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Seismic retrofit of unreinforced masonry walls using timber strong-backs and cross laminated timber panels

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ABSTRACT

The susceptibility of unreinforced masonry (URM) walls to collapse under seismic loading has been repeatedly observed and documented across a multitude of earthquakes worldwide. Out-of-plane and in-plane failure modes have been identified as critical failure mechanisms for URM structures during a seismic event, and both failure modes pose a significant risk to life. Despite various seismic improvement techniques being applied previously, there is a significant lack of experimentally validated simple and cost-effective solutions that also consider the impact on the building tenants, building aesthetics, and heritage fabric of the structure. Such retrofits are needed to facilitate the preservation of the URM building stock and to ensure the safety of those who work and live in and around these structures. The retrofit techniques studied herein consisted of connecting timber elements to the interior surface of a building's walls using mechanical anchors. For out-of-plane strengthening, vertical timber members (strong-backs) were used. For in-plane strengthening, cross laminated timber (CLT) panels were used. The use of mechanical anchors and timber as the seismic retrofit materials results in a cost-effective and low impact solution. The out-of-plane behaviour of as-built and retrofitted masonry walls was investigated by conducting full scale semi-static cyclic airbag tests and shake-table testing on solid and cavity masonry walls. The outcomes of this testing regime include (i) quantification of improvement in seismic capacity and out-of-plane displacement capacity; (ii) comparison of the performance using different strong-back configurations; (iii) providing construction details. The in-plane behaviour of as-built and retrofitted masonry walls was investigated by conducting full scale in-situ semi-static in-plane shear tests on as-built, repaired, and retrofitted masonry walls. The outcomes of this testing regime include quantification of (i) improvement in seismic capacity; (ii) effect on element stiffness; (iii) force vs displacement behaviour.

Keywords: URM, seismic, retrofit, timber, masonry anchors.

1. INTRODUCTION

The susceptibility of unreinforced masonry (URM) walls to collapse under seismic loading has been repeatedly observed and documented across a multitude of past earthquakes worldwide [1]-[3]. Damage observations have often shown that the structural collapse is associated with the activation of local out-of-plane mechanisms, with or without the attainment of in-plane wall capacity [4], [5]. The majority of the existing URM building stock was constructed prior to the introduction of modern seismic loading standards and it is characterized by poor seismic performance. URM building performance has been studied by different authors through in-situ or laboratory testing campaigns [6]-[12]. Consequently, adequate retrofit strategies for out-of-plane and in-plane strengthening need to be adopted to prevent and limit damage to persons and property.

The two testing campaigns reported herein sought to validate an out-of-plane and an in-plane retrofitting technique. The out-of-plane retrofit consisted of connecting vertical timber elements (strong-backs) to an interior surface of URM walls using mechanical screws. The timber elements were connected to purpose-built timber structures designed to replicate timber diaphragms, in order to transfer horizontal load and to avoid cantilever-type failure [13] of the retrofitted wall. The strong-backs then act in flexure to increase the out-of-plane wall resistance. Twelve full-scale static airbag tests were performed on five URM walls in the as-built and retrofitted conditions.

The in-plane retrofit consisted of the connection of Cross Laminated Timber (CLT) panels to the URM walls using mechanical screws. Previous work to drive this testing campaign included a numerical investigation on isolated masonry piers [14] and experimental testing of mechanical connections under cyclic shear loading [15]. The in-plane test campaign was performed in-situ by isolating three URM walls within a late 19th century building structure located in the municipality of *Stenico* in the *Terme di Comano* bath area (Northern Italy). The structure was originally built as a three-storey stone masonry building, to which a fourth storey composed of brick masonry was added in the 1920s. The in-situ testing allowed for a direct check of the feasibility of the strengthening procedure outside of a laboratory testing facility.

2. MATERIALS AND GEOMETRY

2.1 Out-of-plane testing (timber strong-backs retrofit)

Five full-scale walls were constructed for testing. Four walls were constructed using recycled vintage clay bricks (Wall IDs W1, W2, W4, W5), in order to simulate the typical deteriorated condition of in-situ brick walls and thus introduce realistic material variability into the testing. One wall was built using concrete masonry units (CMU) (Wall ID W3) (Figure 1e). Two types of mortar mix were utilised to represent different mortar compositions typically encountered in real vintage URM construction. Table 1 provides a summary of the tested masonry and mortar material properties.

Structural Grade 8 (SG8, [16]) Radiata Pine was used for the timber strong-backs retrofit, the material properties of which are provided in Table 2. The timber strong-backs (Figure 1a) had a horizontal spacing from each other of 600mm and were secured to the URM wall using mechanical anchors. The strong-backs were connected at each end to timber members running horizontally at top and bottom of the wall (Figure 1b, c) to replicate a typical timber diaphragm, using purlin cleats with 10-gauge diameter (4.8mm) x 75mm long timber screws. The mechanical anchor [17] (Figure 1d) used for the timber-to-masonry connection comprised a 230mm long shaft with a different thread on each of two portions of the anchor. The first thread near the tip of the anchor is intended for masonry support and the second thread near the head of the anchor is designed for fixing into timber. The geometric properties of the mechanical anchor are provided in Table 5.

Table 1. Average properties of wall constituent materials for out-of-plane wall specimens

Material testing	Average compressive strength (MPa)	COV (%)	Standards and test methods
Mortar (1:2:9 mix) ($f_{c,m}$)	1.37 (6)	9	[18]
Mortar (1:0:6 mix) ($f_{c,m}$)	2.98 (6)	10	[18]
Brick ($f_{c,b}$)	19.80 (6)	13	[19]
Masonry (f_c)	6.03 (6)	33	[20]

(#) – number of samples tested

Table 2. Timber strong-back properties

Properties	Values
Density (ρ)**	450 kg/m^3
Bending strength ($f_{m,t}$)*	14 MPa
Compression strength ($f_{c,t}$)*	18 MPa
Tension strength ($f_{c,t}$)*	6 MPa
Modulus of elasticity (MoE)**	8000 MPa

The structural properties are verified according to the requirements of NZS 3622 **Error! Reference source not found.**. * Characteristic value ** Mean value

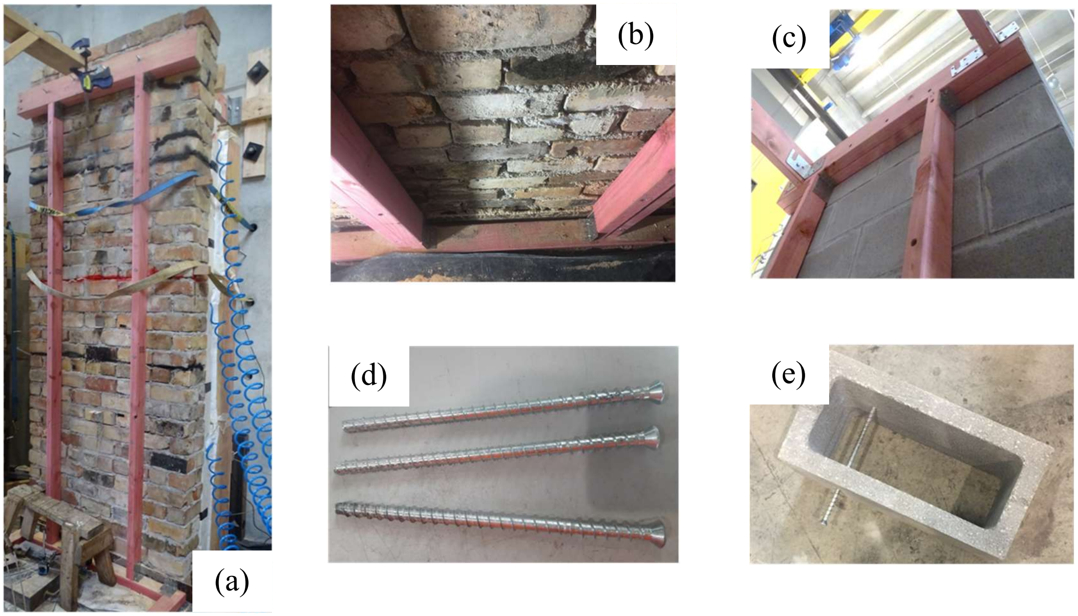


Figure 1. Retrofit test setup for out-of-plane testing (timber strong-backs): (a) Overall view of the retrofit technique and tested wall specimen (W2.T); (b) Strong-backs installation, bottom connection (W2.C); (c) Strong-backs installation, top connection (W3.C); (d) Specially designed masonry screws used for the retrofit; (e) Example of fastener installed into CMU;

2.2 In-plane testing (CLT panels retrofit)

The in-plane test campaign consisted of testing three full-scale brick masonry specimens under semi-cyclic loading conditions. The specimens were created by isolating three approx. 1800mm x 1800mm masonry wall portions from the walls at the top storey of the building. The walls were three-leaf thick (i.e., approx. 340mm) and constructed using approx. 200mm x 100mm x 50mm clay bricks and lime mortar. Table 3 provides a summary of the masonry material properties which were tested in accordance with ASTM C109 (2013) [18] and ASTM C67 (2017) [20].

Table 3. Brick masonry material properties for in-plane wall specimens

Material characteristic	No. of samples	Mean	CoV
Brick compressive strength, f_{bc} (MPa)	15	14.8	0.32
Brick modulus of elasticity, E_{bc} (MPa)	15	1225	0.29
Brick bending tensile strength, f_{bt} (MPa)	7	3.7	0.43
Mortar compressive strength, f_{mc} (MPa)	15	4.6	0.50

3-layer 60mm thick softwood timber CLT panels (1800mm x 1800mm x 60mm) were used for the in-plane retrofit testing campaign, the properties of which are provided in Table 4. Similar to the out-of-plane testing, mechanical fasteners (see Table 5) were used to connect the CLT panels to the wall specimens.

Table 4. CLT panel mechanical properties

Panel element		Spruce CLT [21]
Bending (MPa)	$f_{m,0,k}$	24
	$f_{m,90,k}$	-

Tension (MPa)	$f_{t,0,k}$	14.5
	$f_{t,90,k}$	0.12
Compression (MPa)	$f_{c,0,k}$	21
	$f_{c,90,k}$	2.5
Shear	$f_{v,k}$	2.3
Modulus of elasticity	$E_{0,mean}$	11550
Shear modulus	G_{mean}	450
Density	ρ_{mean}	420
	ρ_k	350

Table 5. Geometric properties of CLT panel-to-masonry fastener

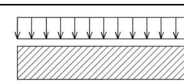
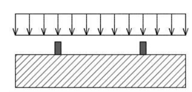
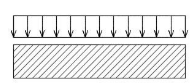
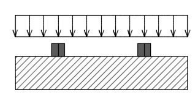
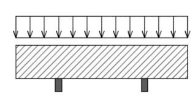
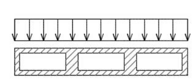
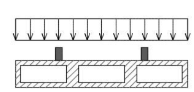
Fastener properties	
Total length, L (mm)	230
Thread length, L_t (mm)	160 (70)*
Thread diameter, d_{thread} (mm)	10 (12)*
Core diameter, d_{core} (mm)	7.5
Hole diameter, d_{hole} (mm)	8

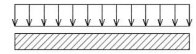
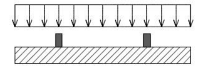
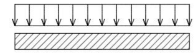
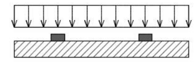
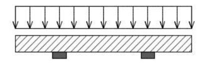
*Values in brackets are the properties of the second thread near the head of the anchor for fixing into timber.

3. EXPERIMENTAL PROGRAM

Table 6 summarizes the characteristics of the tested walls for out-of-plane loading (timber strong-backs retrofit).

Table 6. Test program for out-of-plane retrofit testing (timber strong-backs)

Wall ID	**Wall thickness (mm)**	**Mortar mix***	**Connector spacing (mm)**	**Timber section (mm)****	**Strong-backs side*****	**Schematic**
W1.URM	230	1:2:9	-	-	-	
W1.C	230	1:2:9	270	45×90	C	
W2.URM	230	1:2:9	-	-	-	
W2.C	230	1:2:9	270	90×90	C	
W2.T	230	1:2:9	450	45×90	T	
W3.URM	190	1:0:6	-	-	-	
W3.C	190	1:0:6	500	45×90	C	

W4.URM	110	1:2:9	-	-	-	
W4.C	110	1:2:9	450	45×90	C	
W5.URM	110	1:2:9	-	-	-	
W5.C	110	1:2:9	450	90×45	C	
W5.T	110	1:2:9	450	90×45	T	

*cement : lime : sand; **width × height; ***C – compression side; T – tension side.
Note: All test walls were 3000 mm high and 1200 mm wide. The horizontal spacing of the strong-backs was 600 mm.

Table 7 summarizes the characteristics of the tested walls for in-plane loading (CLT panel retrofit) and the fastener arrangement. The CLT panel to masonry connections were uniformly spread over the surface of the wall specimens, with a minimum wall edge distance of 200mm. Regularity of the spacing pattern may have been slightly altered to allow prevent installation from occurring in the mortar bed joints or the cracks produced by the as-built testing.

Table 7. Test program for in-plane retrofit testing (CLT panels)

Specimen	Configuration	Fastener spacing (mm)	Fastener total number
1	As-built	-	
2	As-built	-	
2	Repaired	400	16
3	Retrofitted	300	25

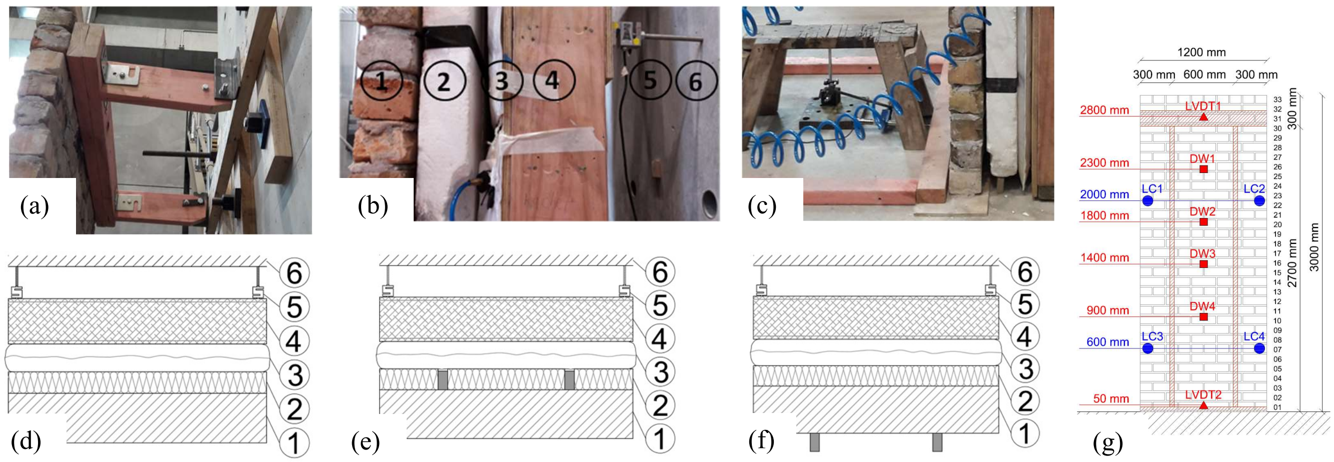
Note: All test walls were 1800mm high and 1800mm wide.

4. TEST METHODOLOGY

4.1 Out-of-plane testing (timber strong-backs retrofit)

The test methodology was designed to simulate typical in-situ boundary conditions for a single-storey URM wall, by purpose designing and building two timber structures to provide the wall specimens with a top and base restraint (Figure 2a, c). Inflated airbags were used to apply uniformly distributed loads to the walls (Figure 2b). The airbags were positioned between the timber reaction frame and a polystyrene layer, the latter of which enabled distribution of the load onto the masonry. The timber reaction frame was supported by a system of frictionless rollers to provide self-weight support without imposing horizontal restraint. The polystyrene layer thickness was slightly greater than the cross-sectional height of the timber strong-backs, in order to transfer lateral loading from the airbags to the masonry surface without directly engaging the strong-backs. Four load cells, four draw-wires and two linear variable differential transducers (denoted as LC#, DW# and LVDT# respectively) were used in the locations shown in Figure 2g.

The airbag testing of the walls was undertaken via displacement control using the DW2 measuring device. The walls were subjected to semi-cyclic out-of-plane loading via the application of uniformly distributed horizontal loads. Multiple load cycles were performed, with load release and application occurring at approx. every 5mm of deformation. All walls were tested with the strong-backs fixed to the compression side of the wall (W#.C). Two walls were further tested with the strong-backs fixed to the tension side (W2.T and W5.T). Figure 2d-f provides schematic representations of the test set-up for the as-built and retrofitted conditions.



Note:

① Tested specimen; ② Polystyrene layer; ③ Airbag; ④ Timber contrast panel; ⑤ Load cell; ⑥ Strong-wall;

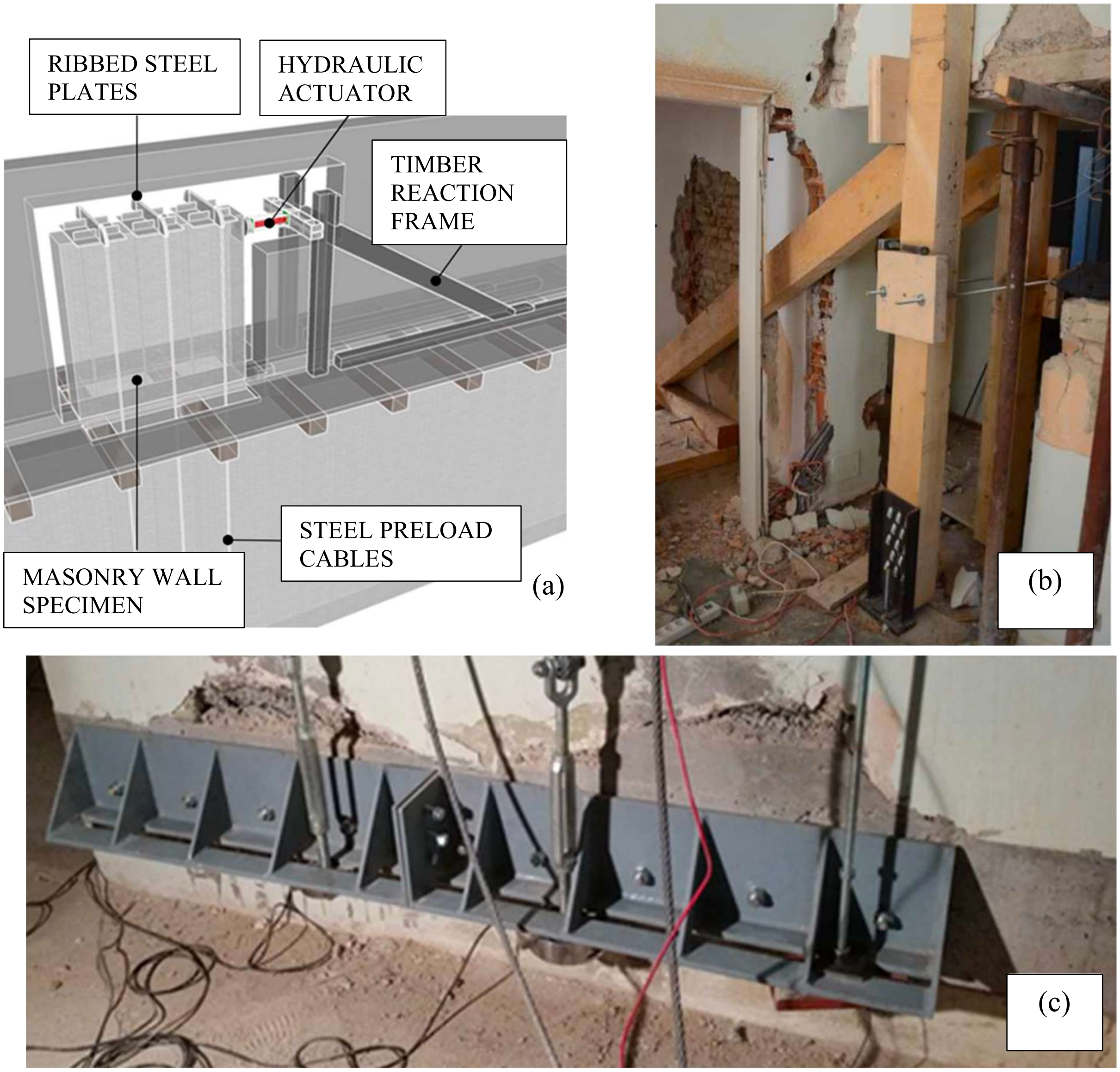
Figure 2. Cross-section views of test set-up and boundary conditions for out-of-plane testing (timber strong-backs): (a) Top wall restraint; (b) Airbag location; (c) Bottom wall restraint; (d) W#.URM test set-up; (e) W#.C test set-up; (f) W#.T test set-up; (g) Schematic of instrumentation locations and adopted test arrangement. Note: (d)-(f) are schematic horizontal cross sections of the test set-up.

4.2 In-plane testing (CLT panels retrofit)

The test methodology for in-plane testing was governed by two aspects in relation to applying the vertical preloading stress to the wall specimens. Firstly, the selected masonry walls for the testing were located at the top storey of the building, resulting in the only available overburden weight being from the timber roof. This amount of overburden is not reflective of the critical in-plane stress levels encountered within URM walls, which are typically those at ground level of multi-storey URM buildings. Secondly, a way to control the masonry vertical stress to 'pilot' the failure mode and engage the wall's shear capacity was required. The magnitude of the vertical compression force applied to the walls required calibration to ensure that the walls failed due to diagonal shear.

The testing solution (Figure 3a) to satisfy these two aspects was to use three steel cables to 'wrap' the specimen and tie it down on either side of it to a reaction beam located at the first-floor level of the building. The anchor points were provided by two L-shaped ribbed steel beams (Figure 3c) bolted to a purpose-cast reinforced concrete (RC) ring beam. A compression load was applied to the wall specimen using conventional tensioners positioned on all six ends of the steel cables. To enable distribution of the compression stress over a wider area, three ribbed steel plates were placed on top of the specimen (Figure 3d). To avoid non-uniform loading and unwanted out-of-plane displacement of the specimen, cables were loaded in 5kN increments starting from the central cables and continuing alternatively to the front and back cables.

The shear load was applied by a 250kN hydraulic jack fixed to the timber reaction frame (Figure 3b) using a ribbed steel I-beam (Figure 3f). The load was applied only to the masonry wall. Once the CLT reinforcement panel was applied, no direct load transfer was present aside from the mechanical fasteners connecting the CLT panel to the wall. To prevent localized crushing of the masonry due to stress concentration at the bearing area, the contact area between the hydraulic jack and the specimen was reinforced by casting a 20mm layer of high strength textile reinforced mortar (TRM) with a 15mm thick steel plate over the mortar layer. To minimize the possibility of eccentric loading due to the potential occurrence of minor out-of-plane rotations of the specimen when under load, optimal load transfer was ensured via a semi-spherical ball and socket joint (Figure 3e) between the hydraulic jack and the specimen. The shear load was applied in force-controlled semi-cycles of 5kN increments up to a load of 30kN, after which the increments were increased to 10kN. Once the shear load approached the wall's maximum capacity (identified by diagonal cracking), the last additional cycles were then under displacement control (semi-cycle increments of 10mm).


RIBBED STEEL PLATES
HYDRAULIC ACTUATOR
TIMBER REACTION FRAME
STEEL PRELOAD CABLES
MASONRY WALL SPECIMEN
(a)
(b)
(c)

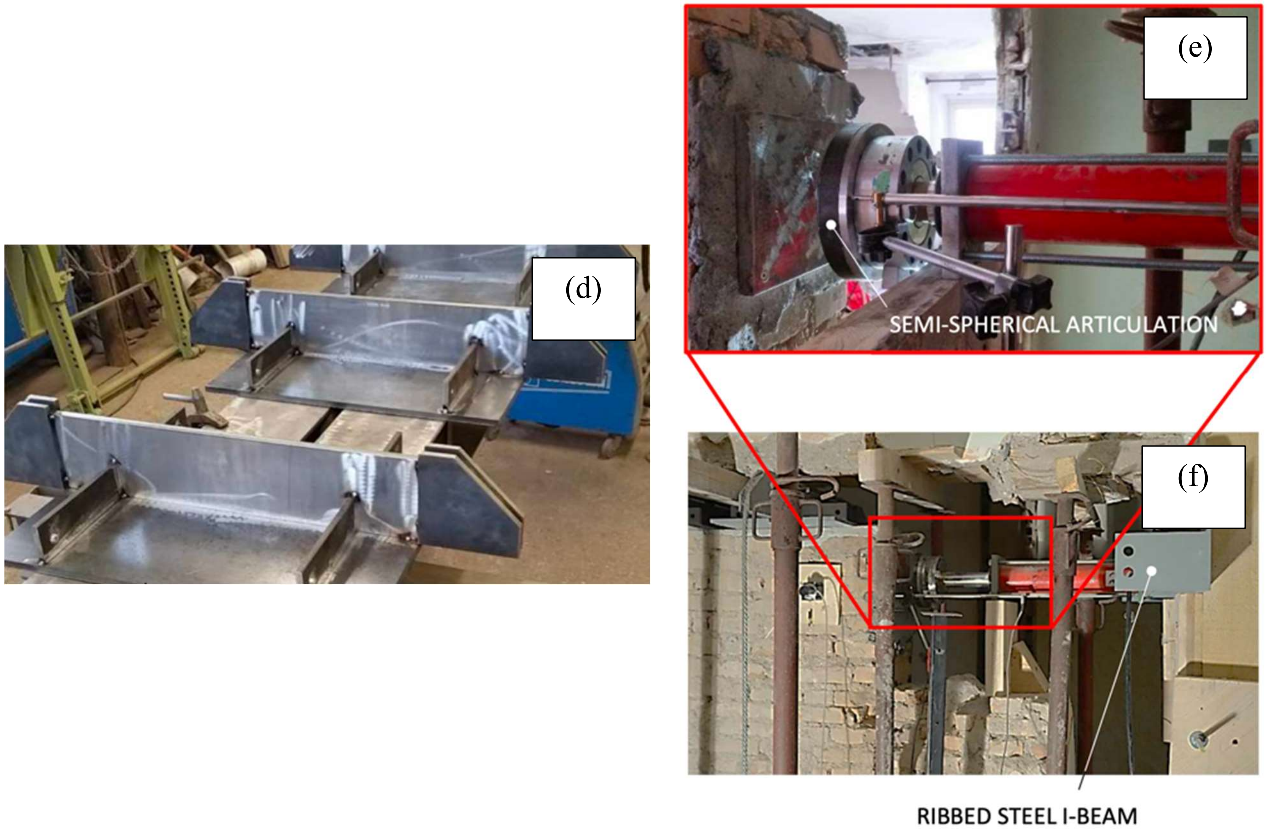


Figure 3. Test set-up of in-situ URM walls for in-plane testing (CLT panels retrofit): (a) Schematic representation of test set-up; (b) Close-up of the timber reaction frame; (c) detail of anchoring system for steel preload cables; (d) ribbed steel plates for vertical pre-load distribution; (e) Close-up of the hydraulic actuator-specimen contact area; (f) Ribbed steel I-beam for horizontal load transfer to timber reaction frame

5. EXPERIMENTAL RESULTS

5.1 Out-of-plane performance (timber strong-backs retrofit)

Table 8 presents the results of the experimental testing campaign. The maximum values of the force F and the corresponding displacements δ obtained during each test were reported. The values of alpha (force/weight) and drift (displacement/height) were calculated to compare the properties of different types of walls. The response of each specimen is reported in Figure 4.

Table 8. Results summary of the experimental test campaign

Wall ID	Weight W (kN)	Horizontal force F (kN)	Alpha F/W (-)	Displacement δ (mm)*	Drift δ/h** (%)	Capacity Increase (%) ***
W1.URM	13.44	4.63	0.344	4	0. 15	-
W1.C	13.44	16.41	1.221	75	2.78	254
W2.URM	13.44	6.03	0.449	37	1.37	-
W2.C	13.44	20.61	1.534	75	2.78	242
W2.T	13.44	33.95	2.527	51	1.89	463
W3.URM	6.50	3.14	0.483	29	1.07	-
W3.C	6.50	8.77	1.349	78	2.89	179
W4.URM	6.65	1.73	0.260	30	1.11	-
W4.C	6.65	10.39	1.563	46	1.70	501
W5.URM	6.65	1.51	0.227	38	1.40	-
W5.C	6.65	6.26	0.941	82	3.04	315
W5.T	6.65	16.73	2.516	76	2.81	1008

Note: *displacement measured when the maximum force was reached; **h = restraint height (2700 mm for all specimens); *** increase calculated above the URM capacity (W#.URM).

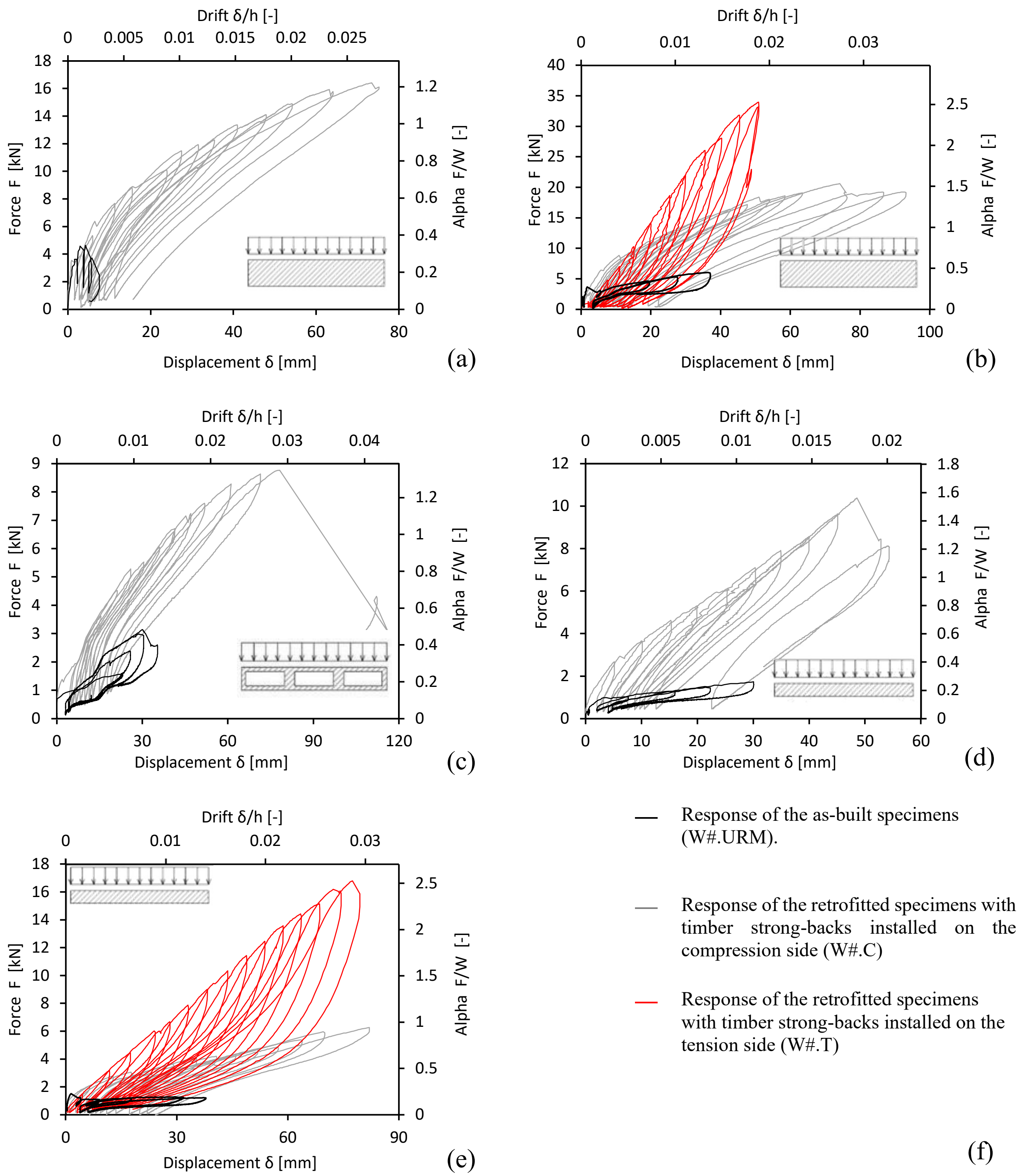


Figure 4. Response of the tested specimens: (a) W1.URM and W1.C; (b) W2.URM, W2.C and W1.T; (c) W3.URM and W3.C; (d) W4.URM and W4.C; (e) W5.URM, W5.C and W5.T; (f) Legend

5.2 In-plane performance (CLT panels retrofit)

This section reports the outcomes and the data analysis of the experimental investigation. The comparison of the full-scale tests performed, reported both in graphical and in tabular form, is shown in Table 9 and in Figure 5.

The derived parameters from the data analysis are:

- F_{max} = Maximum load: maximum value of the horizontal load (LOAD) applied to the specimen;
- K_s = Secant stiffness: measured from the load-displacement (*LOAD-DISP_R*) curve as the slope of the secant passing from the $0.4\ F_{max}$ and $0.1\ F_{max}$ points;
- K_i = Initial stiffness: measured from the load-displacement (*LOAD-DISP_R*) curve as the slope of the secant passing from the $0.4\ F_{max}$ point and the origin;
- E_d = Dissipated energy: calculated as the envelope area of the load-displacement (*LOAD-DISP_R*) curves;
- F_{maxHD} = Maximum force on the hold-down: maximum value of the force registered on the hold-down load-cell (*HD_FORCE*);
- K_{HD} = Secant stiffness of the hold-down: measured from the load-displacement curve of the hold-down (*HD_FORCE-HD_DISP*) curve as the slope of the secant passing from the $0.4\ F_{max\ HD}$ and $0.1\ F_{max\ HD}$ points.

Table 9. Principal parameters derived from the experimental curves (summary of all tests)

Specimen	F_{max} [kN]	K_s [kN/mm]	K_i [kN/mm]	E_d [J]	F_{maxHD} [kN]	K_{HD} [kN/mm]
1 – As Built	69.3	6.62	8.30	1990	-	-
2 – As Built	75.9	5.94	7.44	3057	-	-
2 – Repaired	91.1	4.50	5.40	3732	27.7	3.54
3 - Retrofitted	106.0	5.28	6.84	7484	47.5	2.63

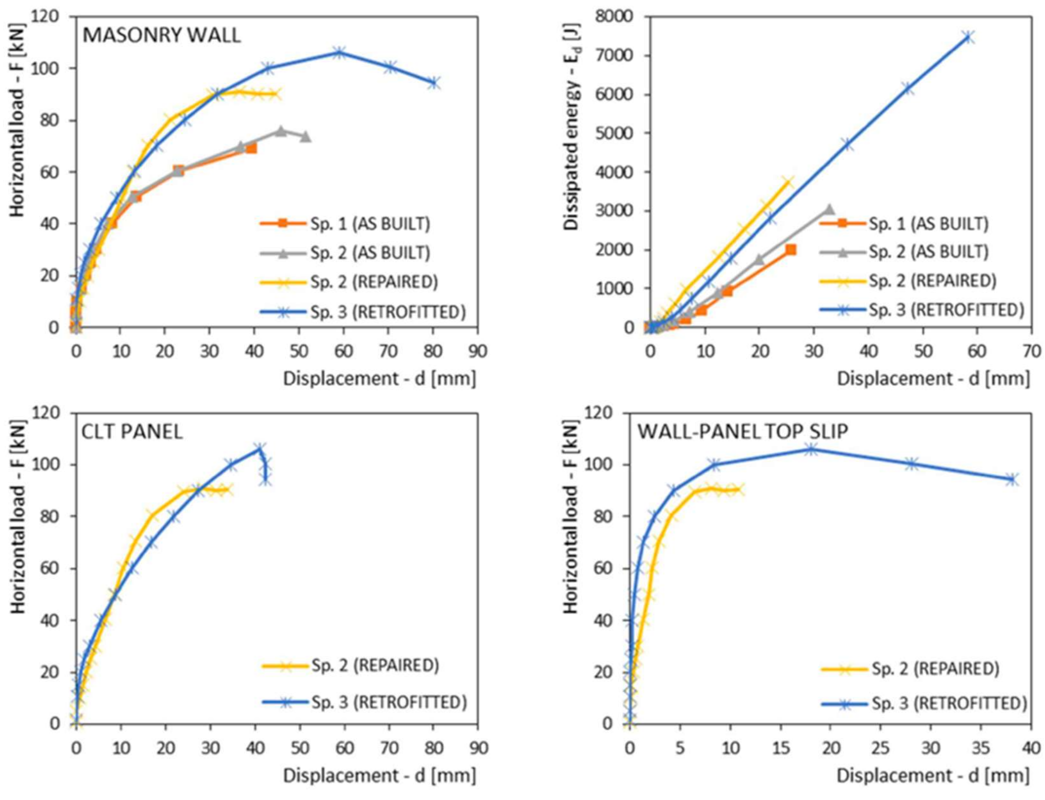


Figure 5. Comparison of the load-displacement backbone curves for the masonry wall, CLT panel and wall-panel slip endured by the connection along with the backbone curves for the dissipated energy at the end of the unload cycles

6. CONCLUSIONS

Two testing campaigns were reported herein which investigated out-of-plane and in-plane retrofit techniques for URM walls. In the first campaign, airbag testing was undertaken in order to experimentally validate the use of timber strong-backs as a simple and cost-effective out-of-plane seismic retrofit solution for clay brick URM walls. The following conclusions were drawn:

- Five different specimens were tested under as-built and retrofitted conditions: two two-leaf URM walls, two one-leaf URM walls and a CMU wall. The application of the timber strong-back retrofit technique in different configurations on these three wall types led to an improvement in capacity of between 2.5 to 5 times that of the as-built wall capacity.
- The behaviour of the retrofitted specimens was characterized by a gradual reduction/increase (depending on the loading direction) of the compression stress and hence the masonry bending capacity. Multiple horizontal cracks propagated at different levels within the upper two-thirds of the wall height until failure occurred of the timber strong-back due to compression/tension and bending.
- As expected, the retrofitted walls' response improves when the moment of inertia of the timber strong-back cross section is increased. The improvement in capacity is also dependent on the wall's characteristics (i.e., solid two-leaf clay brick walls exhibited greater improvement compared to CMU walls, and single-leaf walls exhibited greater increase in capacity than two-leaf thick clay brick walls).
- The adoption of a standard 90 x 45 mm timber cross section represents an adequate retrofit solution for all three investigated masonry types, resulting in performances capable of resisting lateral forces equivalent to acceleration values greater than 1.2g.
- In the more vulnerable loading direction wherein the timber strong-backs are compressed, the retrofitted walls' response does not change when decreasing the connector spacing or increasing the slip modulus of the connection. A 450mm spacing was observed to be sufficient to transmit load from the masonry to the timber. 8mm mechanical timber-to-masonry anchor fasteners were used, which provided sufficient connection between the timber strong-backs and the masonry.
- Timber strong-backs resulted in being a cost-effective and easy-to-install strengthening technique without requiring the use of any specialist techniques for their installation.

In the second campaign, in-situ shear compression testing was undertaken on URM walls to experimentally validate the use of CLT panels connected with mechanical anchor fasteners as an in-plane seismic retrofit technique. The following conclusions were drawn:

- The repair of Specimen 2 enabled 25% extra capacity in addition to complete restoration of the original wall's shear capacity as investigated via testing of the specimen under as-built conditions. Approximately five 8mm diameter mechanical timber-to-masonry fasteners per square meter of wall surface were adopted for the repair.
- A 46% increase in maximum capacity (in comparison to the as-built condition) was observed when the CLT panel was applied to an undamaged masonry wall by using approximately eight 8mm mechanical timber-to-masonry fasteners per square meter of wall surface. The mechanical fasteners exhibited noticeable yielding during the testing as evidenced by the wall-panel slip value at completion of the tests.
- For safety reasons, the ultimate displacement capacity of the specimens could not be attained. However, both repaired and retrofitted specimens exhibited substantial drift capacities (4.5% for the retrofitted configuration).
- The application of CLT panels for repair and retrofit ensured significantly higher values of energy dissipation compared to the as-built condition.
- Unreinforced and reinforced specimens exhibited negligible difference in stiffness. This could allow strengthening of selected walls located in the most severely stressed areas of the structure without interfering with inertial load distribution among the various walls.
- Peak load and stiffness values for the hold down anchors connected to the CLT panel are comparable with the performance of connections currently adopted in timber constructions and already available commercially.

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