Available online at www.sciencedirect.com

ScienceDirect

Procedia Structural Integrity 44 (2023) 1124–1131

Structural Integrity Procedia

www.elsevier.com/locate/procedia

XIX ANIDIS Conference, Seismic Engineering in Italy

Shake table testing of a low-impact technology for the seismic protection of stone masonry

Gianmarco de Felice[a*], Omar AlShawa[b], Stefano De Santis[a], Domenico Liberatore[b], Ivan Roselli[c], Alessandro Colucci[c], Marialuigia Sangirardi[d], Luigi Sorrentino[b]

[a] *Università degli Studi Roma Tre, Dipartimento di Ingegneria, Via Vito Volterra 62, 00146 Roma.*
[b] *Sapienza Università di Roma, Dipartimento di Ingegneria Strutturale e Geotecnica, Via Antonio Gramsci 53, 00197 Roma.*
[c] *ENEA Centro Ricerche Casaccia, Laboratorio Tecnologie per la Dinamica delle Strutture e la Prevenzione del rischio sismico e idrogeologico, Via Anguillarese 301, 00123 Santa Maria di Galeria, Roma.*
[d] *University of Oxford, Department of Engineering Science, Parks Road, Oxford OX1 3PJ.*

Abstract

This paper presents a novel low-impact technique for the seismic protection of fair-face masonry walls. The proposed strengthening solution involves the use of carbon-fibre reinforced polymer (CFRP) connectors installed from the outside by perforating the stone elements, combined with grout injections. The connectors cover ¾ of the wall thickness, so as to leave the inner surface undisturbed. Once the work is completed, they are also substantially invisible. Shake table tests were carried out under natural accelerograms on two full-scale irregular multi-leaf stone masonry wall specimens. In order to replicate materials and construction technique of the Apennine historical buildings, the prototypes were made from stones recovered from the debris of a settlement in the municipality of Accumoli (RI, Italy), and the mortar was designed to reproduce lime-poor mortars surveyed in the field. The experimental setup was designed to induce out-of-plane vertical bending under base seismic motion, while allowing the vertical displacement of the wall top. One specimen was tested "as-built" and the other one was tested strengthened, to investigate the gain in seismic performance, the limitation of progressive damage accumulation and the effects on dynamic properties.

Peer-review under responsibility of the scientific committee of the XIX ANIDIS Conference, Seismic Engineering in Italy.

Keywords: CFRP Connectors; natural accelerograms; 3DVision; Architectural heritage; fair-faced masonry

* Corresponding author. Tel.: +0-000-000-0000 ; fax: +0-000-000-0000 .
E-mail address: defelice@uniroma3.it

Peer-review under responsibility of the scientific committee of the XIX ANIDIS Conference, Seismic Engineering in Italy.
10.1016/j.prostr.2023.01.145

1. Introduction and motivations

Historic centres of many countries, especially in the Mediterranean area, are characterized by the common presence of stone masonry buildings. Under seismic actions, irregular bond pattern, poor quality of the mortar, weak wall intersections and horizontal connections often cause ruinous collapses due to leaf separation and disintegration (Borri et al. 2019; Rezaie et al. 2020; Vlachakis et al. 2020). This damage scenario still represents a major challenge from both scientific and engineering perspectives, as the dynamic response of these masonry types makes seismic capacity assessment via classical rigid-body mechanics approaches complicated or not even feasible (de Felice et al. 2017; Sorrentino et al. 2017; Meriggi et al. 2019). At the same time, to protect the built heritage and the cultural identity that this represents, new sustainable and low-impact reinforcement technologies are needed. Lumped reinforcement solutions, such as metal ties and ring beams, which have been widely adopted after past earthquakes, are aimed at preventing out of plane failure mechanisms and at providing the building with a box-like behaviour. Nonetheless, in order to avoid masonry disintegration and leaf separation, distributed reinforcement systems are primarily needed (Papanicolaou et al. 2011; Kariou et al. 2018; De Santis and de Felice 2021). Furthermore, compatibility and aesthetic requirements ought to be accounted for as well as minimum invasiveness and impact on people living in the buildings to be strengthened.

This paper proposes the application of an innovative low-impact strengthening solution consisting of carbon fibre reinforced polymer (CFRP) connectors nailing, at specific locations, the two masonry wall leaves. This solution, combined with grout injections, provides additional constraint to leaf separation and is particularly convenient as installation can be pursued only from the exterior of a building, leaving the internal surface of the wall undisturbed. Once completed, this retrofit intervention is invisible from the outside, so the architectural value of fair-faced masonry is preserved. Its performance under real strong motion records was investigated by means of shake table tests in which a strengthened masonry wall was subjected to horizontal out-of-plane and vertical excitations with increasing peak ground acceleration (PGA) up to failure. Experimental results are presented and discussed, highlighting the improved seismic capacity of the strengthened wall (named as CC) compared to that of an unstrengthened wall (UR), built with the same materials and geometric features, which was tested previously with the same experimental protocol.

2. Geometry and Materials

The dimensions of the tested walls were determined according to typical features surveyed in Central Italy villages struck by the 2016-2017 seismic sequence (AlShawa et al. 2021). Both specimens were 0.50 m thick, 1.60 m wide and 3.73 m tall, resulting in a height-to-thickness ratio of about 7.5, which is rather common for traditional constructions in that area. They had two external leaves and an inner core made of smaller elements poorly bonded with mortar. To faithfully replicate the architectural characteristics of historical structures, the external side of the walls was not plastered, whilst the internal face was covered with a 30 mm thick layer of premixed natural hydraulic lime (NHL) low-strength mortar. Both the unstrengthened reference (UR) and the carbon connector (CC) strengthened walls were built with natural stones collected from the debris of Collespada, a village in the municipality of Accumoli (RI, Italy), and the bedding mortar was reproduced with the same composition detected on site, characterized by a 1/9 lime to sand ratio, resulting in low strength values (w = 17.3 kN/m^3, flexural strength f_f = 0.56 MPa, and compressive strength f_m = 1.34 MPa). Blocks with average dimensions equal to 50 mm × 50 mm × 150 mm were tested to determine their properties, such as w was = 25.9 kN/m^3, f_f = 19.81 MPa and f_m = 91.45 MPa. Each wall was built on a 600 mm × 450 mm reinforced concrete (RC) beam, provided with holes to lift the structure from the construction site and place it on the table. On top, a reinforced masonry beam was built using the same stone units, bonded in a regular pattern using a modern NHL medium-strength premixed mortar (w = 15.8 kN/m^3, f_f = 3.54 MPa, f_m = 9.75 MPa) and embedding one ply of glass fibre reinforced polymer (GFRP) mesh with 66 mm × 66 mm grid spacing in each bed joint, resulting in a 260 mm deep top beam.

3. Strengthening application

As mentioned, the proposed strengthening solution with CFRP connectors (fig. 1) is characterized by limited disturbance during installation, whose subsequent phases can be summarized as follows:

- Grout Injections. Twenty-four holes are drilled at the mortar joint location on the external face of the wall and three on each side, to inject (from bottom to top) an NHL premixed mortar, moving the injection nozzle out from the bottom of each hole.
- Drilling of the holes for CFRP connectors. After one-week curing time for the injected mortar, 39 holes are drilled through the largest stone units of the external face. An average density of 6.4 connectors per square meter results in 50 cm spacing in the central and lower portion of the wall and about 30 cm in the upper part and along the vertical edges, due to a more likely occurrence of leaf separation in those locations. Holes are drilled with percussion diamond drills having 8 mm and 12 mm diameter bits and have a slight downward inclination. They do not cross the entire thickness so to leave the internal face undisturbed.
- Grouting in the holes of CFRP connectors. Holes are injected with a potassium-silicate primer and a premixed cementitious mortar, and grouted in the holes with a handgun.
- Installation of the CFRP connectors. The bars, having 6 mm diameter, and 420 mm length, are inserted in the holes soon after mortar injection. To improve their bond, their surface is sand-blasted and they are dipped into the grouting mortar before insertion. The length of the CFRP bars ensures the connection between the external and internal leaves of the wall, with the aim of preventing leaf separation. If this intervention is limited to the external walls of a building, its execution can be implemented without suspending its use.
- Finishing. Holes are sealed with the injection grout to hide the ends of the connectors.

It has to be mentioned that retrofitting strategies based on the application of composite materials only on the external part of walls have already been explored, resorting to either externally bonded composites or by means of transversal connectors (De Santis et al. 2021 and references therein). On the other hand, the in-plane shear or monotonic out-of-plane bending response were mainly investigated in the literature, whilst the dynamic bending behaviour is considered in this work.

4. Setup and test protocol

Specimens and setup were designed to mimic the seismic behaviour of a vertical spanning wall, resting on a foundation, constrained at the top simulating the connection to a floor or a roof (fig. 2), so that the inertial forces activated by the seismic base motion could induce a horizontal deflection, a common failure mode extensively reported in literature (Derakhshan et al. 2013; Graziotti et al. 2016; Dizhur et al. 2017; Giaretton et al. 2017; De Santis et al. 2019). Thus, the wall was placed between two braced steel frames supporting two I-beams, placed at the external and internal sides of the wall, at the top beam height. The top restraint allowed free vertical displacements and rotations while preventing tilting. To ensure a horizontal out-of-plane stiffness ranging from about 300 kN/m (large period slabs tested in situ) to about 3400 kN/m (regular sized slabs tested in the laboratory) according to (Giresini et al. 2018), two low-friction rubber rollers were installed on each side of the specimen, fixed to a HEA200 steel beam and tightened against the top beam. The setup was kept almost identical for the reference and the strengthened specimens, except for a relatively minor change, that affected the stiffness of the top restraint, consisting in the addition of threaded rods connecting the metal beams reducing their net span and in the injection of the rollers with a 15 MPa compressive strength mortar. Finally, to simulate roof dead load, fifteen steel plates (with a total weight of 15 kN) were placed on top of the wall and connected with threaded bars, fitted with eyebolts and secured with steel ropes to the crane to protect the table and ease the dismantling of the testing area after the collapse.

Tests 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 15 cm and max specimen load of 30 t (Mongelli et al. 2018). The table allowed to account for vertical seismic input, which is proven to have a relatively high influence on the dynamic response of this poor masonry type (Liberatore et al. 2019).

The motion of 78 retro-reflecting markers attached to the external and internal sides of the wall, as well as to the base and the top beams, was tracked via the 3DVision system (De Canio et al. 2016), consisting of ten near-infrared high-definition digital cameras, at 200 Hz sampling frequency. A triaxial accelerometer was placed on the foundation for an additional measurement of the input, which was also used to calibrate the filtering parameters of markers data to derive walls accelerations.

Three record stations and three events were selected, namely Norcia, NRC (August 24th, 2016), Castelsantangelo sul Nera, CNE (October 26th, 2016), and Amatrice, AMT (October 30th, 2016). This choice was made as the experiments are inspired by the damage recorded in that area after the 2016-2017 seismic sequence and aimed at testing the performance of strengthening solutions to be applied on fair-faced rubblestone masonry that are typical of the Apennine historical villages. The horizontal (H) and the vertical (V) components were applied simultaneously. The selected accelerograms had similar intensity, to pursue a progressive damage occurrence when increasing the intensity, by means of a scale factor on the PGA. The test protocol applied the three signals, scaled both in the horizontal and vertical direction with an increasing non-dimensional scale factor (SF), kept constant within the series, starting from 0.2 and progressing with 0.2 steps. After every set of signals (NRC, CNE, AMT) with the same SF, a white noise (WHN) test was performed for dynamic identification with a nominal PGA equal to 0.05 g and a duration of 120 s only in the horizontal direction. Tests were labelled using the acronym of the record station and the SF. For instance, the series scaled at 80% of the PGA of the natural accelerogram were named as NRC08, CNE08, AMT08. Detailed information on the adopted seismic signals can be found in (de Felice et al. 2022; De Santis et al. 2021).

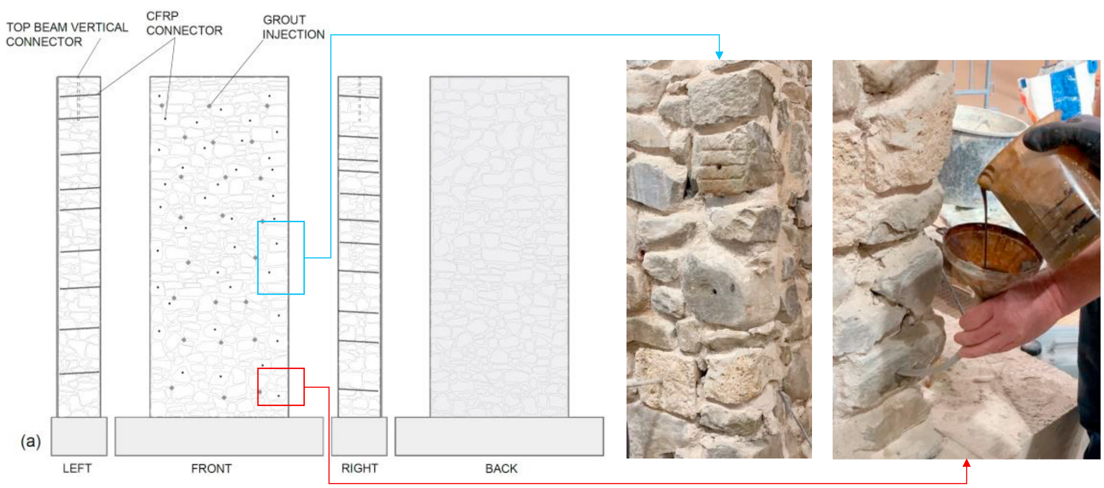

Fig. 1. Sketch of the strengthening distribution and detail of holes drilled for connectors and mortar pouring.

5. Test results

Damage evolution and failure modes were different for the two specimens (fig. 3). More specifically, unstrengthened reference UR specimen showed a marked damage pattern during the test sequence with SF=0.6 and collapsed during CNE08 (de Felice et al. 2022). On the other hand, CC wall was nearly undamaged up to the AMT10 signal, developing a visible crack pattern under the sequence with SF = 1.2. This evidence proved that the strengthened wall would have sustained the selected records of the Central Italy sequence with almost no damage.

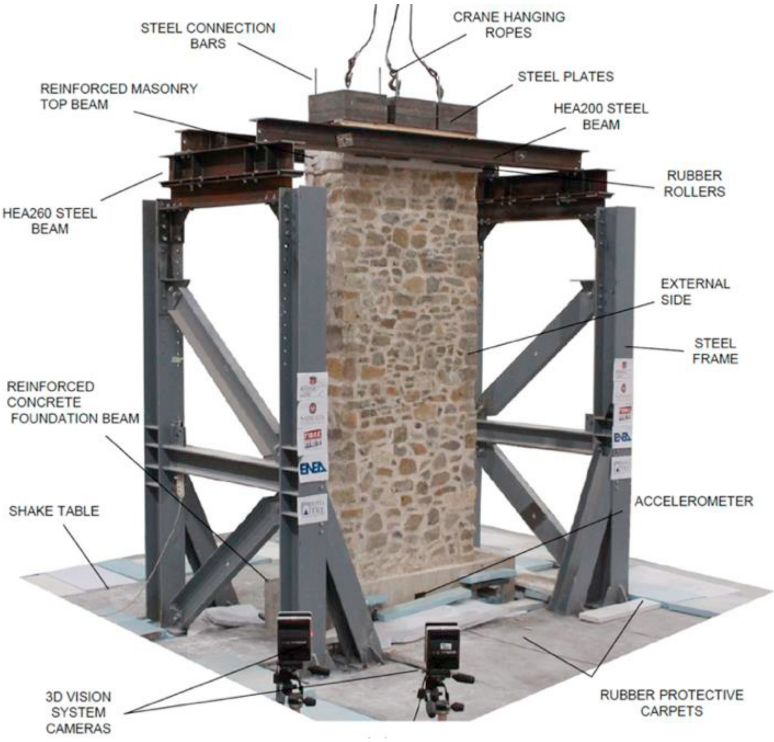

Fig. 2. Test setup.

Then, a local collapse occurred in the top part, triggered by the debonding of one of the stone units right below the top beam under the signal NRC14, followed by the fall of other stone units during the following test (AMT14), both from the external side and the internal side.

At this stage the wall was detached from the top beam and, in this configuration, it was concluded that it had attained its ultimate limit state. Neither evident sign of leaf separation nor masonry disintegration was detected on the rest of the wall. After AMT14, for which the absolute recorded acceleration at the base of the wall was 1.03 g, a white noise test was performed and, because under the following two strong motions the wall was behaving more as a rigid rocking body rather than a pinned- pinned beam, the tests were stopped, and the collapse was assumed to be attained. The evolution of the damage pattern for the two wall specimens can also be interpreted in terms of the fundamental out-of-plane frequency decay. This parameter was calculated with a multiple-input-multiple-output approach (Phillips and Allemang 2003), using the markers on the RC foundation (four in total) as input. The markers on the wall, from the 3rd to the 8th row, were considered as output obtaining acceleration time histories from a double derivative of marker displacements, without any filters. The strengthened wall had an initial frequency of 7.0 Hz, progressively decreasing to 4.5 Hz in the test sequence with SF=1.2, and a frequency at collapse attaining about 3.0 Hz.

The unstrenghtened reference wall, instead, showed an initial lower frequency (around 5 Hz), attributable to the absence of injections and to a slightly different setup. An extensive discussion on the quantitative experimental evidence in terms of leaves separation, displacement profiles and evolution of the dynamic properties of the tested walls are reported in (De Santis et al. 2021), which is complemented by the measurement of damage and dissipated energy evolution in combination with computer-vision based techniques discussed in (Sangirardi et al. 2022).

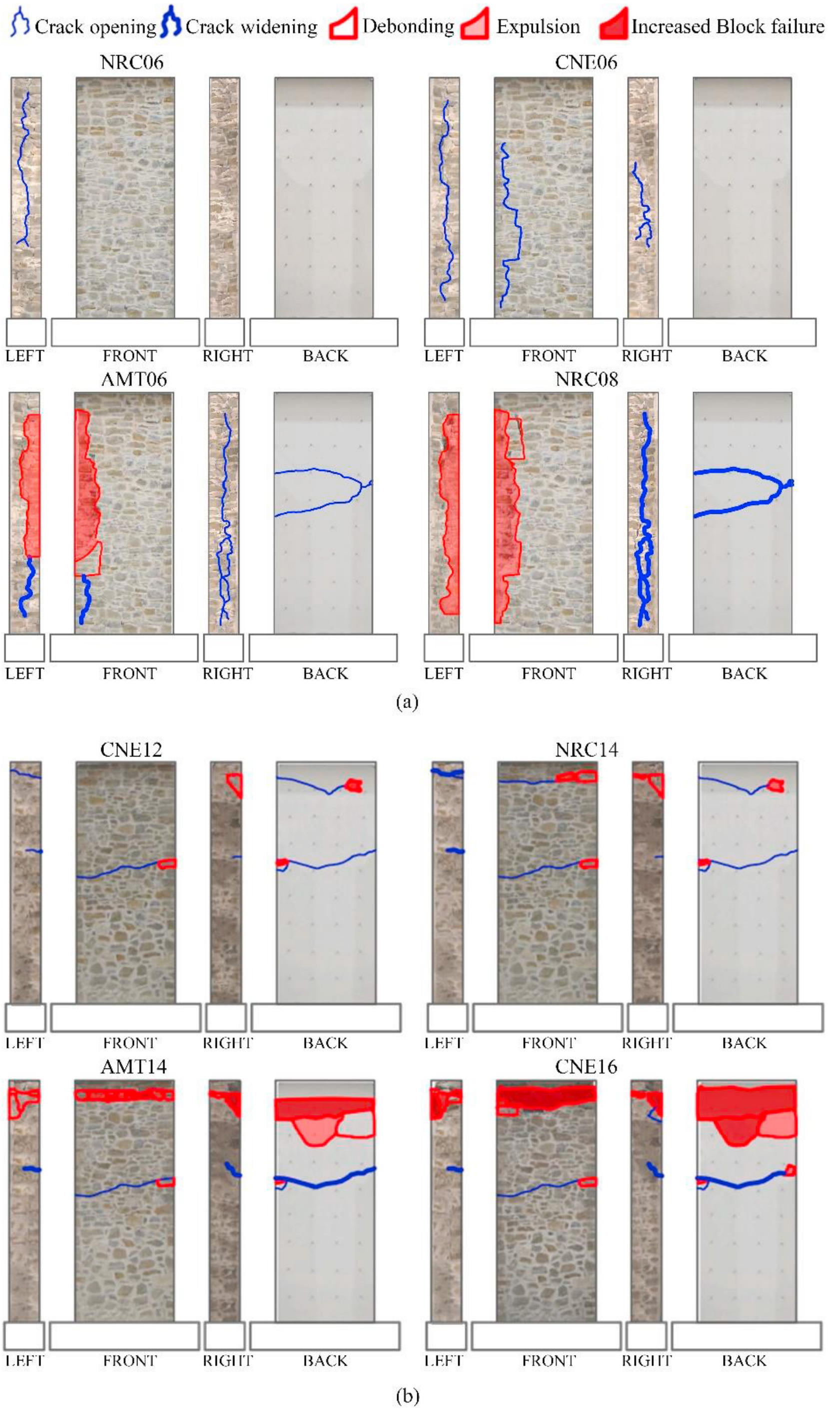

Fig. 3. Progressive damage development on UR (a) and CC (b) walls.

6. Conclusions

The experiments presented in this paper validated the effectiveness of an innovative strengthening system consisting of CFRP connectors installed from outside through the stone units leaving the internal wall surface undisturbed, combined with preliminary and more conventional grout injections. The technique improved the mechanical properties of the masonry enhancing the out-of-plane seismic capacity of the walls under earthquake base excitation with respect to the unstrengthened reference specimen, that was tested first.

A noticeable limitation to the progressive damage accumulation was envisaged from both experimental evidence and frequency decay estimations. Moreover, as a macroscopic indicator of the improved seismic capacity, the acceleration recorded at the base of the walls associated with the occurrence of the first damage increased from 0.22 g (UR wall) to 0.59 g (+168%, CC wall).

The displacement capacity (out of plane deflections at collapse) remained basically unchanged (but collapse was attained under much more intense seismic input in strengthened walls) while a significant increase of the absolute base acceleration increased from 0.45 g (UR) to 1.03 g (+127%, CC) indicated that they could have survived the natural scale records selected for the shake table investigation basically undamaged.

All above was attained with a sustainable and low-impact intervention, that preserves the fair-faced masonry, thus not altering the appearance of the urban contexts. The technique makes use of lime-based mortars for repointing, which ensure the physical-chemical compatibility with original substrate materials, but at the same time, resorting to carbon fibres ensures durability and the effectiveness of the strengthening intervention and the safety level of the strengthened wall in the long-term. For these reasons, the proposed technique is suitable for applications to architectural heritage.

Though rubblestone masonry structures are characterized by very high variability in terms of materials and geometry, the results presented in this paper can be reasonably extended to a wide range of similar masonry structures present in many countries in Europe and worldwide. From an engineering and more practical perspective, the design of this solution, in terms of density and position of the connectors, needs to be driven by some engineering judgement.

Acknowledgements

This work was carried out within the Research Projects “SICURA Sustainable technologies for the seismic protection of the cultural heritage” (2018-2020), “SISMI Technologies for the safety improvement and the reconstruction of historical centres in seismic prone areas” (2018-2019) and “RIPARA Integrated systems for the seismic retrofitting of architectural heritage” funded by Lazio Region, in the frame of the Departments of Excellence Initiative 2018-2022, attributed to the Department of Engineering of Roma Tre University. Fibre Net SpA (Pavia di Udine, UD, Italy) and UniCalce SpA (Lecco, Italy) are kindly acknowledged for providing materials. The intermunicipal operative office of Accumoli and Amatrice is acknowledged for allowing the collection of the stone units from the hamlet of Collespada. OA, LS and DL partially carried out this work under the program ‘‘Dipartimento di Protezione Civile – Consorzio RELUIS’’. The opinions expressed in this publication are those of the authors and are not necessarily endorsed by the Dipartimento della Protezione Civile.

References

AlShawa, O., De Canio, G., de Felice, G., De Santis, S., Forliti, S., Liberatore, D., Mirabile Gattia, D., Perobelli, S., Persia, F., Roselli, G., Sorrentino, L., 2021. Investigation of rubble-masonry wall construction practice in Latium, Central Italy.In *12th International Conference on Structural Analysis of Historical Constructions, Barcelona 29 September - 1 October*

Borri, A., Corradi, M., Castori, G., Sisti, R., De Maria, A., 2019. Analysis of the collapse mechanisms of medieval churches struck by the 2016 Umbrian earthquake. International Journal of Architectural Heritage. 13, 215–228. doi: 10.1080/15583058.2018.1431731

De Canio, G., de Felice, G., De Santis, S., Giocoli, A., Mongelli, M., Paolacci, F., Roselli, I., 2016. Passive 3D motion optical data in shaking table tests of a SRG-reinforced masonry wall. Earthquakes and Structures. 10, 53–71. doi: 10.12989/eas.2016.10.1.053

de Felice, G., De Santis, S., Lourenço, P. B., Mendes, N., 2017. Methods and Challenges for the Seismic Assessment of Historic Masonry Structures. International Journal of Architectural Heritage. 11, 143–160. doi: 10.1080/15583058.2016.1238976

de Felice, G., Liberatore, D., De Santis, S., Gobbin, F., Roselli, I., Sangirardi, M., AlShawa, O., Sorrentino, L., 2022. Seismic behaviour of rubble masonry: Shake table test and numerical modelling. Earthquake Engineering and Structural Dynamics. 51, 1245–1266. doi: 10.1002/eqe.3613

De Santis, S., AlShawa, O., de Felice, G., Gobbin, F., Roselli, I., Sangirardi, M., Sorrentino, L., Liberatore, D., 2021. Low-impact techniques for seismic strengthening fair faced masonry walls. Construction and Building Materials. 307, Submitted. doi: 10.1016/j.conbuildmat.2021.124962

De Santis, S., De Canio, G., de Felice, G., Meriggi, P., Roselli, I., 2019. Out-of-plane seismic retrofitting of masonry walls with Textile Reinforced Mortar composites. Bulletin of Earthquake Engineering. 17, 6265–6300. doi: 10.1007/s10518-019-00701-5

Derakhshan, H., Griffith, M. C., Ingham, J. M., 2013. Out-of-Plane Behavior of One-Way Spanning Unreinforced Masonry Walls. Journal of Engineering Mechanics. 139, 409–417. doi: 10.1061/(ASCE)EM.1943-7889.0000347

Dizhur, D., Giaretton, M., Giongo, I., Ingham, J., 2017. Seismic retrofit of masonry walls using timber strong-backs. Structural Engineering Society Journal - SESOC. 30.

Doherty, K., Griffith, M. C., Lam, N., Wilson, J., 2002. Displacement-based seismic analysis for out-of-plane bending of unreinforced masonry walls. Earthquake Engineering and Structural Dynamics. 31, 833–850. doi: 10.1002/eqe.126

Giaretton, M., Valluzzi, M., Mazzon, N., Modena, C., 2017. Out-of-plane shake-table test of strengthened multi-leaf stone masonry walls. Bulletin of Earthquake Engineering. 1–19. doi: 10.1007/s10518-017-0125-7

Giresini, L., Sassu, M., Sorrentino, L., 2018. In situ free-vibration tests on unrestrained and restrained rocking masonry walls. Earthquake Engineering & Structural Dynamics. 47, 3006–3025. doi: 10.1002/eqe.3119

Graziotti, F., Tomassetti, U., Penna, A., Magenes, G., 2016. Out-of-plane shaking table tests on URM single leaf and cavity walls. Engineering Structures. 125, 455–470. doi: 10.1016/j.engstruct.2016.07.011

Kariou, F. A., Triantafyllou, S. P., Bournas, D. A., Koutas, L. N., 2018. Out-of-plane response of masonry walls strengthened using textile-mortar system. Construction and Building Materials. 165, 769–781. doi: 10.1016/j.conbuildmat.2018.01.026

Liberatore, D., Doglioni, C., AlShawa, O., Atzori, S., Sorrentino, L., 2019. Effects of coseismic ground vertical motion on masonry constructions damage during the 2016 Amatrice-Norcia (Central Italy) earthquakes. Soil Dynamics and Earthquake Engineering. 120, 423–435. doi: 10.1016/j.soildyn.2019.02.015

Meriggi, P., de Felice, G., De Santis, S., Gobbin, F., Mordanova, A., Pantò, B., 2019. Distinct Element Modelling of Masonry Walls under Out-Of-Plane Seismic Loading. International Journal of Architectural Heritage. 13, 1110–1123. doi: 10.1080/15583058.2019.1615152

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

Papanicolaou, C., Triantafillou, T., Lekka, M., 2011. Externally bonded grids as strengthening and seismic retrofitting materials of masonry panels. Construction and Building Materials. 25, 504–514. doi: 10.1016/j.conbuildmat.2010.07.018

Phillips, A. W., Allemang, R. J., 2003. An overview of MIMO-FRF excitation/averaging/processing techniques. Journal of Sound and Vibration. 262, 651–675. doi: 10.1016/S0022-460X(03)00116-0

Rezaie, A., Godio, M., Beyer, K., 2020. Experimental investigation of strength, stiffness and drift capacity of rubble stone masonry walls. Construction and Building Materials. 251, 118972. doi: 10.1016/j.conbuildmat.2020.118972

Sangirardi, M., Altomare, V., De Santis, S., de Felice, G., 2022. Detecting Damage Evolution of Masonry Structures through Computer-Vision-Based Monitoring Methods. Buildings. 12. doi: 10.3390/buildings12060831

Sorrentino, L., D'Ayala, D., de Felice, G., Griffith, M. C., Lagomarsino, S., Magenes, G., 2017. Review of Out-of-Plane Seismic Assessment Techniques Applied To Existing Masonry Buildings. International Journal of Architectural Heritage. 11, 2–21. doi: 10.1080/15583058.2016.1237586

Vlachakis, G., Vlachaki, E., Lourenço, P. B., 2020. Learning from failure: Damage and failure of masonry structures, after the 2017 Lesvos earthquake (Greece). Engineering Failure Analysis. 117, 104803. doi: 10.1016/j.engfailanal.2020.104803