

# Improved natural hydraulic lime mortar slab for compatible retrofit of wooden floors in historical buildings



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## HIGHLIGHTS

- Use of NHL composite overlay in substitution of traditional concrete slabs.
- Structural effectiveness of the technique assessed through full scale experimental tests.
- Material tests and local tests on the wood-mortar stud connection.
- The retrofit enables substantial reduction of the floor deformability, with the floor stiffness increasing by  $4.2 \div 6$  times.
- The solution increases the beam load bearing capacity by  $5 \div 6$  times.

## ARTICLE INFO

### Article history:

Received 3 March 2017

Received in revised form 28 September 2017

Accepted 2 October 2017

### Keywords:

Rehabilitation  
Historical buildings  
Wooden floors  
Natural hydraulic lime  
Compatibility  
Connections  
Mortar-wood beams  
Overlays

## ABSTRACT

Stiffening of wooden floors is often required in the rehabilitation of historical buildings to reduce their deformability in service conditions. Among various techniques available in the literature, the application of an extrados reinforced concrete overlay is often selected because cost/structurally effective and relatively simple to place. Nevertheless, Ordinary Portland Cement (OPC) concrete is considered poorly compatible with historical structures and materials and is, therefore, not well received, especially in case of valuable heritage and monumental constructions. A new retrofit solution based on the replacement of OPC with improved natural hydraulic lime (NHL) is proposed. Like the traditional OPC concrete overlay, the novel solution with improved NHL allows the conservation of the existing planks, and, thus, preserves the integrity of the wooden ceiling. The structural effectiveness of the proposed technique is investigated through experimental tests on full scale beams with different geometries. Full scale tests are supported by material tests and tests on the wood-mortar stud connection, a key aspect of the beam design. Based on the literature in the field of OPC concrete-wood composites, analytical models are developed and applied to predict the behavior of the NHL mortar-wood stud connection and composite beams. Results in terms of both stiffness and strength are encouraging and set the path for the application of NHL mortar overlays in the rehabilitation of heritage wooden floors.

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## 1. Introduction

Rehabilitation of wooden floors is a typical requirement in the restoration of historical buildings. Many old wooden floors exhibit excessive vibrations and large deformability in service conditions. In order to prevent damage to floors, partition walls, and all non-structural elements, the enhancement of the structural stiffness

is often required. Although less frequently, strengthening may as well be needed to improve the overall structural capacity.

Different stiffening/strengthening techniques were developed, mostly based on the design of a composite cross section obtained by coupling the wooden element with an extrados overlay; special connections are employed to allow proper shear transfer between the coupled elements. Among the most common solutions, it is worth acknowledging the following technologies: (i) application of an ordinary or high performance concrete slab [33,1,18,16,11,26], (ii) use of a very thin steel plate [12], (iii) application of Fiber Reinforced Polymers (FRP) for restoration and strengthening

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[31,25,10,37], and (iv) timber-to-timber or timber-to-Cross Laminated Timber (CLT) composite sections [27,18,22,39,34,4,21]. Each solution has its own advantages and shortcomings, which determine the fields of use as briefly discussed hereafter.

Timber-timber and timber-CLT composite cross sections are considered especially interesting as this dry strengthening technique is reversible and highly compatible with the existing floor [22]. An overlay obtained with either additional wooden planks or plywood panels is advantageous to limit structural weight increase [27,18]. As a drawback, however, they can be less effective than the other techniques in providing a satisfactory enhancement of the structural performance, especially in terms of bending stiffness. For further enhancement of bending stiffness, timber-timber cross sections with higher thickness can be adopted, although there may be a conflict with practical limitations to the maximum floor height increase [22,39,34]. When the maximum floor height increase is limited, timber-CLT composite sections can represent a valuable alternative [21,4]. The use of a very thin steel plate, stud-connected to the existing floor, provides higher load-bearing capacity [17]; however, this technique may entail problems in positioning the finishing pavement and may hardly be accepted for listed buildings. The solution with a thin reinforced concrete slab is effective in stiffening the floor and allows for easy leveling of the floor extrados in the case of very deformable floors. Thickness and weight of the overlaying slab can be optimized by accurately designing the cross section at the mid span (Fig. 1). Thick concrete ribs are placed on top of the wooden joists to maximize the structural performance; in order to level the extrados, a composite layer of thinner concrete slab and lightweight polystyrene panels can be placed on top of the wooden plank in the other areas of the floor. In applications where the dead load added by the slab weight entails excessive stress levels in the wooden beam during the transitory stage of concrete pouring and hardening, propping may be necessary prior to casting. More recently, solutions with high performance concrete were successfully investigated; encouraging results showed that the high mechanical properties of this specialized cement-based material allow for a minimization of the slab thickness and the related dead load increase [26]. Different applications of Fiber Reinforced Polymer (FRP) proved to be structurally effective for strengthening and restoration of timber beams. FRP strips were placed inside the cross section of timber beams to preserve richly decorated ceilings [31]. Alternatively, FRP sheets can be applied externally for shear and bending reinforcement [37,10]. Li et al. [25] also suggested a double reinforcement solution for beams exhibiting hollow sections due to significant internal decay; the authors proposed combining a prestressed FRP bar

applied through the hollow section with an external FRP sheet for additional reinforcement. It is worth noting that the effectiveness of the FRP reinforcement relies on the proper adhesion to the timber and resistance to delamination [37], which may be critical especially in the case of beams exposed to significant variation of the hydrothermal conditions.

In the light of well-known compatibility issues, mainly related to hindering moisture release, mechanical incompatibility inducing differential stresses/strains, and detrimental chemical reactions caused by the chemical composition of Ordinary Portland Cement (OPC) concrete among others: [40,35], the use of Portland cement in the retrofit of masonry buildings – especially masonry components but also wooden floor – is discouraged. In addition, Italian Cultural Heritage Offices strongly disapprove the use of Portland cement-based materials and rather encourage the use of more traditional materials, especially in the retrofit of listed buildings.

Other materials such as natural lime, commonly found in the original substratum underneath the pavement layer of historical buildings, represent a more compatible alternative to Ordinary Portland Cement (OPC). In addition, natural lime, requiring lower temperatures of calcination than OPC, has a lower carbon footprint and is therefore considered more sustainable than OPC [24,32]. According to the Inventory of Carbon and Energy of the University of Bath (ICE v2.0, [23]), which collects statistical data from all major European databases and is acknowledged as representative of the average impact of the European production, the manufacture of 1 ton of Ordinary Portland Cement (OPC) is responsible for the emission of 0.95 ton CO<sub>2</sub>. For Natural Hydraulic Limes (NHL), CO<sub>2</sub> emissions depend on the NHL class and is equal to 0.415 ton of CO<sub>2</sub> for 1 ton of NHL5 and 0.336 ton of CO<sub>2</sub> for 1 ton of NHL3.5 (classification follows EN 459-1:2010 [9]). In other words, 0.535–0.614 kg(CO<sub>2</sub>)/kg(binder) are saved by replacing OPC with NHL.

A new retrofit solution for wooden floors, based on the use of structural Improved Natural Hydraulic Lime (NHL) mortars is proposed and discussed in this paper. The retrofit is applied as a stud connected lime mortar slab overlaying the existing wooden floor (Fig. 1). Like other solutions, this technique preserves the integrity of the wooden ceiling as neither removal nor sawing of the existing plank is needed.

Similarly to the technique adopted with OPC [18], the NHL slab has potential to be also conceived as an in-plane shear diaphragm that will reduce the seismic vulnerability of the building, if appropriately connected to the masonry perimeter walls; this use of the NHL reinforcement is subjected to an ongoing research and is beyond the scope of this paper.

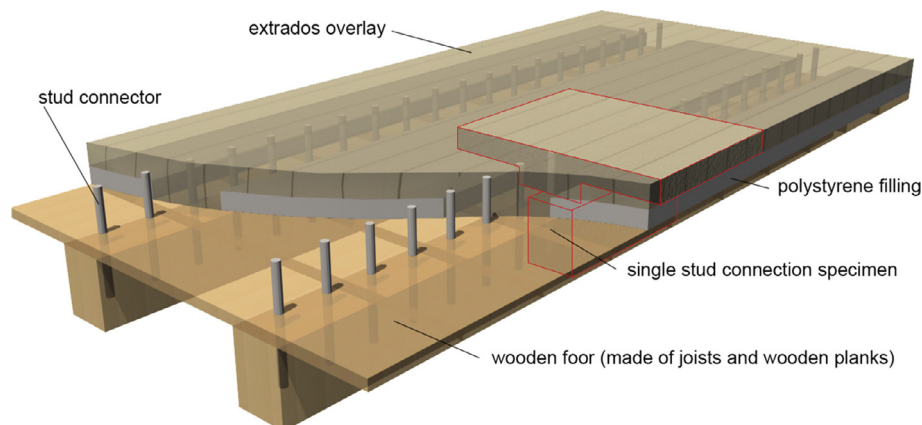


Fig. 1. Typical solution for wooden floor retrofit with extrados overlay and lightweight panel.

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