# THE ROLE OF IN-PLANE FLOOR STIFFNESS IN THE SEISMIC BEHAVIOUR OF TRADITIONAL BUILDINGS

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## ABSTRACT:

The structural behavior of an existing masonry building subjected to seismic action, is strongly affected by the in-plane stiffness of the floors, and by the connections between the horizontal diaphragms and the masonry walls. The aim of the research is to experimentally evaluate the behavior of timber floor refurbished using different techniques, with special regard to the in-plane stiffness. The size adopted for the specimens (5 m span, 4 m width), is similar to the ordinary dimensions of timber floors in historical buildings in Italy. Taking into account the size of the specimens, and the need to determine the in-plane strength and stiffness of the floor, a special test set-up has been designed and adopted in order to allow the free in-plane deformation of the floor itself subjected to lateral load: the load configuration applied to the floor simulates the effect of seismic action on the floor. The experimental phase of the research aims to calibrate engineered models that can be used for studying existing structures.

## KEYWORDS:

Timber floor, historical heritage, masonry structures, in-plane stiffness, horizontal diaphragm

## 1. INTRODUCTION

The structural response of a masonry existing building to seismic actions is strongly affected by many parameters, such as the plan distributions, the texture and the quality of the masonry walls, the plan regularity, the distribution and the size of the openings, the characteristics of the floor and of the connections between vertical and horizontal elements.

The experience of the past earthquakes has shown that a key role is played by the horizontal diaphragm in the transmission of the seismic actions.

Whereas the floor is not satisfactorily connected to the adjacent walls, or the in-plane stiffness is inadequate, different collapse modes can be observed involving overturning of the walls (see Figure 1 c). Masonry walls demonstrates, generally, an insufficient resistance to lateral loads acting out of plane.

Whereas the horizontal diaphragm can be considered perfectly rigid, and the connections between walls and diaphragm are correctly assured, the lateral seismic load can be fully transmitted to the walls parallel to the horizontal action, allowing masonry to counteract a much higher resistance (see Figure 1 b).

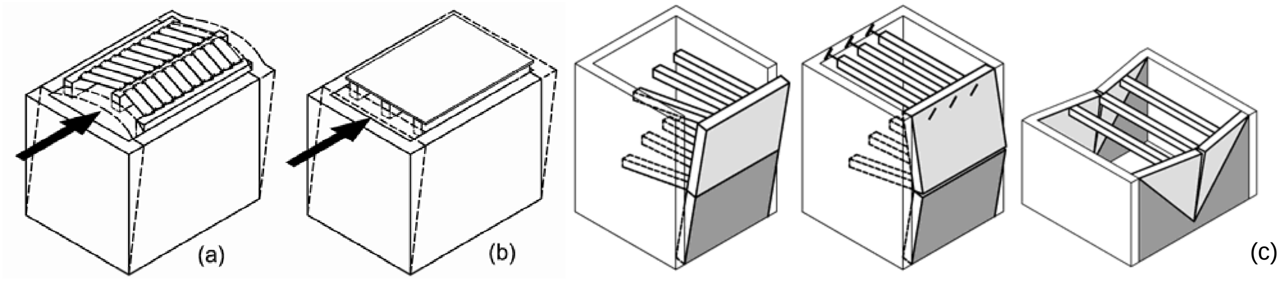

Figure 1. (a) the inadequate in-plane stiffness of the floor causes overturning of the walls perpendicular to the seismic action; (b) a stiff diaphragm allows forces to be transmitted to the walls parallel to the seismic action; (c) some example of wall overturning modes registered during recent earthquakes

The need to increase the in-plane stiffness has induced, in the past, some strengthening solutions which recent earthquakes demonstrated to be inadequate or, in some cases, unfavorable. The substitution of timber floors with concrete ones, the insertion of a concrete tie beam "inside" the thickness of the masonry walls, can imply, respectively, a significant self weight increase and a weakening of the existing masonry walls.
Therefore, after the Umbria Marche earthquake, some floor refurbishment techniques has been reconsidered: the new Italian standard code on existing buildings, appeared in 2003, bans the possibility to insert concrete tie beam in the depth of the existing masonry walls, and suggests new alternative strengthening techniques for the horizontal diaphragm. Some of them are presented in the next paragraphs.

## 2. TIMBER FLOOR TYPOLOGY AND REFURBISHMENT TECHNIQUES

In this paper a simple supported timber floor is considered, where timber beams have a section of 18 x 18 cm, spaced 50 cm, which is a recurrent configuration for the floor structure in Italian historical buildings. The deck system is composed with a simple layer of wood planks (3 cm thick), crossly arranged and nailed to the timber beams (4 nails per intersection between board and beam, see figure 2a). Starting with this configuration, five different reinforcement techniques were studied, which are described in the cited Italian standard as possible approaches in order to increase the in plane stiffness and therefore the building robustness. Moreover, in some cases, the existing floor can benefit of a higher level of out-of plane strength and stiffness, depending on the different techniques considered, as in the case of the timber-to-timber or timber-to-concrete composite structure.
In the first strengthening technique considered, a second layer of wood planks (100 cm width, 3 cm thick) is used, crossly arranged to the existing ones and fixed to the beams by means of 6 mm steel screws (from 2 to 4 screws per intersection between board and beam, see figure 2b).
The application of diagonal bracing (45°) on the existing wood planks, can be done utilizing light gauge steel plates (80 mm wide, 2 mm thick), screwed to the boards (20 screws per m, diameter 5 mm × 25 mm, see figure 2c), or wide strips of CFRP (50 mm wide, 1.4 mm thick), glued to the wood by means of epoxy-based resin (see figure 2d). The mesh of diagonal bracing applied to the floor is 705 mm for both techniques analyzed.
Another strengthening technique analyzed makes use of three layers of plywood panels (21 mm thick), arranged on the existing wood layer, and connected to timber beams by means of polyurethane glue and 10 mm steel rods (glued with epoxy based resin, see figure 3e).
A reinforced concrete slab connected to the timber beams (see figure 3f) is a strengthening technique which was widely used in the past decades when restoring timber floors. Regular concrete slab (50 mm thick) is built on the wood planks; the slab reinforcement is composed by a welded steel mesh (6 mm diameter, mesh 200 × 200 mm). The connections between the timber beams and the concrete slab is obtained by means of L shaped profiled rods (rebars FeB 44 k, 16 mm diameter, 150 mm and 50 mm edges, epoxy glued to timber beams in holes 90 mm deep).
The in-plane shear behavior of the horizontal diaphragm subjected to seismic action can be schematically illustrated as in Figure 5. The lateral forces must be transmitted to the shear masonry walls parallel to the seismic action, and therefore an adequate link between the floor and the walls must be assured.
Moreover the in-plane deflection of the slab induces compression and tension zones in the deck. Compression stresses can be counteracted by the wood planks, while for the tension stresses a reinforcement element must be on purpose designed.
Two technological solutions were considered in the analysis. For the floor typology depicted in Figures 3.a, b, c d , a steel tie ring encloses the perimeter of the floors. This tie beam has the double role to take up the tension stresses of the deck, and to transmit the shear forces to the lateral walls.
In the solution proposed by Doglioni (2000), an L-shaped profile is connected to the floor by means of screws; both the end sides of the profile are linked to the lateral masonry through threaded steel bars (diameter varying from 20 to 30 mm), which are chemically or mechanically connected to the masonry walls (see Figure 4). Along the floor border, additional connectors can be placed, in order to guarantee the shear transmission to the lateral walls, and to prevent the possibility of out-of-plane mechanisms.
For the concrete slab floor depicted in Figure 3e, the concrete tie ring is guaranteed by additional steel bars inserted along the border of concrete deck (see Figure 4.a), in order to avoid the insertion of a concrete beam "inside" masonry, that can weaken significantly the existing walls.

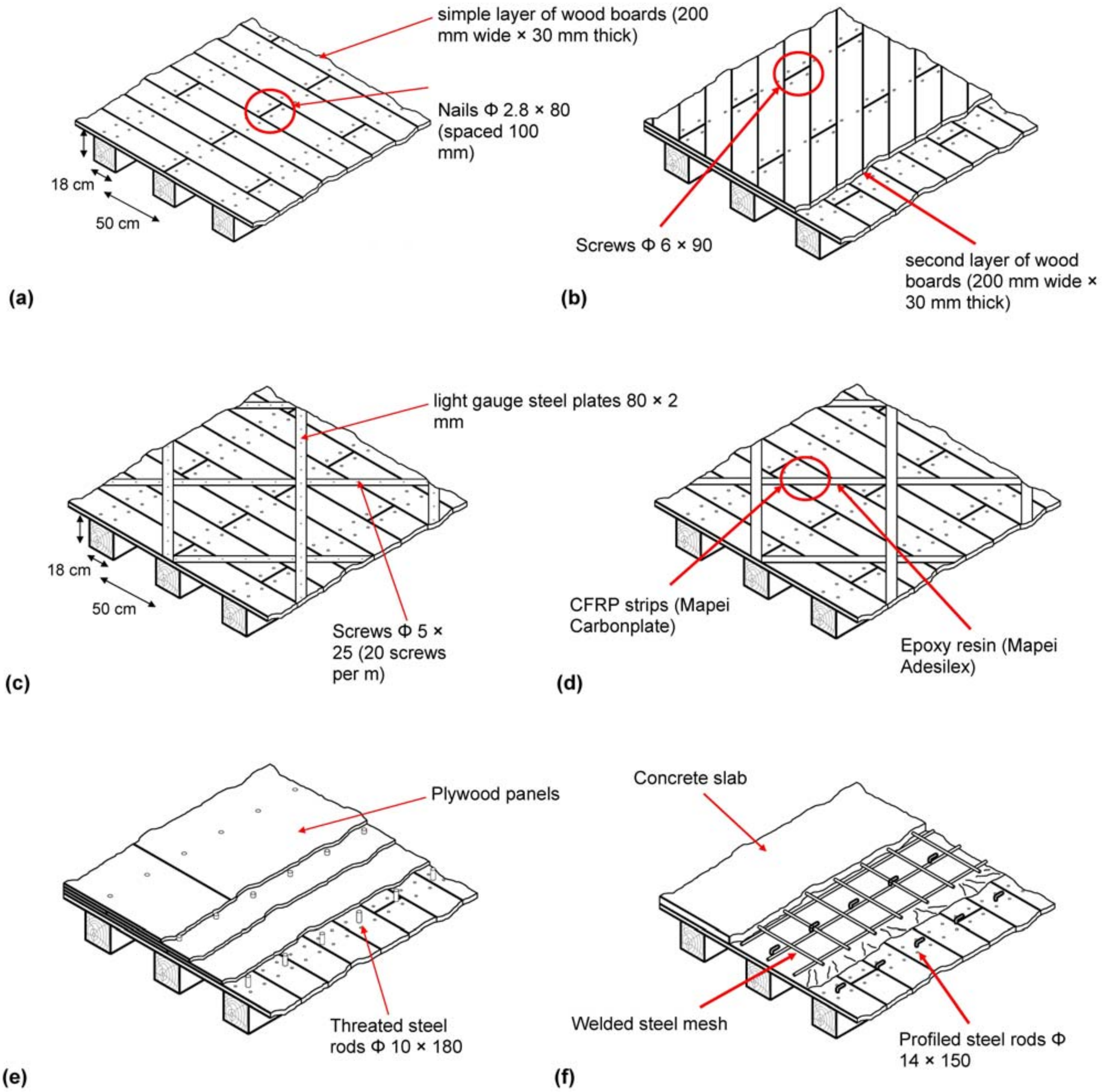

Figure 2. Different timber floor in plane shear strengthening techniques: (a) existing simple layer of wood planks on the timber beams; (b) second layer of wood planks crossly arranged to the existing one and fixed by means of steel screws; (c) diagonal bracing of the existing wood planks by means of light gauge steel plates; (d) diagonal bracing of the existing wood planks by means of FRP laminae; (e) three layers of plywood panels glued on the existing wood planks; (f) a RC slab connected by means of studs (all measures in mm)

## 3. EXPERIMENTAL CAMPAIGN

### *3.1. Test set-up*

The experimental test apparatus was thoroughly designed taking into account the specimen dimensions, the boundary conditions and the load configuration. The floors were built in the laboratory adopting different specimen sizes: the first monotonic pilot tests were performed on small size floors (1 × 2 m); then the cyclic tests were performed on real size floor specimens (4 × 5 m).

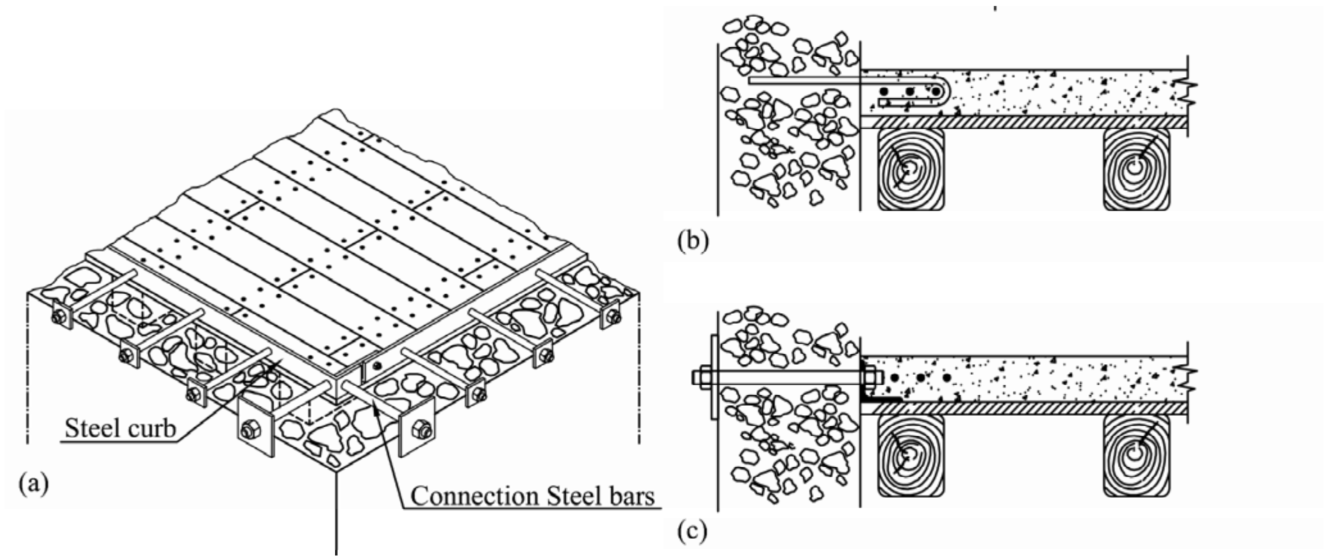

Figure 3. (a) Steel tie beams between the shear reinforced planking and the masonry walls, (b) Connection between the concrete tie beam and the walls, and (c) between the steel tie beam and the walls.

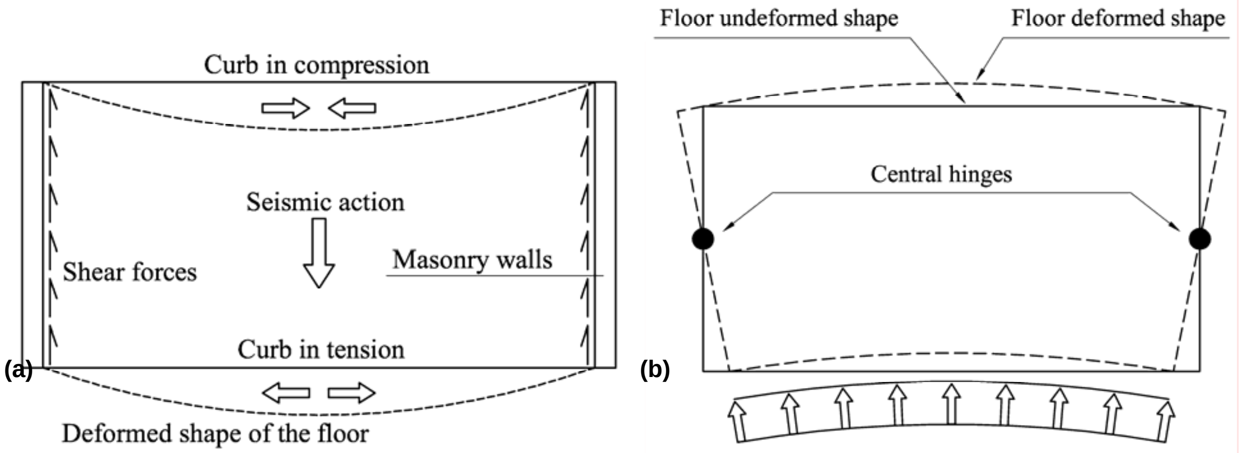

Figure 4. (a) Actual "in-situ" behavior of the horizontal diaphragm, taking into account the real boundary condition and the role of the lateral connectors; (b) set up configuration adopted for the laboratory tests

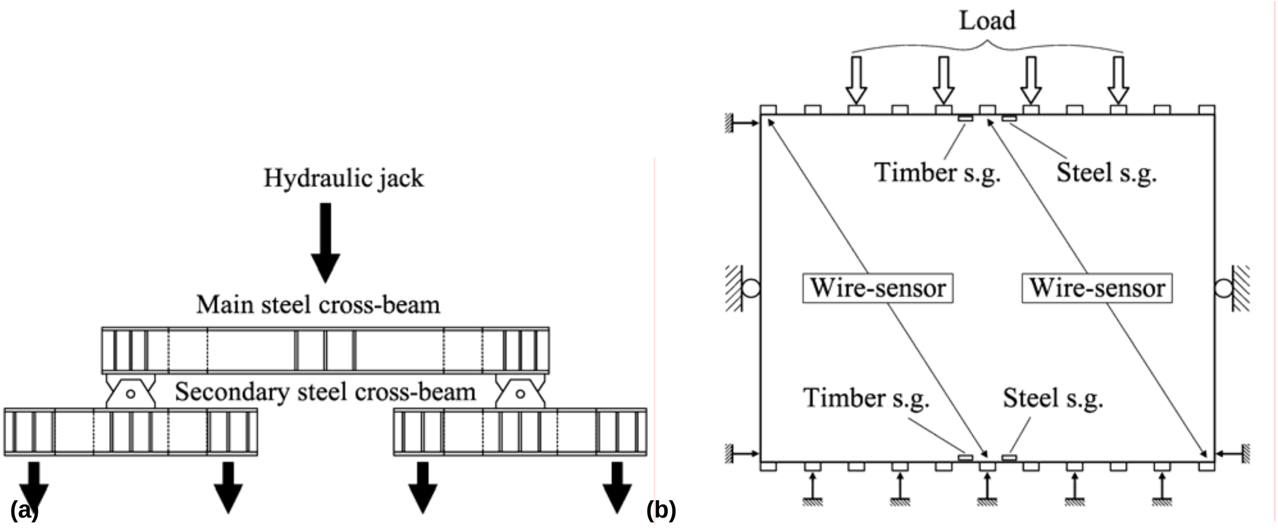

Figure 5. (a) whiffle tree set-up adopted for the force transmission; (b) instrumentation layout

In both test configurations, real size timber elements were used: beams (0,18 × 0,18 × 4,2 m), planks (0,2 × 0,03 × *l* m, with *l* varying from 0,6 to 1,6 m), and the previously described reinforcement elements. The real size dimensions showed to be necessary in order to correctly simulate the real contribution of the secondary elements (planks and reinforcement elements).

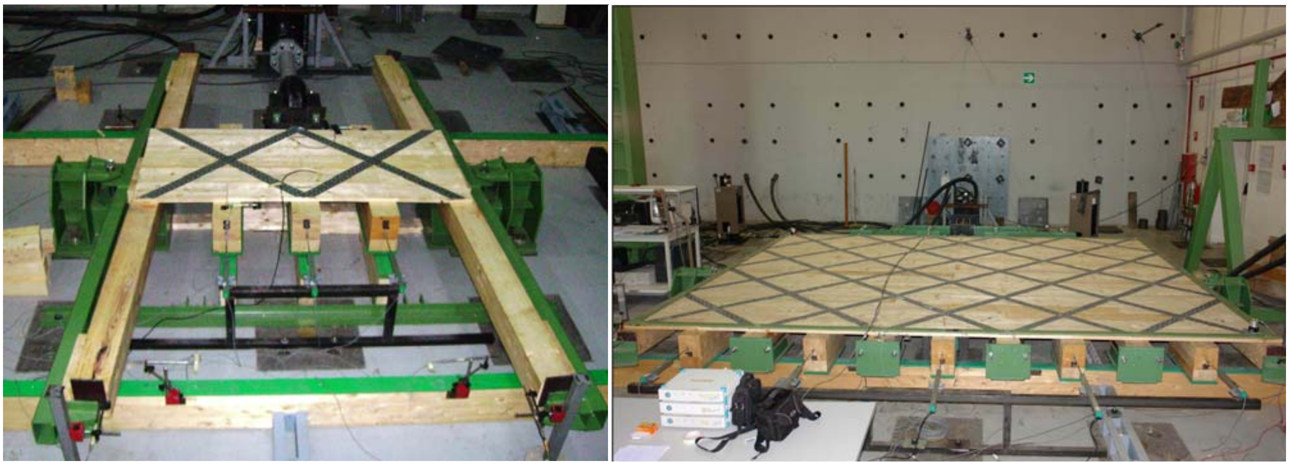
(a) (b)

Figure 6. Set-up adopted for the preliminary monotonic test (a) and for the cyclic tests (b)

Another important aspect concerning the design of the test apparatus is the boundary conditions of specimens.
Instead of reproducing, in the test apparatus, the actual boundary conditions of the floor in situ, the adopted design approach was intended to allow free in-plane deformation of the diaphragm. In fact an experimental reproduction of the interaction between floor and masonry wall was considered unpractical, with many problems involved in understanding and analyzing the experimental results. On the contrary, the adopted configuration allows an accurate measuring of the in-plane stiffness of the deck, which is one of the key parameters in the structural restoration design. Therefore the floor specimen was linked to the laboratory reaction floor by means of two external hinges, according to the scheme depicted in Figures 5 and 6. The hinges are positioned centrally, at the neutral axis level.
Particular attention was paid on the loading system, in order to reproduce the transmission of seismic forces through the floor. During an earthquake, the lateral forces are proportional to the vertical load applied on the floor, which can be considered uniformly distributed. Therefore a uniformly distributed horizontal action should be applied to the floor under experimentation.
The setup adopted for the force transmission is depicted in Figure 5, where two levels of steel cross-beams were adopted in order to distribute the load of the single hydraulic jack onto four timber beams. A preliminary numerical analysis proved this configuration to be able to accurately reproduce a uniformly distributed load.
Four different load configurations were considered, from the theoretical condition of uniform load to the real condition adopted during the test, which can be estimated sufficiently accurate according to the numerical results reported in Table 1. It is worth nothing that the real size floor tested is made up of 11 timber beams.

Table 1. Comparison of the numerical floor deflections

| Load | Displacement | Deviation | |
|---|---|---|---|
| | (mm) | (mm) | (%) |
| Uniform | 25,65 | - | - |
| 11 beams | 23,86 | 1,79 | 7,0 |
| 6 beams | 23,38 | 2,27 | 8,8 |
| 4 beams | 23,54 | 2,11 | 8,2 |

The floor specimens and the steel beams forming the test apparatus rested on some timber supports fixed to the reaction floor. In order to reduce friction effects during the tests, Teflon plate were added at the interfaces between materials.

In the real size specimens, cyclic tests were performed, therefore the loading system should work in both directions: beside the pushing system depicted in Figure 5, a pulling system composed by steel plates applied to both ends of the floor beams, and connected with pre-tensioned tie-rods, was adopted (Figure 6).

Movements, deflections, and loads were measured at multiple locations on the diaphragm specimens using electronic sensors of various types, connected to a computer controlled data acquisition system.

In Figure 5b, the instrumentation layout is shown. In order to find the in-plane shear deflection of the floor, two wire sensors were used, diagonally arranged. At the ends of the 5 beams, not directly loaded, 5 LVDTs transducers were used in order to record the floor in-plane deformation.

Three other LVDTs instruments were placed for finding lateral movements of the tested floor (orthogonally to the jack direction); finally, in the zones of the slab characterized by maximum tension/compression stresses, 4 strain gauges were used, 2 of which applied on the metallic profile and 2 on the planks, so to find the efficacy of the steel tie beam.

### *3.2. Test protocol for cyclic tests*

Cyclic quasi-static tests were performed under displacement control, with a loading rate varying from 0,05 e 2 mm/s, according to the test procedure described in the European standard EN 12512.

In this procedure, cyclic tests are defined as a function of the yielding value, which can only experimentally be determined through a preliminary monotonic test. Such preliminary tests were conducted on the small size specimens, with the hydraulic jack acting only on the central timber beam.

## 4. EXPERIMENTAL RESULTS

### *4.1. Floor shear stiffness*

The test program has been concluded for all the floor typologies depicted in figure 2.

The preliminary monotonic test results, which were carried out on small size specimens (1×2 m) without using the steel ring tie, are reported in the diagram of figure 7.a in term of force of the hydraulic jack versus the displacement of the central timber beam, for the different techniques analyses. The cyclic test just for the simple board reference floor is reported in figure 7.b, also in term of force of the hydraulic jack versus the displacement of the central timber beam. For the cyclic protocol all the real size specimens (4×5 m) were tested adopting a steel ring tie along the perimeter of the floor.

Those diagrams can adequately represent the in plane stiffness of the floor: the value of stiffness was taken, from monotonic tests, according to the precise procedure described in EN 12512. For real size specimens the stiffness was carried out directly from cyclic diagrams, adopting a graphical method.

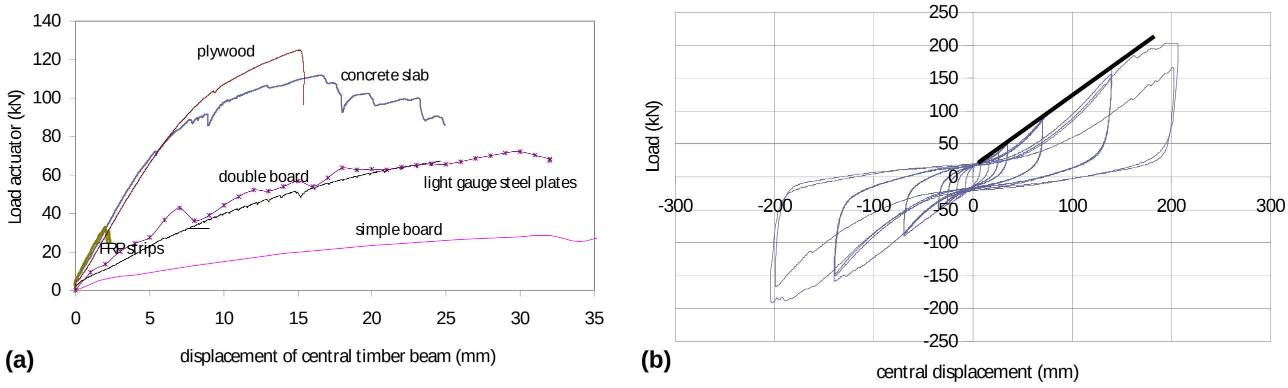

Figure 7. Experimental results for monotonic small size specimens (a), and cyclic test results on the timber simple board floor (b)

Both small size and real size specimens confirmed a common “hierarchy” in terms of in-plane stiffness, between the different refurbishment techniques considered in the analysis (see figure 9.a). Starting from the reference simple board floor, the sequence seems to be the double board floor, the diagonal bracing system (where the FRP strips seems more effective than the light gauge nailed plates), the concrete slab and the plywood planks (this latter showing surprisingly an higher value than the concrete).
Considering the different geometry configuration between the small size and real size test set-up, is not convenient to define the floor stiffness as the ratio between the force of the hydraulic jack $F_t$ and the displacement of the central timber beam Δ, as reproduced in figure 8.

$$k = \frac{F_T}{\Delta} \quad (\text{kN/mm}) \tag{4.1}$$

In order to get the results independent from the geometry, an equivalent shear modulus has been defined:

$$G = \frac{F_T \cdot L}{4 \cdot \Delta \cdot B \cdot t} \quad (\text{MPa}) \tag{4.2}$$

where $t$ is the thickness of the board (see figure 8).

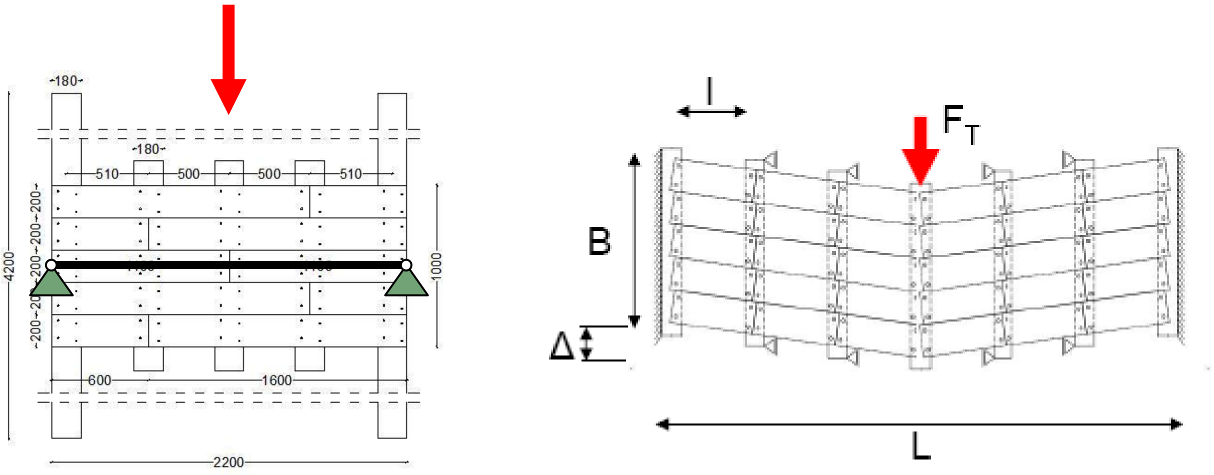

Figure 8. Experimental set up and loading configuration for small size specimens (a), in plane deformation of timber floor, geometrical parameter for the equivalent shear modulus $G$ (b)

According to figure 9b, is worth noting that the real size specimens provided higher values in terms of stiffness for the refurbishment techniques depicted in figure 2c, d, e, f. This fact seems to confirm the opportunity to consider real size specimens for accurately detect the in-plane stiffness of the floor, with a load system more similar to the actual seismic load configuration. Analyzing the experimental results of real size specimens in terms of equivalent shear modulus, we can conclude that, compared with the reference floor system, the double board floor seem to increase the original stiffness more or less ten times the experimental, the concrete slab and plywood planks seem to increase up to one hundred times. Between those techniques and intermediate behaviour is provided by the diagonal bracing system (from 20 to 50 times the original in-plane stiffness value).

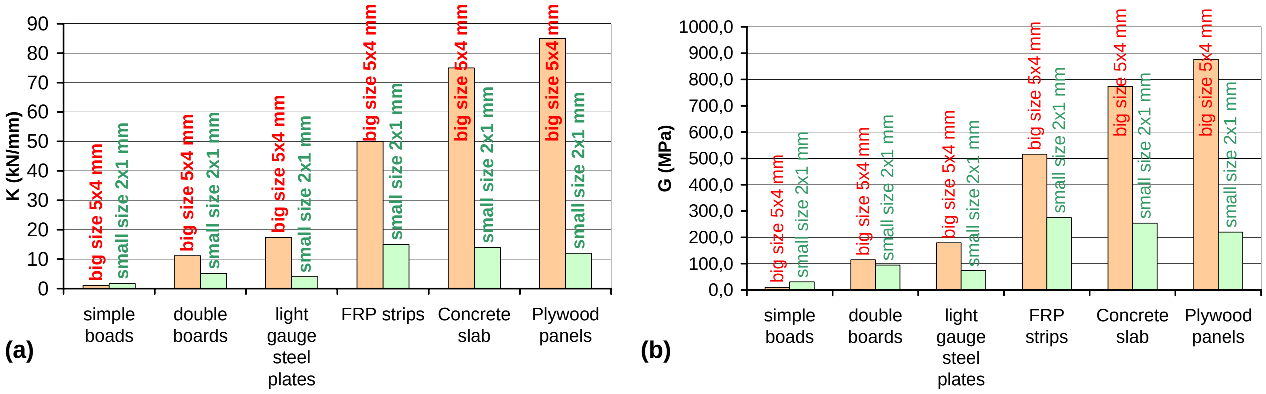

Figure 9. Experimental results for small size and real size floor specimens in term of a general stiffness parameter k (a), and a equivalent shear stiffness parameter G (b)

## 5. CONCLUSIONS AND FUTURE WORKS

The in-plane stiffness of the floors strongly affects the structural behavior of an existing masonry building subjected to seismic action. It defines the seismic distribution of forces on lateral walls and the request displacement for verifying the out–of–plane mechanism of the walls.
The real size used for the specimens proved to be very important in order to determine the in-plane stiffness of the floor and to adequately simulate the real contribution of the secondary elements (planks and reinforcement elements).
The tests showed also the efficiency and the contribution of the steel ring tie, mainly in terms of strength rather than of the initial stiffness. The possibility to have many connectors along the floor border guarantees a nearly uniform transmission of shear forces to lateral walls. Its strength contribution is essential in the tension zones of the deck. Finally, the ductility of steel curb ensures a constant strength contribution when cyclic loadings are applied.
Some main conclusions, regarding the experimental tests done, can be hereafter summarized:

- the experimental results of the so-called “small specimens” seem to be affected by a sort of size effect;
- the specimens with CFRP strips applied show to be more stiff than those with light steel gauges;
- the stiffness of the specimens with three layers of plywood and those with a concrete slab are similar;
- the steel ring tie doesn’t seem to affect the in-plane stiffness values of the diaphragms.

Future researches will take into account other kind of refurbishment techniques, always with particular regard to the in-plane stiffness of the floor.
For the next phase of the research, we are developing suitable equivalent shell models for the timber floors differently refurbished so to be possible to easily adopt them for the numerical modelling of traditional buildings. This will allow to study the effectiveness of the different in-plane strengthening techniques on the overall behaviour of a masonry building, by means of reliable numerical models, in order to organize a guidance for adopting adequate strengthening strategies for existing timber floors and to optimize them for each particular building.

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