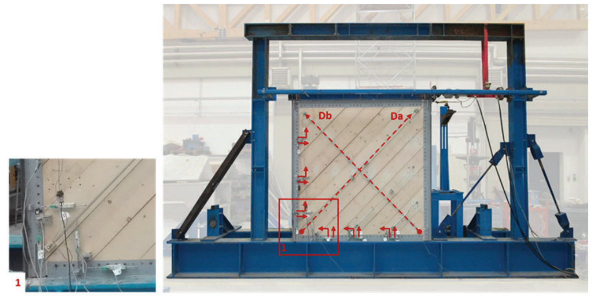

Figure 7*: Details of the test set up.*

4.3 EXPERIMENTAL RESULTS

Eleven symmetrical cycles of increasing amplitude were applied to the top of the specimen up to a 0.5% drift (corresponding to a lateral displacement η of 10 mm) when a significant damage in the nailed perimeter connections between the steel chord and the diagonal planks was observed. The test started with two cycles with 0.25 mm and 0.5 mm top displacement, respectively, followed by five cycles having an increment of 0.5 mm up to 3.0 mm amplitude. Finally, the last four cycles had an amplitude increment of 2.0 mm.

In Figure 8 the cyclic behaviour of the tested diaphragm is shown in term of shear force (V) versus applied drift (d_r). A symmetrical response of the diaphragm was observed, with an anelastic behaviour beyond a drift of 0.025%, corresponding to a lateral displacement of 0.5 mm and a shear action of 5 kN. The elastic stiffness measured for a drift of 0.025% was K_d=12 kN/mm.

For an applied load equal to the design shear action in the diaphragm of the reference building (V_d=30 kN), a top displacement of 4.55 mm was measured, corresponding to a drift of 0.23%. The secant shear stiffness of the wooden diaphragm is therefore equal to K_d=6.6 kN/mm. The behavior was mainly stable up to the design shear action V_d=30 kN, whilst the failure of the connections at the specimen corners was observed for V=1.5V_d. Then, the test was interrupted to avoid damage in the steel chords.

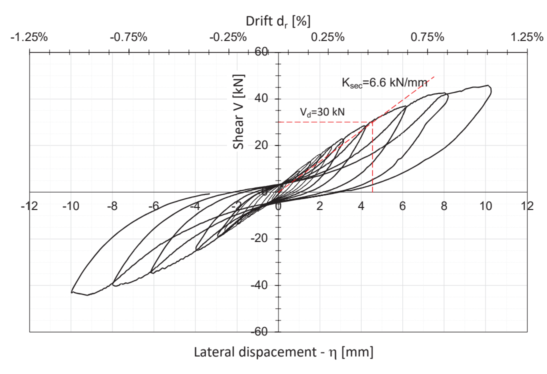

Figure 8*: Test results: horizontal shear load (V) vs. drift (d_r)*

The measured relative slips between the outer steel chord and the inner web of the diaphragm are shown in Figure 9. It should be noted that the slip parallel to the perimeter

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chord (black curves) increases with the applied load, but it gradually reduces along the chord proceeding from the left end (H1), where the longest diagonal plank is located, towards the right corner (H3), where the planks are shorter. A similar trend was measured for the relative slip perpendicular to the perimeter chord (red curves in Figure 9), which shows the maximum value in correspondence to the device (V1) placed on the left longest diagonal plank. Similar values of the relative slips between the outer steel chord and the diaphragm web panel were measured along the vertical left side of the specimen [32]. Based on the experimental results, it can be stated that shear flow between the web and the outer chords of the diaphragm is not uniform, as usually assumed in the current design practice, but it has a linear trend with the maximum value at the corner, where the longest diagonal plank is placed, as shown in Figure 10.

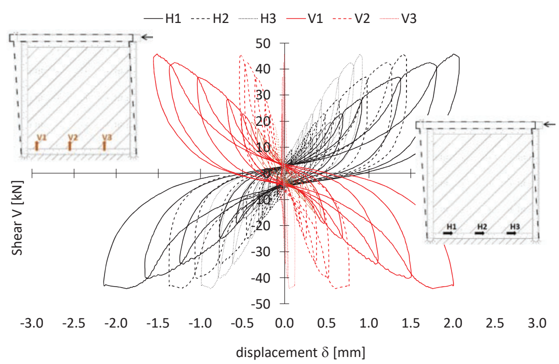

Figure 9*: Test results: horizontal shear load (V) vs. slip (δ) between the perimeter steel chord and the inner wooden web*

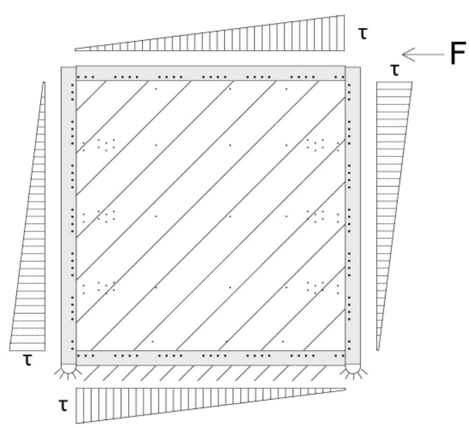

Figure 10*: Scheme of the distribution of the shear flow along the edges of the diaphragm web.*

5 CONCLUSION

In the seismic retrofit of existing masonry buildings, the global, box-like structural behavior may be guaranteed through the correct organization of the floor diaphragms and their connections to the masonry walls.

Aim of this research is to study the in-plane shear response of wooden diaphragm made with the double planking technique. The proposed technique is characterized by the use of new diagonal planks overlaying the existing planks (which are laid perpendicular to the floor joist). The in-plane shear resisting mechanism of the floor diaphragm is guaranteed by the nailed connections between the perimeter steel chords and the double-crossed overlaying planks. This double planking technique is easy to apply and allows for a significant reduction of the number of nailed connections with the respect to the traditional double crossed timber planks with orthogonal timber boards.

The research focuses on the role and the arrangement of the connections on the transmission of actions from the perimetral chords to the inner web of the diaphragm. An analytical model is proposed to assess the stiffness and the strength of these connections.

The experimental results of a quasi-static cyclic test on a portion of the diaphragm subjected to in-plane shear action show a stable behaviour of the diaphragm up to a load 1.35 times higher than the design shear action. Furthermore, the test results highlight a linear trend of the shear stresses along the perimeter steel chords, contrary to the usual design practice that assumes a uniform distribution.

The shear flow distribution along the edges of the diaphragm is mainly governed by the stiffness of the perimeter nails connections, which is much lower than the axial stiffness of the diaphragm core planks. As a result, the shear flow along the edges of the diaphragm web tends to concentrate where the panel undergoes larger deformation, that is in correspondence of longer planks of the diaphragm core.

ACKNOWLEDGMENTS

The study presented in the paper was partly carried out within the research activities carried out in the frame of the 2022–2023 ReLUIS Project—WP5 funded by the Italian Department of Civil Protection. Note that the opinions and conclusions presented by the authors do not necessarily reflect those of the funding entity. The assistance of Eng. A. Molinari and Eng. M. Rizzi during the experimental campaign is gratefully acknowledged.

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 https://doi.org/10.52202/069179-0049