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Efficacy Assessment of Timber Based In-Plane Strengthening of Wooden Floors on the Seismic Response of Masonry Structures by means of DEM Analyses

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Abstract

Masonry buildings are highly vulnerable to seismic loading, and their dynamic response is strongly influenced by the timber floor in-plane deformability and by the quality of the wall-to-floor connections. Understanding the behavior of timber floors and roofs and their interaction with the masonry walls is therefore important for the protection of historical buildings. In a previous research project, different timber-based dry-connected floor strengthening solutions were tested under in-plane loads. The experimental results show a significant increase in shear strength and stiffness.
Discrete Element Method is here used to evaluate the effectiveness of the strengthening solutions in avoiding the triggering of the out-of-plane collapse of masonry walls, first on a simple masonry cell, and then on a heritage listed masonry building. A detailed cyclic model of the floor behavior was implemented: the unreinforced and reinforced floors were described by beams connected with non-linear springs, reproducing the experimental hysteretic response. Both the case studies highlight the effectiveness of the strengthening solutions in reducing the out-of-plane displacements of masonry walls, confirmed also by a comparison with the ideal rigid diaphragm case. The reinforced floor is able to transfer the seismic forces to the shear-resistant walls. The out-of-plane displacements are compatible with the wall capacity, and the reinforced floor hysteretic cycles contribute to dissipate part of the input energy. Moreover, a proper connection design can also cap the transferred seismic forces to an acceptable level for shear-resistant walls.

Keywords: Retrofitting intervention; Timber floor; Seismic loading; Discrete Element Method; Non-linear dynamic analysis

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1. Introduction

Several factors affect the dynamic behavior of existing masonry buildings: the in-plane flexibility of traditional timber floors and the lack of effective connections to load bearing walls are recognized as responsible for the development of local collapse mechanisms. The seismic performance can usually be improved by floors with high in-plane stiffness and proper connections to the walls. In this way a box behavior of the building is achieved, the seismic loads are transferred to the shear-resistant walls and the out-of-plane overturning of perimeter walls are avoided. The first interventions aimed at reaching a box behavior were characterized by invasive substitutions of timber floors with hollow brick and concrete slab floors, but on-site inspections after recent Italian earthquakes demonstrated their inefficiency on buildings of poor masonry quality (Binda et al. 1999; Modena et al. 2004). Furthermore, the modern consensus is that the use of concrete slabs is not sufficiently reversible and therefore not adequate for listed buildings.

Different in-plane strengthening techniques for timber floors have been experimentally studied in recent years, with a particular focus on the reversibility of the intervention and its compatibility with the existing parts of the buildings. These solutions may use steel elements, fiber-reinforced polymer strips, timber boards or timber-based panels (Gubana, 2015; Gubana and Melotto, 2018). Accordingly, numerical studies and analytical models of their in-plane behavior have been proposed (Wilson et al., 2014; Rizzi et al., 2019; Gubana and Melotto 2021 b).

The influence of the mechanical properties of floors on the global seismic behavior of masonry buildings has been the focus of different studies using linear dynamic numerical analysis (Tena-Colunga nd Abrams,1996) push-over analysis (Ortega et al. 2018; Jiménez-Pacheco et al. 2020) and non-linear dynamic analysis (Gubana and Melotto 2021a; Scotta et al. 2018, Gubana and Melotto 2021 c).

In addition to the floor in-plane properties, the quality of the connections between the floors and the vertical elements strongly influences the seismic response. Proper connections are needed to reduce the vulnerability to out-of-plane actions. However, in most existing masonry buildings, timber beams are simply inserted in pockets on the perimeter walls and the force transfer is mainly friction-based. Many solutions have been studied and implemented to connect joists to masonry walls by using steel elements anchored to the floor. A review of these techniques can be found in Moreira et al. (2014).

The results of the cyclic in-plane tests of a previous experimental campaign on different timber-based dry-connected floor strengthening solutions showed a significant increase in shear strength and stiffness (Gubana and Melotto, 2018). The experimental samples replicate traditional timber floors, unreinforced or reinforced with timber-based panels connected to the original floor by means of nails or self-tapping screws. These techniques are reversible and minimally invasive and are characterized by small mass and low thickness. The experimental results were at the basis of a detailed cyclic model of the floor, used to analyze different configurations (Gubana and Melotto, 2021 b). The gathered data were then applied to develop a macroscopic model of the floor cyclic behavior, useful to be included in structural analyses. It was firstly applied to a simple masonry structure (Gubana and Melotto, 2021a) to evaluate the efficacy of the intervention, and then to a more complex listed heritage building (Gubana and Melotto, 2021 c).

The masonry behavior was analyzed by means of the Discrete Element Method (DEM). This has been recently applied to masonry structures, as it allows to consider the complete separation of bodies and the formation of new contacts during the evolution of the seismic event. Stresses and deformations are transmitted by contact forces between blocks, and thus, collapse sequences can be followed in detail. The DEM approach can be adopted to better understand the complex dynamic behavior of masonry structures under seismic action (Bui et al., 2017) and to simulate all the mechanisms (out-of-plane rocking and out-of-plane collapse of masonry piers) observed in masonry buildings without box behavior. Moreover, recent studies (Baraldi et al., 2020, Pulatsu et al., 2020) confirm the efficiency and robustness of the DEM in simulating also the in-plane behavior of regular masonry wall panels.

The application of the floor cyclic model to a simple DEM masonry cell emphasized the capability of the DEM to capture the triggering of the out-of-plane mechanisms of masonry walls and the effectiveness of the considered strengthening interventions in preventing their failure.

Also in the case of a more complex structure, such as the listed building considered as case study in this work, the use of DEM gave several information about the dynamic responses of the structure with un-strengthened and strengthened floors. The results are compared, and the effect of the cyclic hysteretic response of the floor and its capability to dissipate energy are investigated.

2. Model of the timber floor cyclic behavior

Traditional timber floors made by beams and boards were tested as unreinforced specimens in Gubana and Melotto (2018). An overlay of Oriented Strand Boards (OSB) or Cross-Laminated Timber (CLT) was connected to the traditional floor by different fasteners (ring-type nails and self-tapping screws) to increase the in-plane stiffness and strength. Twelve different floor full–size specimens (3 m x 3 m) were tested during the experimental program, under a pure-shear in-plane cyclic loading. Tests were performed applying the shear force on the samples in the joist direction, and this was replicated in the numerical models. Only four experimental results are considered in this study: two regarding traditional timber floor (UR), and two regarding the floors reinforced with Cross Laminated Timber panels (CLT). Moreover, the ideal rigid floor case is considered for a comparison.

The main results of the experimental tests are reported in Table 2. P_{max} is the maximum load reached during the test and G_d is the shear modulus value, evaluated from the experimental measures of the diagonal elongations. The equivalent viscous damping ratio $\nu_{d,max}$ in the cycle at the maximum load is also reported.

Table 1. Mechanical properties of the materials used in the experimental tests (Gubana and Melotto 2018). Coefficients of variation (CoV) are shown in parentheses.

	Description	ρ (kg/m^3)	f_m (MPa)		E_m (MPa)	
Timber joists	Class GL24h, cross section 160 mm x160 mm	480.8 (1.5%)	-		-	
Timber boards	Class C24, cross section 145 mm x 23 mm	472.5 (3.5%)	69.7 (15.7%)		10131 (15.2%)	
CLT panels	Thickness 60 mm, 3 layers of C24 class boards	421.3 (2.1%)	long. dir. 44.6 (13.6%)	transv. dir. 75.8 (9.1%)	long. dir. 9653 (8.8%)	transv. dir. 19531 (12.0%)

Table 2. Timber floor specimens test results, from (Gubana and Melotto 2018).

ID	**P_{max} [kN]**	**G_d [kN/mm]**	**$\nu_{d,max}$ [-]**
UR-1	3.2	0.30	0.281
UR-2	3.7	0.65	0.282
CLT-1	45.6	1.96	0.125
CLT-2	52.1	2.83	0.126

The floor global behavior is modelled in a macroscopic form by using non-linear springs between each couple of adjacent joists, as shown in Fig. 1.

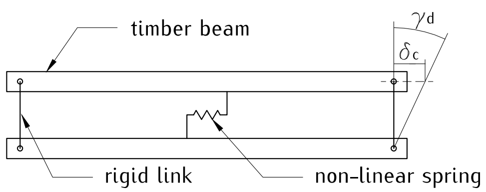


Fig. 1. Modelling approach for the timber floor.

The behavior assigned to the non-linear connectors is directly derived from the experimental tests with a phenomenological approach and it replicates the cyclic hysteretic response. In particular, the stiffness and strength decrease due to the cyclic action are properly taken into account. The assigned properties (stiffness, strength, hardening and damage) are the average ones extrapolated from the experimental results for each floor type.

Due to limits on the available constitutive models, each non-linear connector between the beams is modelled as an assembly of 5 different ABAQUS elements divided into 3 parallel branches. A scheme of the connection model is represented in Fig. 2.

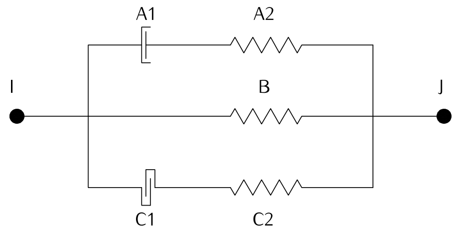


Fig. 2. Scheme of the connection between each timber beam for the simplified modelling of the floor.

The behavior assigned to the spring B is elastic-plastic with kinematic hardening. Branches A and C are made by a stop connector and a non-linear spring in series (A1+A2, C1+C2). Branch A can be loaded only for a positive slip, while branch B only for a negative one. The behavior assigned to springs A2 and C2 is elastic-plastic with kinematic hardening. A displacement failure criterion is defined and the stiffness and strength degradations for high displacements are considered by using the ABAQUS connector damage model.

With this connector model, the pinching effect and the strength and stiffness degradation of the floor can be properly considered. This simplified approach with beam-to-beam springs was used to model the experimental samples and to check the correct response of the non-linear elements.

3. Application of the floor model to a simple DEM masonry cell

A simple single-story masonry cell is taken into consideration to analyze the effect of the timber floor behavior and thus the effectiveness of the strengthening solutions. The numerical simulations are carried out by using the Discrete Element Method with the commercial general-purpose software ABAQUS Explicit. Due to the high computational cost of DEM analyses, this simple case is useful to understand if the chosen numerical approach is adequate and to compare the results of floors with different stiffness and strength.

Four different geometries of the cell structure are considered. The structure has a floor size of about 10.5 m x 6.0 m. Two different floor levels, equal to 3.6 m and 4.4 m, and two masonry thickness values, equal to 40 cm and 60 cm, are considered. Openings are present on the longer walls of the masonry cell. The sizes assigned to the structure are typical of a single room cell in many Italian historic listed masonry buildings. All the analyzed models are reported in Table 3.

In the DEM model, the timber beams lay on the masonry walls and a Coulomb friction interaction is considered between the two materials. The chosen friction coefficient is $\mu = 0.4$. A reduction of the thickness is considered at the top of the walls and the possibility of contact between the joist heads and the masonry is taken into account. In some configurations, elastic links between the floor and the masonry are placed along the perimeter. These links are spaced 50 cm and have a stiffness of 15 kN/mm. This value was chosen considering the relationship reported in Brignola et al. 2012) for a 16 mm diameter steel bar connection.

In the DEM, the heterogeneity of the masonry is explicitly taken into account by considering masonry blocks that interact through contact points at the interfaces. The masonry walls are divided into distinct blocks, whose size is about 0.8 m x 0.6 m x 0.4 m or 0.8 m x 0.4 m x 0.4 m, depending on the considered wall thickness. The block division is not intended to describe the wall texture and the block size is chosen due to computational limits. However, the block size is considered small enough for a first study of the collapse mechanisms of the masonry walls.

The material assigned to the masonry blocks is isotropic, homogeneous and elastic. The density and the elastic modulus are typical of an Italian stone masonry. All the masonry non-linearity is concentrated at the interfaces between blocks. The interaction in the normal direction is of rigid contact with infinite compressive strength. In the tangential direction, a Coulomb isotropic friction relationship is considered.

A cohesive model with a tensile-shear Rankine failure criterion is also adopted. Thus, masonry elements are glued at the beginning of the analysis and, when the interface failure criterion is reached, a separation takes place. From this moment on, large displacements between the two blocks can occur. The tensile and shear strengths and the friction coefficient are typical of the considered masonry type. The properties assigned to the blocks and the interactions are reported in Table 4.

Table 3. List of the performed numerical analyses

ID	Geometry Height	Wall thickness	Floor type	Floor-to-wall connection
H4.4-60-UR-0	H = 4.4 m	60 cm	Unreinforced	Simply supported
H4.4-60-UR-1			Unreinforced	Elastic
H4.4-60-CLT-1			CLT-reinforced	Elastic
H4.4-60-RIG-1			Rigid	Elastic
H3.6-60-UR-0	H = 3.6 m	60 cm	Unreinforced	Simply supported
H3.6-60-UR-1			Unreinforced	Elastic
H3.6-60-CLT-1			CLT-reinforced	Elastic
H3.6-60-RIG-1			Rigid	Elastic
H4.4-40-UR-0	H = 4.4 m	40 cm	Unreinforced	Simply supported
H4.4-40-UR-1			Unreinforced	Elastic
H4.4-40-CLT-1			CLT-reinforced	Elastic
H4.4-40-RIG-1			Rigid	Elastic
H3.6-40-UR-0	H = 3.6 m	40 cm	Unreinforced	Simply supported
H3.6-40-UR-1			Unreinforced	Elastic
H3.6-40-CLT-1			CLT-reinforced	Elastic
H3.6-40-RIG-1			Rigid	Elastic

The ABAQUS "General Contact method" was used and the significant contact pairs have been automatically generated by a Phyton script and applied as "surface to surface contacts".

The reliability of the assigned contact model was assessed recognizing that the density of contact points has a key role in the correct evaluation of the stress distribution and of the failure mechanism. This was done studying simple stacks of blocks for out-of-plane and shear actions, comparing the numerical results with the analytical ones. The contact point density was progressively increased and a mesh size of 10 cm has been chosen as a reasonable compromise between accuracy and computational time (Melotto, 2017).

Table 4. Properties assigned to the masonry blocks and to the interfaces.

Masonry property	**Value**
Density	2100 kg/m^3
Elastic modulus	1700 MPa
Shear modulus	590 MPa
Friction coefficient	0.7
Tensile strength	0.10 MPa
Shear strength	0.07 MPa

The structure is loaded in two stages. In the first one, gravity is applied and the equilibrium state is reached. The vertical loads are the self-weight of the masonry and the floor. A floor load of 5.0 kN/m^2 is applied as a distributed mass. The load is chosen in the hypothesis of a public use of a listed building.

In the second stage, an acceleration history is applied to the rigid base in direction perpendicular to the longer walls and parallel to the floor joists. Three real earthquakes have been considered in this study. The first is the seismic motion recorded during the second shock of the 1976 Friuli (Italy) earthquake, which reached a peak acceleration of about 0.6g. The second is the one recorded during the 2009 L'Aquila (Italy) earthquake, which reached a similar peak acceleration. The third record is the second shock of the 2012 Emilia (Italy) earthquake.

All the detailed results are reported in Gubana and Melotto (2021a).

In general, analyses on the models with the unreinforced floor clearly show the development of an out-of-plane mechanism of the masonry walls. The maximum out-of-plane displacement clearly depends on the geometry of the wall (height and thickness), but it is also strongly dependent on the considered earthquake despite the similar peak ground acceleration. This is due to the different frequency content of the three seismic motions, to the different dynamic response of the structures and to their damage evolution.

When no connection is modeled between the floor and the walls, the masonry walls reach out-of-plane displacement values as high as 16 cm (L'Aquila 2009 earthquake) or 34 cm (Friuli 1976 earthquake). In this case, the floor beams slide over the masonry blocks and the floor in-plane deflection is smaller than the out-of-plane displacement (about 11 cm and 20 cm for the previously reported cases). The high out-of-plane displacement values does not activate an overturning collapse of the walls thanks to dynamic rocking and dissipation effects.

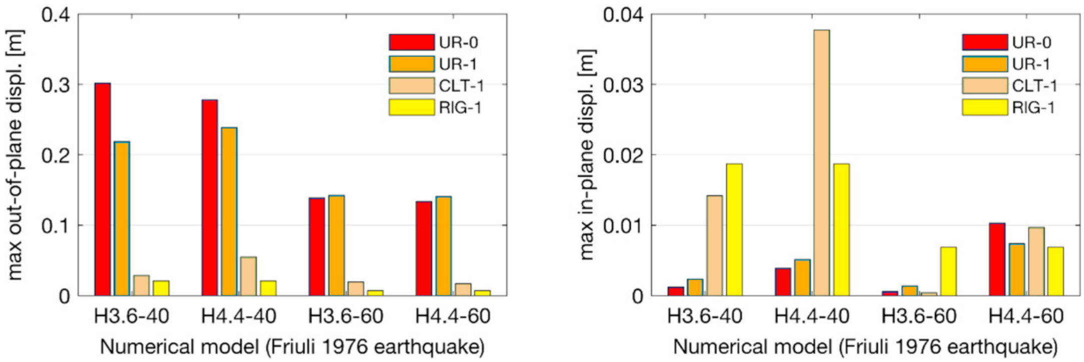
When a connection is considered between the unreinforced floor and the masonry walls, the floor in-plane deflection and the masonry out-of-plane displacement values are almost coincident. In this case, a reduction of the out-of-plane displacement can be observed for the models with masonry thickness of 40 cm, whereas a slight increase is observed for the 60 cm masonry thickness case.

The in-plane displacement of the side walls is almost negligible in all the analyses with the unreinforced floor (either connected or not connected to the masonry walls). This is due to the low strength of the floor, which is not able to transfer the seismic load to the bearing walls even when connected to them.

When the CLT-reinforced floor connected to the masonry walls is considered, the out-of-plane displacements of the masonry walls (and the floor in-plane deflection) are much smaller than in the case with the unreinforced floor. The stiffened floor is particularly effective in the Friuli 1976 earthquake case, where a reduction of the out-of-plane displacements of about 10 times can be observed. In many cases, this is linked to a strong increase of the in-plane displacement of the side walls, due to their shear collapse.

The results of the models with the CLT-reinforced floor are similar to the ones observed for the ideal rigid floor case. This reinforced configuration is thus effective in creating a diaphragm effect on the masonry structure. It should be noted, however, that the peak base shear force is higher in the reinforced floor cases since the structural integrity is maintained and less dissipation occurs.

Some of the discussed results are reported in Fig. 3, where the Friuli 1976 earthquake record is considered. The first histogram graph shows the maximum out-of-plane displacement of the face-loaded wall for each model geometry and for each floor type. The second one compares the maximum in-plane displacement of the side walls for the same models.



(a) Maximum out-of-plane displacement (b) maximum in plane displacement

Fig. 3. Comparison between the results of the different models for the Friuli 1976 earthquake case. The maximum out-of-plane displacement of the face-loaded wall and the maximum in-plane displacement of the side walls are shown.

4. Application of the floor model to a listed building DEM model

The building selected as case study is a typical example of a noble villa in north-eastern Italy. The detailed description of the building and of the performed analyses in reported in Gubana and Melotto (2021c). The cyclic model of the floor was implemented in a three-storey building masonry DEM model. All the results confirmed the prevention of the out of plane collapse when the floor is strengthened.

In these analyses the effect of elastic-plastic connections rather than elastic ones between the floors and the walls was also investigated. The plasticization of the connectors can be observed as a displacement difference between the floor and the top of the lateral walls. These results confirm the possibility of properly designing and calibrating the strengthening intervention to cap the shear forces transferred to the shear-resistant walls and to dissipate energy, simultaneously reducing the out-of-plane displacements of the walls within their capacity. In Fig. 4 the reported energy values are the kinetic energy of the structure, the energy dissipated by the floor hysteretic behaviour and the energy dissipated by the masonry walls due to damage and friction effects, in case of elastic connection and elastic-plastic (EP) connections.

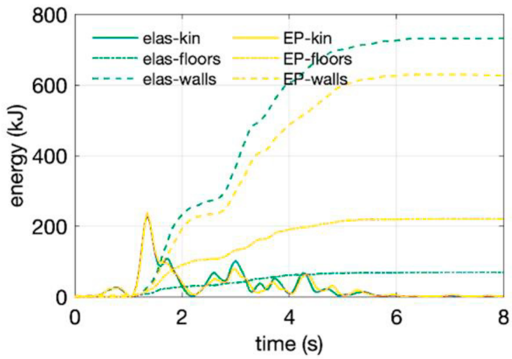


Fig. 4. Comparison between the results of the different models for the Friuli September 1976 earthquake case.

5. Conclusion

A simple model of the cyclic behaviour of traditional timber floors and of retrofitted timber floors was developed on the basis of experimental tests made on real size samples. The model of the floor was first implemented on a simple masonry cell described by DEM and then on a listed heritage building, to prove the effectiveness of the strengthening solutions. The DEM approach can be used to analyse aspects of the masonry structure that cannot be captured by other numerical approaches, due to its ability to simulate the triggering and development of out-of-plane and in-plane collapse mechanisms. The analyses were focused on the triggering of first-mode mechanisms, which were shown to be the governing mechanisms in all the analysed cases with unreinforced floors.

Both the simulations highlight the effectiveness of the proposed wood-based strengthening solution in reducing the out-of-plane displacements of the masonry walls and so in preventing overturning collapse mechanisms. The analyses also emphasised the ability of the reinforced floor to transfer the seismic forces to the shear-resistant walls by triggering in-plane shear collapse.

A comparison with the ideal rigid floor case confirms the good performance of the strengthening solution. The observed out-of-plane displacements are compatible with the masonry wall capacity, and energy is dissipated because of the reinforced floor hysteretic cycles.

The effects of different floor-to-wall connections are also assessed. Connections are needed to transfer the load to the bearing walls, but elastic-plastic connections can also be used to cap the load and to dissipate energy. This reduces the out-of-plane displacement of the face-loaded walls and limits the in-plane damage to the seismic bearing walls.

In reality, floors that are too stiff could be detrimental to the seismic performance of masonry buildings, and in these cases it is particularly important to cap the shear forces transferred to the shear-resistant walls. By using retrofitting solutions such as those considered in this work, the in-plane performance of the floor can be properly designed and calibrated to maximise the energy dissipation without exceeding the capacity of the existing masonry structure. The combined approach of DEM modelling and timber floor cyclic modelling discussed here has proven to be a valid strategy to perform further investigations on the possibility of controlling the energy dissipation involved in the dynamic responses of masonry buildings with strengthened timber floors.

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References

Baraldi, D., De Carvalho Bello, C.B., Cecchi., A. 2020. Refined Rigid Block Model for In-Plane Loaded Masonry. Advances in Civil Engineering, article ID 8844759. https://doi.org/10.1155/2020/8844759

Binda, L., Gambarotta, L., Lagomarsino, S., Modena, C. 1999. A multilevel approach to the damage assessment and seismic improvement of masonry buildings in Italy. In: Bernardini A (ed) “*Seismic damage to masonry buildings”*. Balkema, pp 170–195

Brignola A, Pampanin S, Podestà S (2012) Experimental evaluation of the in-plane stiffness of timber diaphragms. Earthquake Spectra 28.4:1687-1709

Bui, T.T., Limam, A., Sarhosis, V. 2019. Failure analysis of masonry wall panels subjected to in-plane and out-of-plane loading using the discrete element method. European Journal of Environmental and Civil Engineering. doi: 10.1080/19648189.2018.1552897

Gubana, A. 2015. State-of-the-Art Report on high reversible timber to timber strengthening interventions on wooden floors. Construction and Building Materials 97:25–33

Melotto, M. (2017) Wood-based in-plane strengthening solutions for the seismic retrofit of traditional timber floors in masonry buildings. Doctoral Thesis. Supervisor Gubana A., University of Brescia.

Gubana, A., Melotto, M. 2018. Experimental tests on wood-based in-plane strengthening solutions for the seismic retrofit of traditional timber floors. Construction and Building Materials, vol. 191, p. 290-299, ISSN: 0950-0618, doi: 10.1016/j.conbuildmat.2018.09.177

Gubana, A., Melotto, M. 2021 a. Discrete-element analysis of floor influence on seismic response of masonry structures. Structures and Buildings, Proceedings of the Institution of Civil Engineering, p.1-14, ISSN 0965-0911, doi:101680/jstbu.19.00099

Gubana, A, Melotto M. 2021 b. Cyclic numerical analyses on wood-based in-plane retrofit solutions for existing timber floors. Structures 33:1764-1774. doi.org/10.1016/j.istruc.2021.05.037

Gubana, A., Melotto, M. 2021 c Evaluation of timber floor in-plane retrofitting interventions on the seismic response of masonry structures by DEM analysis: a case study. Bulletin of Earthquake Engineering, Vol. 19, Issue 14, Pages 6003–6026, ISSN 1570761X, doi:10.1007/s10518-021-01190

Jiménez-Pacheco, J., González-Drigo, R., Pujades Beneit, L.G., Barbat, A.H., Calderón-Brito, J. 2020. Traditional High-rise Unreinforced Masonry Buildings: Modeling and Influence of Floor System Stiffening on Their Overall Seismic Response. International Journal of Architectural Heritage

Modena, C., Valluzzi, M.R., Binda, L. 2004. Vulnerability of historical centres in seismic area: reliability of assessment methods for different building typologies. In: Martens D, Vermeltfoort A (eds) Proceedings of the 13th International Brick and Block Masonry Conference. Amsterdam

Moreira, S., Ramos, L.F., Oliveira, D. V., Lourenço, P.B. 2014. Experimental behavior of masonry wall-to-timber elements connections strengthened with injection anchors. Engineering Structures 81:98–109. doi: 10.1016/j.engstruct.2014.09.034

Ortega, J., Vasconcelos, G., Rodrigues, H., Correia, M. 2018. Assessment of the influence of horizontal diaphragms on the seismic performance of vernacular buildings. Bulletin of Earthquake Engineering. doi:10.1007/s10518-018-0318-8

Pulatsu, B., Erdogmus, E., Lourenço, P.B., Lemos, J.V., Tuncay, K. 2020. Simulation of the in-plane structural behavior of unreinforced masonry walls and buildings using DEM. Structures 27:2274-2287. https://doi.org/10.1016/j.istruc.2020.08.026

Rizzi, E., Giongo, I., Ingham, J.M., Dizhur, D. 2019. Testing and Modeling In-Plane Behavior of Retrofitted Timber Diaphragms. Journal of Structural Engineering 146.2:04019191

Scotta, R., Trutalli, D., Marchi, L., Pozza, L. 2018.Seismic performance of URM buildings with in-plane non-stiffened and stiffened timber floors. Engineering Structures 167:683–694. doi: 10.1016/j.engstruct.2018.02.060

Tena-Colunga, A., Abrams, D. 1996. Seismic behavior of structures with flexible diaphragms. Journal of Structural Engineering 122:439–445

Wilson, A., Quenneville, P., Ingham, J.M. 2014. In-plane orthotropic behavior of timber floor diaphragms in unreinforced masonry buildings. Journal of Structural Engineering 140:. doi: 10.1061/(ASCE)ST.1943-541X