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Experimental tests on wood-based in-plane strengthening solutions for the seismic retrofit of traditional timber floors

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HIGHLIGHTS

- Timber-based floor strengthening solutions are reversible and minimally invasive.
- Reinforced floors evidence an interesting in-plane stiffness and strength increase.
- Some reinforced floor configurations maintain the load after several cycles.
- The tests demonstrated a dissipative cyclic behaviour of reinforced timber floors.
- Low-weight timber-based solutions can be alternative to the use of concrete topping.

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ABSTRACT

Traditional timber floors in masonry buildings are characterized by low in-plane stiffness and lack of effective connections to the main walls, so the structure seismic performance is negatively affected and a reinforcement is often needed. In-plane dry strengthening solutions for timber floors in existing masonry buildings are faced: OSB panels or CLT panels were connected to 12 traditional full-scale timber floors and tested under monotonic and cyclic loads. The results of the tested solutions are compared to the unreinforced floor results. The whole experiment supports the effectiveness of this kind of strengthening intervention.

1. Introduction

Past earthquakes evidenced the high vulnerability of historical masonry buildings to seismic actions. Their capacity is influenced by the development of local collapse mechanisms, which involve the formation of rigid blocks independently responding to inertial loads. The formation of these mechanisms precludes a global response of the building and strongly reduces the resistance to earthquake loads [1–4].

The presence of floor and roof diaphragms in masonry buildings allows to effectively transfer the seismic loads to the shear resistant walls and to rely on a global box behaviour. Traditional timber floors, generally made with joists and planks, are characterized by low in-plane stiffness and by lack of effective connections to the main masonry walls, thus increasing the probability of local collapses [5]. In earthquake prone areas, timber floors and roofs have often been subjected to invasive substitutions by means of reinforced concrete slabs. On-site inspections after the most recent earthquakes in Italy have proven the inefficiency of these kind of interventions on buildings of poor masonry quality, where they often caused new and more brittle collapses [6,7]. Another widely used technique for floor strengthening is based on the connection of a new concrete topping to the existing timber floor. The concrete slab, if properly connected with the vertical walls, is able to give an effective three-dimensional behaviour to masonry buildings, thus improving the lateral load resistance. Fasteners generally assure the effective collaboration between the two different materials, also increasing the floor flexural stiffness and strength. A thin concrete slab, however, adds undesirable weight on the floor and, consequently, the seismic actions and the foundation loads increase. The use of lightweight concrete for the slab has been considered in composite floors and it can partially solve this problem [8]. However, the concrete slab is now often considered not sufficiently

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reversible and therefore it may be not allowed in listed buildings of historical value.

Thanks to an increased sensibility towards the preservation of cultural heritage [9,10], the attention is now focused on strengthening techniques which can guarantee as much as possible the conservation of the materials and of the original function of the structure, the reversibility of the intervention and its compatibility with the existing parts of the buildings. Different less invasive and reversible solutions have been developed for the in-plane strengthening of timber floors, based for example on the use of steel elements, Fiber Reinforced Polymers (FRPs) or timber based elements.

Several tests have been performed on reinforced timber floors considering an in-plane pure-shear load set-up. Among these it is worth acknowledging the tests described in [11], where ten specimens of size 3.0 m × 3.0 m were tested, considering two wooden floor typologies and different reinforcements: a second layer of planks, Glass Fiber Reinforced Polymer (GFRP) composite materials or a reinforced concrete slab.

A similar set-up has been used in [12], on slightly smaller specimens (about 2.2 m × 2.2 m): diagonal punched metal strips and single or double layers of diagonal boards placed over the existing floorboard were considered. In [13], specimens of the same size were strengthened with a second layer of boards, placed orthogonal to the first layer, or with Cross-Laminated Timber (CLT) panels of 65 mm thickness. In [14] a new layer of boards with 45° inclination is placed over the original floorboard and steel plates (100 mm × 3 mm cross section) are nailed along the specimen perimeter. The same set-up is used also in [15], considering timber floors of 4 m × 4 m size, subjected to cyclic loading. Nailed steel plates used to join adjacent timber boards or diagonal Carbon Fiber Reinforced Polymer (CFRP) strips are considered as strengthening techniques.

A different test set-up, intended to allow a pure-bending in-plane deformation of the floor, is considered in [16]. The as-built timber floor specimens, of size 5.0 m × 4.0 m, are strengthened with different configurations: a second layer of wood planks, a diagonal bracing made by light gauge steel plates or CFRP strips, a triple layer of plywood panels and a reinforced concrete slab. In [17] and in [18] the chosen set-up aims to reproduce the actual loading and boundary conditions of a real floor. Both shear and flexural deformations, as well as floor-to-wall shear connectors, were considered in the tests. In the first study, three floor specimens (size 7.3 m × 3.7 m) were tested using different retrofit methods, including enhanced perimeter shear connectors, a steel truss attached to the bottom of the joists and plywood overlays connected to sheathing and joists. In the second one, ten floor specimens (size 4 m × 3 m) were tested, five representing an as-built configuration and five retrofitted by means of a new plywood layer on the top of the floor boards.

A similar set-up is used in [19], where tests were performed in both the principal loading directions, considering also the effect of a typical stairwell opening on the diaphragm performance. Four as-built diaphragms and four retrofitted diaphragms of size 10.4 m × 5.5 m were tested. In retrofitted diaphragms a plywood panel overlay with stapled sheet metal blocking systems (SMBS) is applied.

The test results from different experimental campaigns highlight the nonlinear and low stiffness orthotropic behaviour of the as-built timber floors. The different proposed retrofit solutions can effectively improve the floor shear stiffness and strength. However, many authors [18–20] have underlined the poor estimate of floors in-plane properties using available standards [21–24].

Despite the importance of a correct evaluation of the in-plane response of floor timber diaphragms, the scientific literature is not yet exhaustive. The few tests available are generally referred to different setups, test rigs and boundary conditions, and to different size and aspect ratio of the floor samples, making difficult a comparison of the results. Also, the recorded parameters and the formulas used in literature to evaluate the stiffness are very different, so it is difficult to achieve a shared approach to stiffness evaluation. More experimental tests are needed to complete an exhaustive experimental database, in order to check the reliability of the analytical models already proposed or to develop new ones [25].

In this paper, an extensive experimental campaign is carried out in order to characterize the effectiveness of timber-based, dry-connected strengthening solutions for the in-plane retrofit of timber floors [26,27]. Twelve full-scale floor specimens are subjected to monotonic and cyclic tests. Traditional timber floors made by joists and boards have been considered as unreinforced specimens. The chosen configuration (joists spacing, boards size, nails size and spacing) is typical of floors in existing masonry buildings in many areas of Europe. The considered reinforced configurations use Oriented Strand Boards (OSB) panels [28] or Cross-Laminated Timber (CLT) panels [29], dry connected to the unreinforced floor, in order to increase the in-plane stiffness and strength. These strengthening solutions are reversible and minimally invasive and are characterized by low mass and low thickness, thus evidencing great benefits for the restoration of existing buildings. Different fasteners (ring-type nails and self-tapping screws) have been considered.

The experimental results are compared in terms of stiffness, strength, dissipated energy and strength degradation.

2. Materials and methods

In this section the full-scale floor specimens are described, together with the results of specific tests on materials and on the behaviour of the adopted fasteners.

The test set-up, here detailed, was specifically designed to apply an in-plane shear load on the full-scale specimens.

Table 1
Overview of the timber floor specimens.

ID	Reinforcement	Fasteners	Loading protocol
UR-0	–	–	monotonic
UR-1	–	–	cyclic
UR-2	–	–	cyclic
OSB90-R-0	OSB panels, perpendicular to joists	ring-type nails	monotonic
OSB90-R-1	OSB panels, perpendicular to joists	ring-type nails	cyclic
OSB90-R-2	OSB panels, perpendicular to joists	ring-type nails	cyclic
OSB0-R-1	OSB panels, parallel to joists	ring-type nails	cyclic
OSB0-R-2	OSB panels, parallel to joists	ring-type nails	cyclic
OSB0-S-1	OSB panels, parallel to joists	self-tapping screws	cyclic
OSB0-S-2	OSB panels, parallel to joists	self-tapping screws	cyclic
CLT0-S-1	CLT panels, parallel to joists	self-tapping screws	cyclic
CLT0-S-2	CLT panels, parallel to joists	self-tapping screws	cyclic