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Eccomas Proceedia COMPDYN (2025) 4094-4102

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COMPDYN 2025
10th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15-18 June 2025

EXPERIMENTAL INVESTIGATION OF THE IN-PLANE AND OUT-OF-PLANE CAPACITY OF TYPICAL ITALIAN INFILL WALLS

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Abstract

Infill walls used in existing Italian reinforced concrete (RC) buildings are highly vulnerable and their failure can lead to economic losses and human casualties, mainly in case of seismic events. For this reason, the study of their vulnerability becomes particularly significant during extreme events, such as volcanic eruptions, windstorms, and floods, when the interior of buildings offers protection. This paper discusses the design process of shaking table tests conducted on a full-scale reinforced concrete 3D frame structure. The single-story structure has four hollow brick infills samples, three fully infilled and one with a central opening and will be tested under both in-plane and out-of-plane loading. A six-degree-of-freedom shaking table will be used to apply the seismic load.
The reinforced concrete structure has been designed to withstand testing without damage, enabling multiple trials with various infill wall types. Once damaged, the infill walls will be strengthened with lightweight, easily applied systems to test repair and reinforcement solutions suitable for disaster-affected areas that require quick intervention.

Keywords: Dynamic Tests, Shaking Table, Masonry infill walls, Non Structural Elements.

ISSN:2623-3347 © 2025 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2025.
doi: 10.7712/120125.12717.25854

1 INTRODUCTION

The study of the capacity of typical infill walls used in existing Italian reinforced concrete (RC) buildings, both in-plane (IP) and out-of-plane (OoP), is of significant interest because these elements are highly vulnerable. They can lead to economic losses and human casualties, mainly in case of seismic events when their collapse can also contribute to the obstruction of escape routes. For this reason, their vulnerability becomes particularly significant during extreme events, such as volcanic eruptions, windstorms, and floods, when the interior of buildings offers protection.

Since the 1990s, numerous studies have focused on assessing the IP and OoP vulnerability of masonry infills [1–3]. Some of these studies have also investigated the correlation between OoP vulnerability and damage induced by IP actions [4–13], which has proven to be a critical factor in accurately determining vulnerability.

Two significant studies [14–15] were conducted on a shaking table, with out-of-plane tests performed after in-plane tests to investigate the correlation between the resulting damage patterns. However, dynamic tests on masonry infills remain relatively scarce due to the complexity of execution. In most cases reported in the literature, pseudo-dynamic tests are employed. In such tests, the horizontal load is typically simulated through the application of linear loads, point forces, or uniform pressure. This approach fails to realistically replicate the dynamic behaviour of masonry panels, as it does not account for critical aspects such as inertia effects, crack propagation and closure during motion reversals, or the influence of variable loading rates. Moreover, understanding the static and dynamic properties of existing buildings is essential for assessing their structural behaviour in seismic areas [16]. With the aim to broadly investigating the behaviour of infill walls in various geometric configurations, shaking table tests have been designed on a single-story, full-scale reinforced concrete frame structure with hollow brick infills. The designed structure has a square plan measuring 350 cm and a height of 310 cm from the foundation (Fig. 1). The columns have a square cross-section, leaving space for square infill panels. The 3D frame with four infill samples, realized by single-leaf hollow clay brick, will be tested under both IP and OoP loading. The RC structure will remain undamaged during the tests, allowing for repeated executions with various geometric and mechanical masonry configurations.

Once damaged, the infill walls will be strengthened with lightweight, easily applied systems to test repair and reinforcement solutions suitable for disaster-affected areas that require quick intervention.

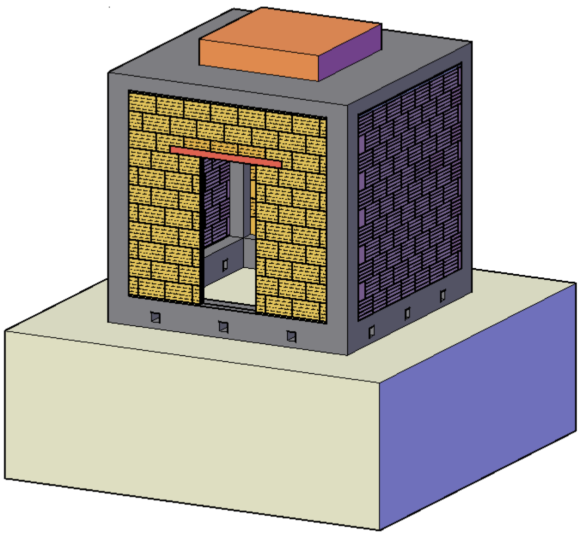


Figure 1: 3D numerical model of the analysed structure.

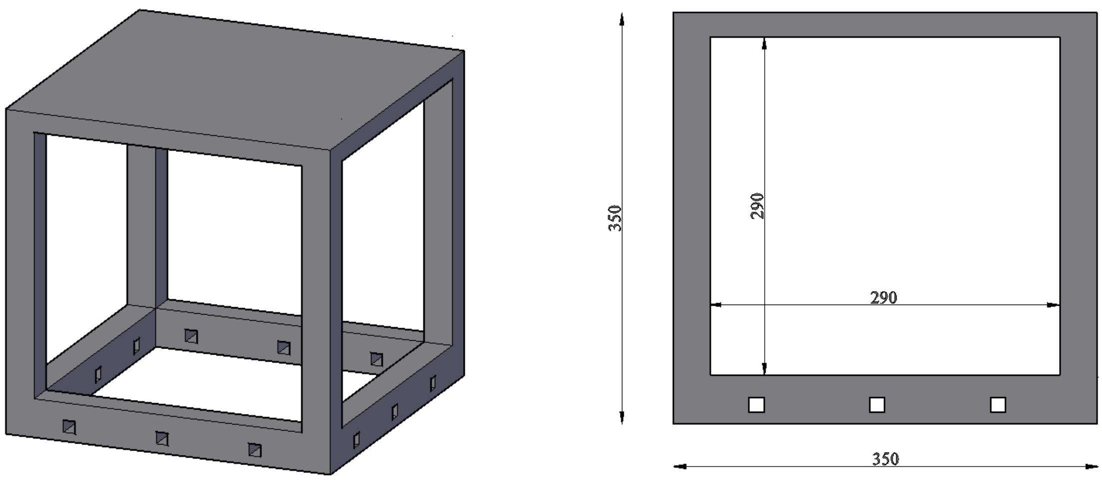
2 DESCRIPTION OF STRUCTURE AND SPECIMENS

In this section, the experimental campaign is illustrated. A three-dimensional structure, designed according to the Italian past code for not seismic area, has been created to accommodate four infill panels for each test under different types of seismic solicitation. The tests will be carried out on both reinforced and unreinforced infill walls, leveraging the structure's ability to remain undamaged under applied forces.

2.1 3D Frame Structures details

The structure has a square plan measuring 350 × 350 cm and a height of 310 cm from the foundation (Fig. 2). The columns have a 30 × 30 cm cross section reinforced with 4 × 12 mm steel longitudinal rebars and 8 mm stirrups spaced at 15 cm as transvers reinforcement. The beams measure 20 × 40 cm, longitudinal reinforcement consisting of 3 × 10 mm rebars on the upper side and 3 × 12 mm rebars on the lower side. Transverse reinforcement consists of 8 mm double stirrups spaced at 15 cm.

The floor slab is a one-way, cast-in-place joist slab with a height of 20 cm, including a 4 cm topping slab.



(a) (b)

Figure 2: 3D (a) and lateral (b) view of RC Frame.

Great attention has been given to the design of the foundation beams, which, in addition to ensuring adequate stiffness throughout testing, must be strong and stiff enough to facilitate the movement of the structure. The specimen was not manufactured directly on the shaking tables but rather in an adjacent construction area to preserve the integrity of the shaking table and maintain adequate safety standards for the workers.

The foundation beams have a 30 × 40 cm cross section and are reinforced with 12 × 10 mm steel rebars. Z-shaped rebars were inserted into the foundation beams to ensure shear strength during the specimen's translation (Fig.3). These are positioned around twelve square holes (three on each side), designed to allow the structure's movement. The RC elements are characterized by a C25/30 class of concrete, longitudinal and transverse rebars are characterized by a B450C steel typology, with a nominal yielding strength equal to 450 MPa.

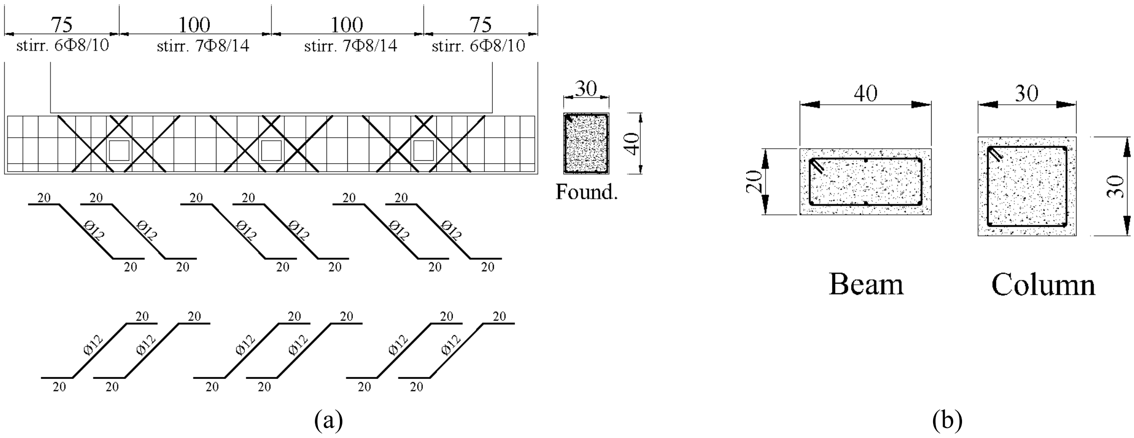


Figure 3: Reinforcement in the foundation beams (a) and cross sections of frame's structural elements.

2.2 Specimen's details

Typical bricks used in existing Italian buildings will be used; these have dimensions of 10 × 25 × 25 cm and a hole percentage exceeding 65%. The bricks have an average compressive strength of approximately 5 MPa in the direction parallel to the holes and 1.5 MPa in the orthogonal direction, as ensured by the manufacturer. Compressive tests in both the orthogonal and parallel directions will be carried out to define the actual strength of the bricks.

To assemble the walls, M2.5 mortar (2.5 MPa compressive strength) will be used. According to European Standard UNI EN 1015-11:2019 [17], tests will be conducted to define its characteristics.

The possibility of having four panels on the same structure allows for carrying out trials on different types of panels during the same test. For this reason, two different types of infill panels will be constructed: one 80 mm thick and the other 120 mm thick, with one-leaf masonry panels placed on opposite sides of the structure (Figure 4). The first has a slenderness ratio (height-to-thickness, h/t) of 36.25, while the second has a slenderness ratio of 24.17. One panel will feature a central opening to study its influence on the behaviour of the panels (Fig. 5). Moreover, the panels will be realized with different boundary constrain conditions to investigate the vulnerability associated with different levels of constraint.

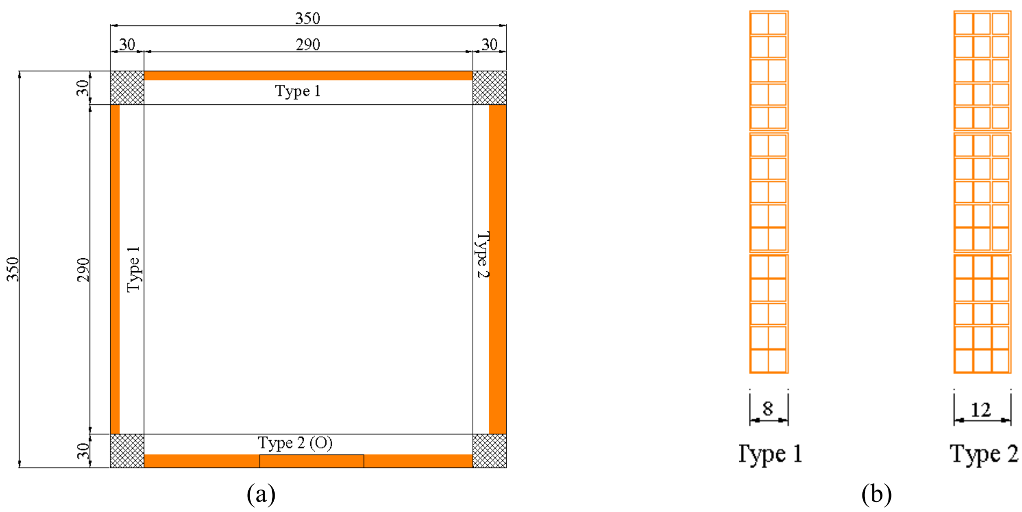
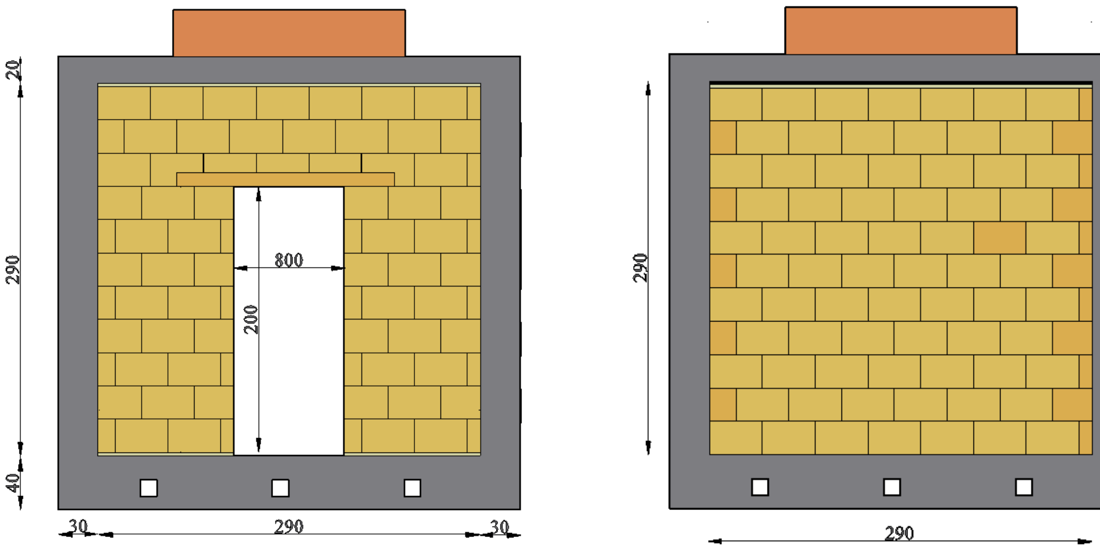


Figure 4: Walls plan layout (a) and types of panels (b).



(a) (b)

Figure 5: Frontal (a) and lateral (b) view of structure.

2.3 Test Facilities

Seismic tests on the specimen were performed on the 4 m × 4 m wide shake table at the ENEA Casaccia laboratory in Rome, Italy. Four horizontal and four vertical actuators provide the table with six degrees of freedom and an operating frequency range of 0-50 Hz, a max stroke of 12.5 cm and max specimen load of 30 t. [18].

The specimen and the table will be instrumented with about 100 markers of the 3DVision system and 8 capacitive accelerometers, which will be used as reference for the markers data. The 3DVision is a passive 3D motion capture system installed at the ENEA Casaccia R.C. [19]. It is based on 14 Vicon cameras. Each camera's LED strobe irradiates Near-Infrared (NIR) light, which is reflected by cheap spherical markers covered with retroreflecting sheeting. All data in the present experimental campaign will be acquired at 200 fps (i.e. 200 Hz of sampling frequency). The markers will be located at the positions corresponding to most significant nodes of the numerical model, according to the results of numerical analysis and modal shapes. Among the many advantages of using the 3DVision system in potentially destructive testing, like this shaking table application, the risk of loss of passive markers does not constitute any instrumentation damage and the acquisition of a large number of channels is guaranteed also in the event of the specimen collapse.

2.4 Input details

The first phase of the tests involves the dynamic identification of the sample. This phase is crucial because allows for the determination of the dynamic characteristics of the structure as a whole, as well as the individual infill panels, which, as mentioned, will be constructed with different boundary conditions. It will also be possible to assess how any damage caused by the seismic tests alters the dynamic behaviour of the panels and how this affects their strength and vulnerability.

This approach is the same as that is recommended by FEMA 461, which suggests an incremental performance evaluation test procedure and states that dynamic identification tests should be conducted both before and after each performance evaluation test. This approach is well-established in the literature; for example, in [20][21], dynamic identification was performed during the incremental tests, and both dynamic properties and the exhibited damage were correlated with the testing intensities. A similar comparison can be made between the panels before and after reinforcement.

The seismic input will be chosen with particular attention to both the characteristics of tectonic and volcanic seismic events, taking into account the frequency content of the seismic signals to adequately excite the infill walls.

To ensure that the structure undergoes an adequate displacement due to the acceleration given by the shaking table, a lumped mass will be placed at the top of the structure.

2.5 Reinforcement system details

After the initial tests on unreinforced panels, a reinforcement and seismic strengthening system will be applied to assess its effectiveness and quantify its impact.

Before installing the reinforcement system, the walls will be repaired to eliminate any severely damaged parts.

The chosen system consists of a 200 g/m² glass fibre mesh and a one-component, water-based adhesive in polyurethane dispersion. This system is easy to apply, quick to implement, and well-suited for emergency situations.

3 FEM ANALYSIS

A finite element model was developed to have initial estimates of the response of the prototype to be updated during experimental analysis. The model is based on beam elements for the frame and plate elements for the walls. The stiffness of the plates is assumed to be different in horizontal and vertical directions, applying a scale factor.

According to yield line theory, possible mechanisms were defined, and gaps were inserted in the walls accordingly. Nonlinear links with elastic plastic moment-rotation relationships were used to link the wall interface at gaps. Elastic properties were instead assigned to axial and transversal directions for the links. The model has 2422 nodes, 271 beam elements, 1762 plate elements, 248 nonlinear links.

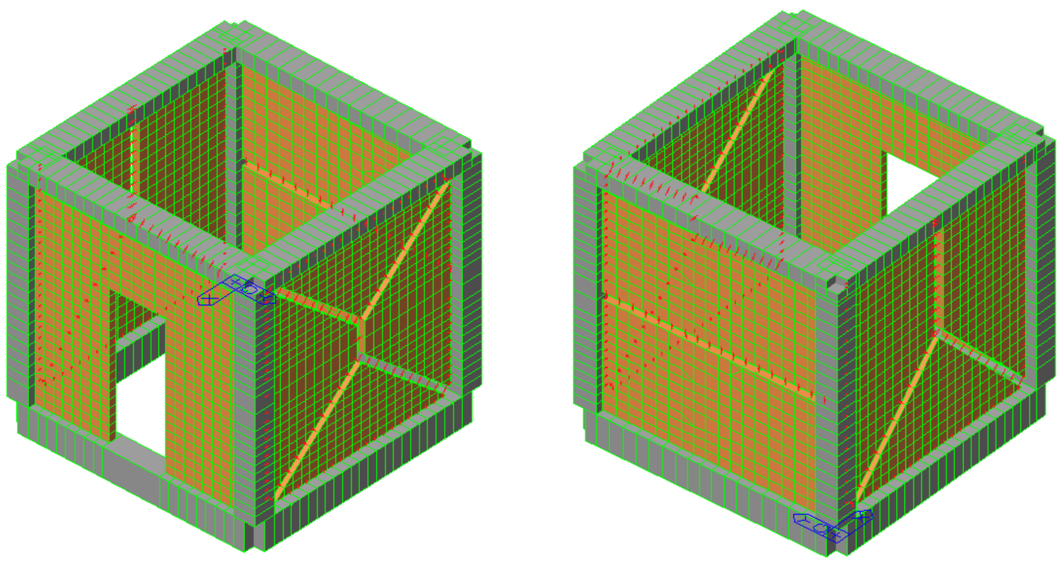


Figure 6: Views of the finite element model.

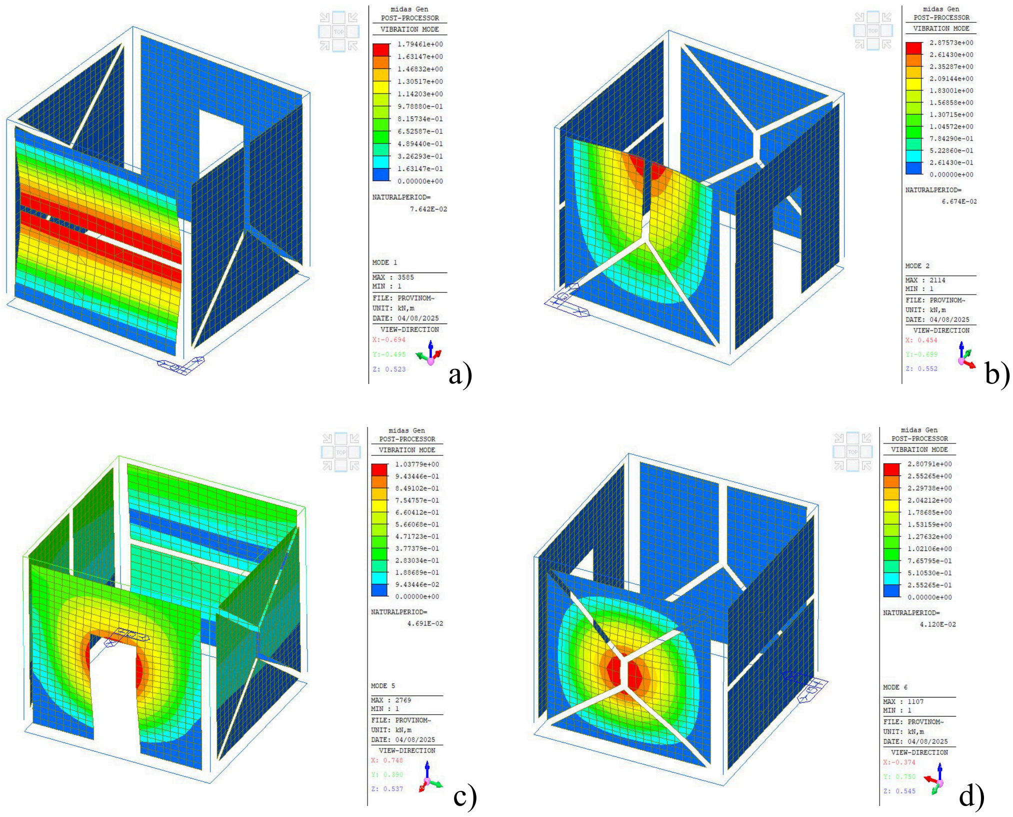


Figure 7: First four modal shapes of the walls.

Ritz modal vectors are used to obtain a relevant mass participation and nonlinear time history analysis was done using anyway the superposition of the linear modes to lower computational effort.

Figure 7 shows the first four modal shapes of the infill walls, whereas Figure 8 shows the maximum displacement obtained using as input the seismic acceleration recorded in Amatrice in 2016. These preliminary results are not conclusive and a better calibration of the model and of its parameters will be carried out when experimental data is available.

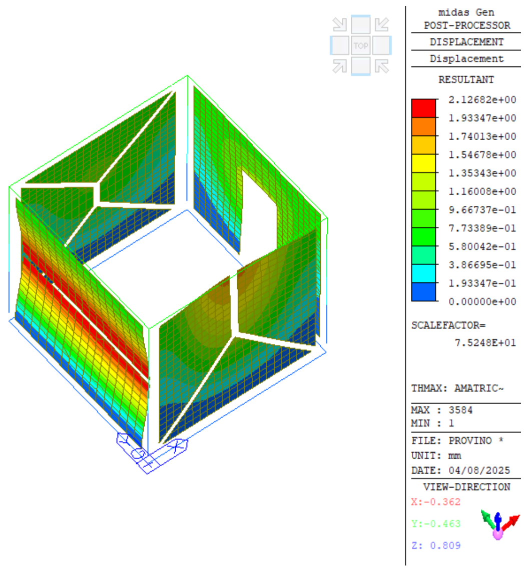


Figure 8: Example of maximum displacements under a selected ground motion.

4 CONCLUSIONS

The study illustrates the preparatory phase of a laboratory experimental campaign on clay infill walls. The campaign began with the design and construction of a 3D RC frame structure. The structure was designed with sufficient strength and stiffness to remain undamaged throughout the entire campaign. Four clay brick panels, with two different thicknesses, were constructed on each side of the structure in order to study both IP and OoP behaviour. Finite Element (FE) analyses, developed using Midas® software, were conducted to predict the main dynamic characteristics of the RC structure–panel system. These preliminary results have been used for a first calibration of the shaking table tests. Additional details about non-linear behaviour of the model will be considered in the next steps of the study.

Different seismic inputs will be used to study the behaviour of the panels, taking into account the frequency content of the seismic signals in order to adequately excite the infill walls.

ACKNOWLEDGEMENTS

This study was carried out within the RETURN Extended Partnership and received funding from the European Union Next-GenerationEU (National Recovery and Resilience Plan – NRRP, Mission 4, Component 2, Investment 1.3 – D.D. 1243 2/8/2022, PE0000005).

REFERENCES

[1] T. Bashandy, N.R. Rubiano, R.E. Klingner, *Evaluation and analytical verification of infilled frame test data*. Phil M. Ferguson Structural Engineering Laboratory, University of Texas at Austin, 1995.

[2] R.D. Flanagan, R.M. Bennett, Bidirectional behaviour of structural clay tile infilled frames. *J Struct Eng,* **125(3)**, 236-244, 1999.

[3] R.D. Flanagan, R.M. Bennett, Arching of masonry infilled frames: Comparison of analytical methods. *Pract Period Struct Des Constr,* **4(3),** 105‑110, 1999.

[4] R. Angel, D.P. Abrams, D. Shapiro, J. Uzarski, M. Webster, *Behavior of Reinforced Concrete Frames with Masonry Infills*. University of Illinois Engineering Experiment Station, College of Engineering, University of Illinois at Urbana-Champaign, 1994.

[5] G.M. Calvi, D. Bolognini, Seismic response of reinforced concrete frames infilled with weakly reinforced masonry panels. *J. Earthq. Eng.* **5(2),** 153–185, 2001.

[6] F. da Porto, G. Guidi, M. Dalla Benetta, N. Verlato, Combined in-plane/out-of-plane experimental behaviour of reinforced and strengthened infill masonry walls. *Proc. 12th Canadian Masonry Symposium*, Vancouver, Canada, June 2-5, 2013.

[7] S. Hak, P. Morandi, G. Magenes, Out-of-plane experimental response of strong masonry infills. *2nd European conference on earthquake engineering and seismology (2nd ECEES)*, Istanbul, Turkey, August 25-29, 2014.

[8] A. Furtado, H. Rodrigues, A. Arede, H. Varum, Experimental evaluation of out-of-plane capacity of masonry infill walls. *Eng. Struct.* **111,** 48–63, 2016.

[9] V. Palieraki, C. Zeris, E. Vintzileou, C.E. Adami, In-plane and out-of plane response of currently constructed masonry infills. *Eng. Struct.* **177,** 103–116, 2018.

[10] M. Di Domenico, P. Ricci, G.M. Verderame, Experimental assessment of the influence of boundary conditions on the out-of-plane response unreinforced masonry infill walls. *J. Earthq. Eng.* 1–39, 2018.

[11] P. Ricci, M. Di Domenico, G.M. Verderame, Empirical-based out-of-plane URM infill wall model accounting for the interaction with in-plane demand, Earthq. *Eng. Struct. Dynam*. **47(3),** 802–827, 2018.

[12] C. Butenweg, M. Marinkovic, R. Salatic, Experimental results of reinforced concrete frames with masonry infills under combined quasi-static in-plane and out-of plane seismic loading, *Bull. Earthq. Eng*. **17**, 3397–3422, 2019.

[13] P. Morandi, S. Hak, R.R. Milanesi, G. Magenes, In-plane/out-of-plane interaction of strong masonry infills: from cyclic tests to out-of-plane verifications. *Earthq. Eng. Struct. Dynam.* **51(3),** 648–672, 2022.

[14] S. Komaraneni, D.C. Rai, V. Singhal, Seismic behavior of framed masonry panels with prior damage when subjected to out-of-plane loading. *Earthq. Spectra,* **27(4),** 1077–1103, 2011.

[15] R.R. Milanesi, P. Morandi, C.F. Manzini, L. Albanesi, G. Magenes, Out-of-plane response of an innovative masonry infill with sliding joints from shaking table tests. *J. Earthq. Eng.,* **26(4)**, 1789–1823, 2022.

[16] C. Tripepi, F. Saitta, P. Clemente, G. Buffarini, G. Bongiovanni, Experimental Vibration Analysis in the Knowledge Process of a Historic Confined Masonry Building, *Buildings,* **13(10)**, 2560, 2023. https://doi.org/10.3390/buildings13102560.

[17] UNI EN 1015-11:2019 - Methods of test for mortar for masonry - Part 11: Determination of flexural and compressive strength of hardened mortar; Comité Européen de Normalisation.

[18] M. Mongelli, I. Roselli, G. De Canio, F. Ambrosino, Quasi real-time FEM calibration by 3D displacement measurements of large shaking table tests using HPC resources. *Advances in Engineering Software*, **120,** 14–25, 2018. doi: 10.1016/j.advengsoft.2016.07.005.

[19] G. De Canio, M. Mongelli, I. Roselli, 3D Motion Capture Application to Seismic Tests at ENEA Casaccia Research Center: 3DVision System and DySCo Virtual Lab, *WIT Transactions on The Built Environment*, **134**, 803-814, 2013.

[20] C. Petrone, G. Magliulo, G. Manfredi, Shake table tests on standard and innovative temporary partition walls. *Earthquake Engineering & Structural Dynamics*, **46(10)**, 1599–1624, 2017.

[21] E. Cosenza, L. di Sarno, G. Maddaloni, G. Magliulo, C. Petrone, A. Prota, Shake table tests for the seismic fragility evaluation of hospital rooms. *Earthquake Engineering & Structural Dynamics*, **44(1)**, 23–40, 2015.