SHAKE TABLE TESTS OF A NOVEL SEISMIC-RESISTANT TECHNOLOGY FOR FAIR FACE MASONRY RECONSTRUCTION

M. Sangirardi[1], S. De Santis[2], F. Mosele[3], A. Dudine[4], I. Roselli[5], D. Liberatore[6] & G. de Felice[2]

[1]University of Oxford, Department of Engineering Science, Oxford, UK.

[2]Roma Tre University, Department of Civil, Computer and Aeronautical Engineering, Rome, Italy.

[3]Consorzio Poroton® Italia, Verona, Italy.

[4]Fibre Net SpA, Pavia di Udine (UD), Italy.

[5]ENEA Centro Ricerche Casaccia, Santa Maria di Galeria (Rome), Italy.

[6]Sapienza University of Rome, Department of History, Representation and Restoration of Architecture, Rome, Italy.

Abstract: *Observing the extensive destruction left behind by some recent earthquakes (e.g., Central Italy 2016-2017 and Turkey-Syria 2023) it is reasonable to ask if repair is the most sustainable option or weather reconstruction is to be considered in some cases. Once this alternative is picked, concerns related to the compatibility between safety and aesthetics arise, especially in historic centres, where fair face appearance of masonry façades represents an invaluable architectural asset. This paper presents an innovative technology for the reconstruction of masonry walls consisting of a two-leaf structure. A reinforced clay masonry, compliant, per se, with building code requirements and provided with high thermal performances, is the internal leaf and is connected to an external leaf built with fair face stone masonry. This solution would restore the architectural consistency with pre-existing structures while ensuring much higher seismic resistance than original rubblestone walls. It is also sustainable as rubble stones recovered from debris might be used to build the front leaf, avoiding their disposal and the supply of new materials. A key element is the glass fibre reinforced polymer (GFRP) mesh, which provides connection and prevents the disintegration of rubble masonry. An extensive experimental investigation was carried out at different scales. Preliminary laboratory tests were performed to characterize the mortars adopted for the brickwork, the mesh, and the connection system. Then, shake table tests were carried out on a full-scale wall prototype under natural seismic signals, with gradually increasing peak ground acceleration. The main results are shown in terms of displacement profiles and observed crack pattern, which testify that the wall specimen, even under the most severe actions, did not suffer any critical damage, proving the possibility to be implemented for reconstruction in highly seismic prone areas.*

1 Introduction

In Italian and Mediterranean regions fair face rubblestone masonry is a common building technology. However, these constructions have proven to be very vulnerable during past destructive earthquakes. They are made of multi-leaf rubble masonry with poor mechanical properties and are prone to leaf separation and disintegration, which prevents the activation of in-plane failure modes. Many buildings in the municipalities of Amatrice and Accumoli, hit by the 2016-2017 Central Italy seismic sequence (de Felice et al., 2022, Borri et al. 2019, Sorrentino et al. 2019), showed catastrophic disintegration collapses. The same mechanisms were also detected after many other destructive earthquakes as reported in (Göçer, 2014, Sherafati and Sohrabi, 2016, Brando et al., 2017, Marotta et al. 2017, Penna, 2015). In some cases, especially when the structural integrity of the wall is not preserved, distributed strengthening, acting on both sides of the wall or designed to be applied from the external side only, can ensure a satisfactory strength recovery to damaged structures (De Santis et al., 2021, Cascardi et al., 2020, Gattesco et al., 2023). Nonetheless, in case of extreme damage scenarios, strengthening may be unpractical, suggesting reconstruction as the unique possible solution. This paper presents a new reconstruction technology, aimed at ensuring appropriate seismic resistance while coping with architectural compatibility issues. It combines the external appearance of traditional rubblestone low-rise buildings with the high structural performance of reinforced clay masonry. The two leaves of the wall are connected by a newly designed pre-cured glass fibre reinforced polymer (GFRP) mesh embedded in the joints of both the back and the front leaf.

In the following, the proposed technology is briefly described. Then, details on the mechanical properties of its constituents are provided and the main experimental results of the shake table tests conducted on a full-scale masonry wall are presented. The outcomes confirmed that the proposed technology is a viable reconstruction technique whose merit is to preserve the aesthetic appearance of old constructions via a sustainable reuse of existing materials while ensuring high seismic capacity.

The experimental investigation presented in this paper is part of a large research project coordinated by Roma Tre University, in collaboration with La Sapienza University of Rome and ENEA, with the contribution of the Lazio Region and the participation of Fibre Net SpA and Consorzio POROTON® Italia.

2 The novel reconstruction technology

2.1 Construction of a wall prototype

To ensure adequate seismic safety in highly seismic areas while preserving fair faced appearance, the proposed technology combines a reinforced clay masonry internal leaf with an external one made of rubblestone (Figure 1a). A full-scale wall was built and tested on the shake table in the ENEA Casaccia Research Centre facility, in Rome. It had the same geometric properties of the ones already tested in previous investigations (de Felice et al., 2022, De Santis et al., 2021), to ensure a consistent comparison. In line with previous prototypes, the wall was 60 cm thick (considering both leaves) and 4.5 m high. It was anchored to a 35 cm high footing beam and had a 30 cm high top beam. The width of the wall was 1.7 m.

The wall was assembled by first building the back leaf, made of 40 cm POROTON® clay blocks and M10 cementitious mortar. Vertical bars (3Ø18) and horizontal (Ø 8) stirrups placed in alternated joints were placed to provide seismic resistance according to Italian building code (NTC2018). The clay masonry units also ensured thermal-acoustic insulation and guaranteed simple and rapid on-site work. A pre-cured glass fibre reinforced polymer (GFRP) mesh, specifically produced by Fibre Net SpA., with 132 mm × 132 mm mesh spacing, was placed in alternated joints (those where stirrups were not present) as shown in Figure 1b, making sure that part of it came out from the joint to act as a connection with the front leaf. This latter, having 20 cm thickness, was built using the stones collected after collapse or demolition of buildings after the 2016-2017 Central Italy seismic sequence. Stones were laid with a M10 strength class natural hydraulic lime-based (NHL) mortar (Figure 1c). During the construction of the front face, NHL mortar was used also in the vertical joint between clay units and stones.

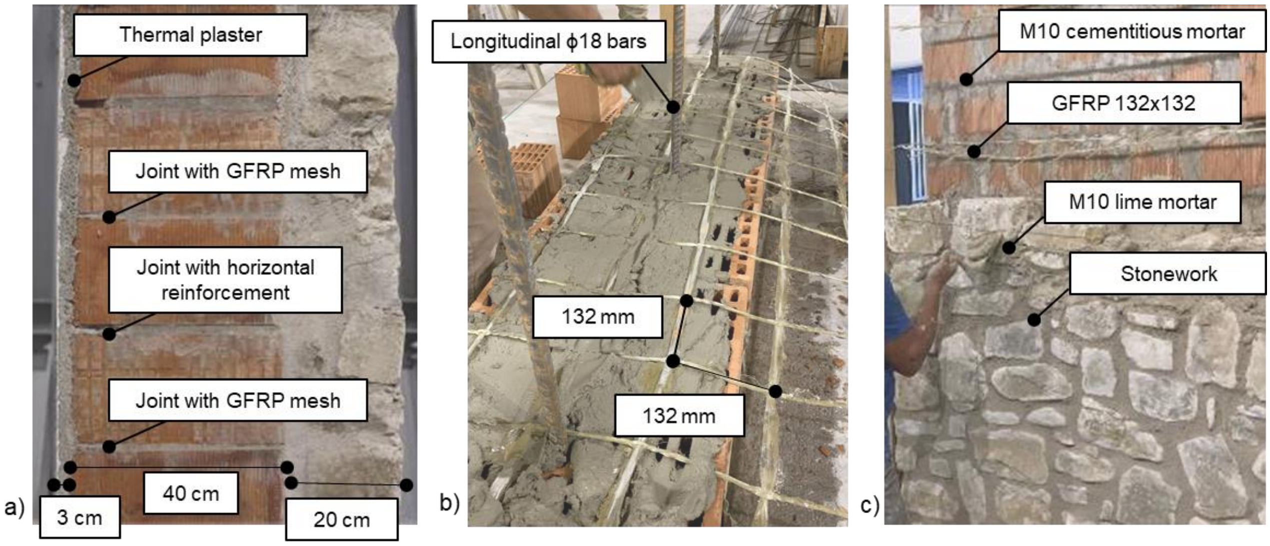

Figure 1. Horizontal joint with embedded mesh (a), side view (b) and front view of the wall during construction (c).

2.2 Mechanical characterization of constituent materials

All the adopted materials were preliminarily tested to determine their mechanical properties and to investigate one of the key aspects influencing the performance of the proposed technology: the yarn-to-matrix bond behaviour. This was explored performing pull-out tests on single bundles of the GRFP mesh embedded in mortar cylinders.

Direct tensile tests on single bundles of the GFRP mesh were performed in the weft direction according to (CNR - DT 203/2006). Bundle specimens were cut to 350 mm and provided with 50 mm × 30 mm × 3 mm aluminium tabs at the ends, to ensure proper gripping in the wedges of the testing machine (Figure 2a). Machine stroke displacement controlled monotonic tensile tests were carried out a 0.01 mm/s rate. Data were recorded at 10Hz sampling frequency. Load was recorded by the load cell integrated in the testing machine and divided by the nominal area of the bundle (assuming a nominal diameter of the bundle equal to ~ 4 mm, according to technical data sheet) to calculate stress. Displacement was recorded by an LVDT transducer and divided by the free length of the specimen to determine strain (assumed as uniformly distributed along the specimen length, which is reasonable in this case, since no local strain discontinuities were envisaged).

Test results are reported in Table 1 whereas the tensile stress versus tensile strain response curves for six specimens are plotted in Figure 2b, showing an elastic-brittle behaviour, characterized by sudden and repeated strength drops corresponding to the tensile failure of the glass wires constituting the GFRP bundle.

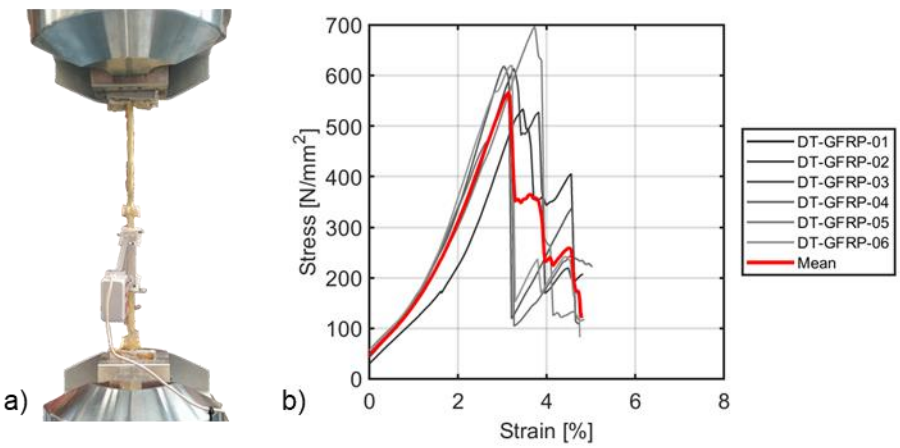

Figure 2. Tensile test specimen (a); tensile response of the strand (b).

Table 1. Tensile test results for the single twisted fibres bundle.

Specimen name	F_{fu} [N]	E_f [GPa]	ε_{fu} [%]
DT-GFRP-01	4923	11.9	3.46
DT-GFRP-02	5663	15.4	3.25
DT-GFRP-03	5705	16.4	3.03
DT-GFRP-04	5169	16.3	3.18
DT-GFRP-05	6422	15.6	3.72
DT-GFRP-06	5721	17.1	3.21
Mean	5600.5	15.5	3.3
CoV (%)	9.3	11.9	7.4

Indirect tensile and compressive tests on mortar specimens were performed according to EN1015-11 on both NHL and cement-based mortar prisms, prepared in the laboratory, and cured in humid environment for 90 days. Indirect tensile strength $f_{ft,m}$ was found to be equal to 5.64 MPa and 5.77 MPa, compressive strength $f_{c,m}$ equal to 26.9 MPa and 25.7 MPa, and Young's modulus E_m equal to 1770 MPa and 1900 MPa for lime and cement based mortar respectively. Mechanical properties of both mortar types resulted compatible and well above the expected values for the adopted materials (this can be partly due to curing time and thus be considered as representative of long-term behaviour).

Twenty pull-out tests (ten on specimens prepared with the NHL based mortar and ten with the cement-based mortar) were performed with a custom designed push-pull setup configuration inspired by the works of Dalalbashi et al. (2018) and Dalalbashi et al. (2021). The specimens were cast in cylindrical PVC moulds having 63 mm diameter and 170 mm height. The GFRP mesh bundle had a total length of 390 mm. It was immersed in the mortar for a bond length of 170 mm, had a free (unbonded) length of 160 mm and was gripped in the wedges of the testing machine for a length equal to 60 mm (Figure 3a). As in direct tensile tests, aluminium tabs were glued to the GFRP bundle in the load introduction areas to ensure homogeneous stress distribution.

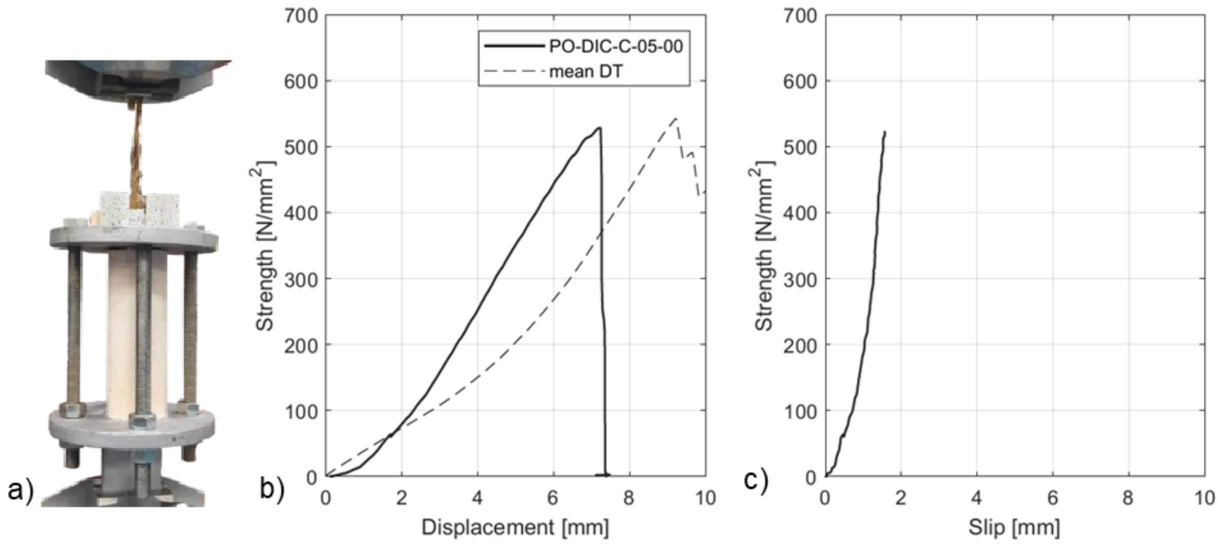

Figure 3. Setup of the pull-out test (a), MTS displacement vs stress response curve (b), and DIC slip vs stress response curve (c).

The embedded length (~170 mm) was designed to induce tensile failure of the glass fibres, preventing, or minimizing the slip between the bundle and the matrix. This length is also like the thickness of the front wall (~200 mm), thus being a realistic lower bound value to test the effectiveness of the connection in a configuration resembling actual installation conditions. Since the mortar cylinders were not confined nor subjected to any circumferential pressure, these tests were sought to be conservative as in reality the mesh will be subjected to a stress perpendicular to the yarns due to the self-weight of the wall.

The results in terms of both measured displacement of the loading head (Figure 3b) and relative slip detected with digital image correlation (DIC) (Figure 3c) showed that this value of embedded length was greater than the effective bond length for both cement and NHL mortar specimens, though the attained failure load was, on average, 10% lower than the tensile strength provided by direct tensile tests on GFRP bundles. Two failure modes could be recognized: tensile failure of the fibres at the mortar top interface or at the clamping zone, sometimes inside the clamped area. This latter mode is generally associated to a more brittle failure and to a lower value of the peak strength.

3 Shake table test setup and seismic inputs

3.1 Setup and instrumentation

After seven months of curing, the seismic behaviour of the full-scale prototype wall was investigated by means of shake table tests. The wall foundation was firmly connected to the table. At the top, the panel was constrained by steel I-girders, which rested on lateral braced steel frames, bolted to the shake table. A detailed description of the test setup can be found in de Felice et al. (2021) and in De Santis et al. (2021). Steel rollers were installed at the contact between the top beam and the I-girders, allowing vertical displacement and rotation, to replicate the actual boundary conditions experiences by a wall. Laboratory tests aimed at representing the collapse mechanism by vertical bending of a façade wall (e.g., of the top wall of a residential building). The weight of the roof was simulated adding steel plates on top for a total vertical load of 15 kN. Steel plates were connected to the wall by threaded steel bars and securely hooked to a crane to prevent their fall in case of collapse.

Base accelerations were recorded at 200 Hz sampling frequency by an accelerometer placed on the reinforced concrete foundation beam. The response of the wall prototype was recorded with a passive 3D motion capture system named 3DVision (De Canio et al., 2016), which recorded at 200 Hz sampling frequency the position of 64 retroreflecting spherical markers, through high resolution digital cameras working in the near infrared (NIR) field. Markers were placed on the specimen on four columns and eight rows equally spaced over the front and back wall surfaces.

3.2 Seismic inputs

The seismic inputs assigned to the shake table were selected from the Italian database to be representative of 2016-2017 Central Italy seismic sequence. Table 2 lists the event and its moment magnitude (M_W), the record station and its label and the peak ground acceleration (PGA), velocity (PGV) and displacement (PGD) of the inputs. The signals were applied in the out-of-plane and in the vertical directions, gradually increasing the intensity in terms of peak ground acceleration by means of a scale factor starting from 0.2 up to 2.8. Each equally scaled series of the three signals NRC-CNE-AMT was preceded and followed by a white noise signal of 2 min duration and 50 cm/s^2 PGA, aimed at allowing the dynamic identification of the structure in terms of its natural frequency.

Table 2. Selected earthquake ground motion records.

Earthquake information			Horizontal Component			Vertical component		
Event	**M_W**	**Record Station**	**PGA [cm/s^2]**	**PGV [cm/s]**	**PGD [cm]**	**PGA [cm/s^2]**	**PGV [cm/s]**	**PGD [cm]**
24/08/2016 01:36	6.0	Norcia (NRC)	352.8	29.7	-5.3	211.3	-11.6	-3.0
26/10/2016 19:18	5.9	Castelsantangelo sul Nera (CNE)	-527.0	23.1	2.7	-389.2	-19.6	-3.0
30/10/2016 06:40	6.5	Amatrice (AMT)	521.6	-37.9	-6.0	317.8	-31.4	4.4

4 Shake table test results

The evolution of damage on the wall specimen was quantitatively monitored detecting the displacements of the retroreflective markers. The separation between the back (internal) reinforced clay masonry leaf and the front fair face rubble stone masonry one, considered as one possible collapse trigger, was measured throughout the tests calculating the relative displacement between two symmetric markers placed at the same height, one on the front side and one on the back side (these are highlighted in red in the small pictogram on the right side of Figure 4). The relative displacement δ between markers A54 and B54 is shown in Figure 4, in which time is on the x-axis. The test sequence is split into two sub-sequences from NRC02 to AMT14 (Figure 4a) and from NRC16 to CNE28 (Figure 4b). In test labels, the first three letters identify the record station, and the number indicates the scale factor, (e.g., 02 stands for scale factor equal to 0.2, 14 for 1.4, etc).

The calculated value of δ was always smaller than 1 mm and fluctuating most likely because of instrumental noise and because of elastic deformations of the mortar layers. The complete reversibility of these relative displacements confirmed the elastic response of the specimen up to the highest base accelerations attained in the last tests, which were beyond 16 m/s^2. This remark was consistent with the lack of cracks detected by visual inspections. Figure 4 also reports with black numbered dots two interventions aimed at reducing the setup deformations, necessary as the intensity of the signal progressed. These are sought to have a negligible effect on the relative displacement.

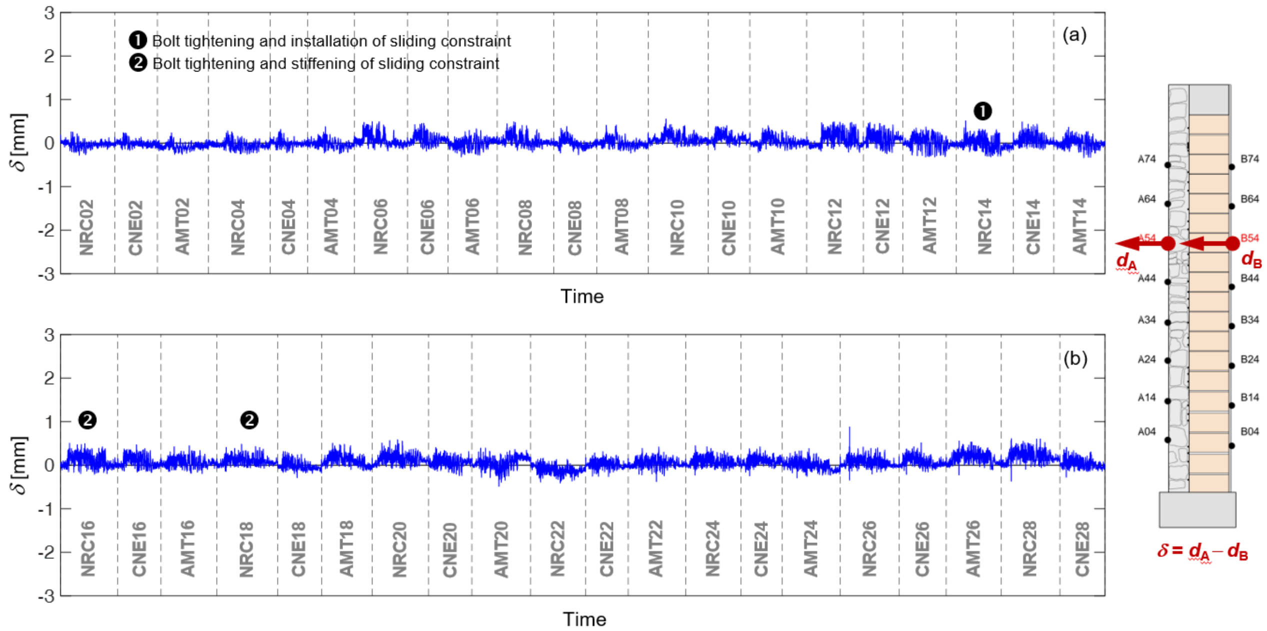

Figure 4. Relative displacement between the two leaves under strong motion tests NRC02-AMT14 (a) and NRC16-CNE28 (b).

Figure 5 reports the observed damage at the end of the seismic sequence with a scale factor equal to 2.2. Micro-cracks associated to out-of-plane flexural displacements did only appear on the back face of the wall (marked with red solid lines), on the finishing plaster layer. No other visible sign of damage could be detected with naked eye, confirming what already concluded observing the relative out-of-plane displacements of the markers.

Figure 5. Damage pattern at the end of the seismic sequence with scale factor 2.2.

5 Conclusions

A novel reinforced masonry technology was developed to ensure both high seismic capacity and aesthetic compatibility with traditional, fair face stone masonry architecture, characterizing most of the historic low-rise residential building stock, especially in the Mediterranean area. Though this research was inspired by the observation the devastating consequences experienced during the Central Italy seismic sequence in 2016-2017, a general significance is envisaged.

The technology consists of two masonry leaves: a reinforced clay masonry (conceived as the internal leaf) and a rubblestone fair faced one (developed to be the front leaf). The two leaves are connected by means of a custom designed glass fibre reinforced polymer mesh characterized by a non-standard spacing and a high flexibility to be embedded in the mortar joints of front and back leaves, also ensuring an effective gripping of the disordered front face stone pattern (thus preventing its collapse by disintegration).

After an extensive experimental characterization phase performed on constituent materials, a shake table investigation was carried out on a full-scale wall prototype under natural seismic signals, applied in vertical and horizontal (out-of-plane) directions with increasing intensity. Seismic test results demonstrated the effectiveness of this innovative technology, which withstood earthquake base motions nearly three times as intense as those recorded during the Central Italy seismic sequence, while maintaining its structural integrity, without showing any visible damage. The GFRP mesh embedded in the bed joints of the two leaves effectively prevented leaf separation and the disintegration of the rubble stone masonry, both sought as the main cause of catastrophic collapses. Detailed measurement of the relative out-of-plane displacements between front and back face of the wall quantitatively confirmed the absence of damage, and the development of small, elastic, and reversible deformations.

The promising results of the experimental investigation fostered the application of this technique in field reconstruction activities, as described in a companion paper (Mosele et al., 2024).

6 Acknowledgments

This work was carried out within the Research Project "RIPARA - Integrated systems for the seismic retrofitting of architectural heritage (2021-2023), funded by Regione Lazio. Fibre Net SpA (Pavia di Udine, UD, Italy) and Consorzio POROTON® Italia (Verona, Italy) are kindly acknowledged for providing materials and technical advice. The intermunicipal operative office of Accumoli and Amatrice is kindly acknowledged for allowing the collection of the stone units from the hamlet of Collespada.

7 References

Borri A., Corradi M., De Maria A. (2020). The failure of masonry walls by disaggregation and the masonry quality index. *Heritage*, *3*(4): 1162-1198.

Brando G., Rapone D., Spacone E., O'Banion M.S., Olsen M.J., Barbosa A.R., Stravidis, A. (2017). Damage reconnaissance of unreinforced masonry bearing wall buildings after the 2015 Gorkha, Nepal, Earthquake. *Earthquake spectra*, *33*(1_suppl): 243-273.

Cascardi A., Leone M., Aiello M.A. (2020). Transversal joining of multi-leaf masonry through different types of connector: Experimental and theoretical investigation. *Construction and Building Materials*, *265*: 120733.

CNR (2006). *Consiglio Nazionale delle Ricerche, Istruzioni per la Progettazione, l'Esecuzione ed il Controllo di strutture di Calcestruzzo Armato con Barre di Materiale Composito Fibrorinforzato*, CNR Consiglio Nazionale delle Ricerche, Roma.

Dalalbashi A., Ghiassi B., Oliveira D.V., Freitas A. (2018). Effect of test setup on the fiber-to-mortar pull-out response in TRM composites: experimental and analytical modeling. *Composites Part B: Engineering*, *143*: 250-268.

Dalalbashi A., De Santis S., Ghiassi B., Oliveira D.V. (2021). Slip rate effects and cyclic behaviour of textile-to-matrix bond in textile reinforced mortar composites. *Materials and Structures, 54*: 108.

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*(1): 53-71.

de Felice G., Liberatore D., De Santis S., Gobbin F., Roselli I., Sangirardi M., Sorrentino L. (2022). Seismic behaviour of rubble masonry: Shake table test and numerical modelling. *Earthquake Engineering & Structural Dynamics*, *51*(5): 1245-1266.

De Santis S., AlShawa O., de Felice G., Gobbin F., Roselli I., Sangirardi M., Liberatore D. (2021). Low-impact techniques for seismic strengthening fair faced masonry walls. *Construction and Building Materials*, *307*: 124962.

Gattesco N., Rizzi E., Boem I., Facconi L., Minelli F., Dudine A., Gams M., (2023). Full-scale cyclic tests on a stone masonry building to investigate the effectiveness of a one-side application of the composite reinforced mortar system. *Engineering Structures*, *296*: 116967.

Göçer C. (2020). Structural evaluation of masonry building damages during the April 24, 2014 Gökçeada earthquake in the Aegean Sea. *Bulletin of Earthquake Engineering*, *18*(7): 3459-3483.

Marotta A., Sorrentino L., Liberatore D., Ingham J.M. (2017). Vulnerability assessment of unreinforced masonry churches following the 2010-2011 Canterbury (New Zealand) earthquake sequence. *Journal of Earthquake Engineering 21*(6): 912–934.

Mosele F., Barbieri L., de Felice G., De Santis S., Sangirardi M., Zampa A. (2024). Reconstruction of a stone masonry building with a new technology of fair-face double leaf masonry wall. In *Proceedings of the 18th World Conference on Earthquake Engineering, Milan 30th June – 5th July 2024*.

Penna A. (2015). Seismic assessment of existing and strengthened stone-masonry buildings: critical issues and possible strategies. *Bulletin of Earthquake Engineering*, *13*(4): 1051-1071.

Sherafati M.A., Sohrabi M.R. (2016). Performance of masonry walls during Kaki, Iran, earthquake of April 9, 2013. *Journal of Performance of Constructed Facilities*, *30*(3): 04015040.

Sorrentino L., Cattari S., Da Porto F., Magenes G., Penna, A. (2019). Seismic behaviour of ordinary masonry buildings during the 2016 central Italy earthquakes. *Bulletin of Earthquake Engineering*, *17*(10): 5583-5607.

UNI (2019). *EN 1015-11:2019, Metodi di prova per malte per opere murarie - Parte 11: Determinazione della resistenza a flessione e a compressione della malta indurita*, UNI Ente Italiano di Normazione, Milan.