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Out-of-Plane Testing of Masonry Walls Retrofitted with Oriented Strand Board (OSB) Timber Panels

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Several studies on different techniques can be found on retrofitting existing unreinforced masonry (URM) walls using varieties of materials ranging from reinforced plaster, grout, and epoxy injection to fibre reinforced polymers (FRPs). Still, there is a significant lack of experimental data that consider using a material such as oriented strand board (OSB) timber-panels that can be easily sourced around the globe, considered to be economical and sustainable. Hence, this paper presents the first stage of a multi-phase experimental investigation into the possibility of retrofitting URM walls using OSB panels. Since an experimental program with full-scale testing is expensive, small-scale testing such as the one presented here is ideal for an insight when proposing a new retrofit technique. In this paper, flexural strength in form of four-point bending tests has been obtained on three plain masonry prisms and six OSB retrofitted specimens (615 x 215 x 102.5mm). The effectiveness of the proposed OSB-panel retrofit techniques has been assessed in term of flexural strength, out-of-plane load capacity and displacement. It was observed that the application of the OSB panel at the back of masonry prism greatly influenced the out-of-plane behaviour of the retrofitted specimen by increasing its flexural capacity and also by preventing its quasi-brittle collapse.

< **Keywords:** Anchors, Masonry, Strength & testing of materials

Masonry is a configuration of brick units bonded together with mortar often categorized as a homogenous brittle composite material. Prior to the emergence of more recent building materials such as concrete and steel, masonry was the predominant building material. Masonry materials are available at low cost and can be easily used with semi-skilled workers. This makes masonry construction to be popular as one of the earliest building categories. Consequently, substantial amounts of unreinforced masonry (URM) structures were built all over the world in the past and now they constitute a unique historical value for civilization, besides the evident housing value (Ramos and Lourenço, 2004). Old URM structures were often designed and built using construction techniques with no conformity to any construction codes but rather to building's ''rules of art'' (Menon and Magenes, 2013; Vasconcelos and Lourenço, 2009). They have been found to perform weaker than recent structures when subjected to excessive loading, which may result in catastrophic failure (Lin et al., 2016). Therefore, the retrofit of old URM structures is highly encouraged to avert substantial damages and loss of lives.

The failure of URM walls can occur as out-of-plane (bending) or in-plane (shear), but out-of-plane collapse is the predominant mode of failure of URM walls belonging to existing buildings (Lourenco et al., 2017; Abrams et al., 2017; Costa et al., 2011; Derakhshan et al., 2016). Most existing URM walls are vulnerable when subjected to out-of-plane loading (face-load) due to the lack of tensile resisting elements (Costa et al., 2011; Derakhshan et al., 2016; Hamoush et al., 2001). Under severe out-of-plane loading, the failure of a masonry wall is likely to be sudden and severe, producing devastating damage, with loss of property as well as injuries or death of occupants and passers-by [10]. Walls collapsing in out-of-plane direction thus cause the most significant amount of damage. Out-of-plane loading can be due to blast effect induced by an explosion, impact from a snow-avalanche in a mountain area, the effect of wind or earthquake, and more generally any wall subjected to normal pressure (face-loading) on the out-of-plane (Priestley, 1985; Zeiny and Larralde, 2010).

The understanding of the response of URM walls to out-of-plane excitation has been one of the most complex and ill-understood areas (UMINHO, 2006; Menon and Magenes, 2013). Recently, considerable efforts have been made by researchers to understand the behaviour of URM walls submitted to out-of-plane loading both experimentally and numerically (ElGawady et al., 2004). As such, many of the existing retrofit techniques for URM walls found in technical literature were tested for out-of-plane performance, which motivated the experimental study reported herein. Therefore, this work studies the out-of-plane performance of a proposed timber-based retrofit technique of URM wall. The retrofit material proposed in this study is an oriented strand board (OSB) timber panel which is economical, easily sourced around the globe and can be considered as a sustainable material.

Retrofitting is an important issue across the urban infrastructure. In the case of historical URM structures, the problem is complex because of the need for their retrofitting to satisfy modern environmental standards and, of course, preserve the historical values. This particular requirement is an impetus for research on how to develop sustainable retrofit techniques. Owing to its significances in civil and structural engineering domain, retrofit of historical URM structures has been the subject of multiple earlier studies. As such, many retrofit technologies have evolved. For instance, grout and epoxy injection, reinforced plaster and shotcretes, steel column and plate as external reinforcement, elastomeric spray, internal concrete skin, post-tensioning and confining URM walls using reinforced concrete tie columns and masonry piers have all been considered (Oliveira et al., 2012; Chrysostomou et al., 2015). These techniques are instigated to make existing masonry stronger and more capable of resisting the effects of out-of-plane loads safely. Several techniques require a considerable amount of time for implementation, disrupt the historical and aesthetical form of the existing structures and encroach the functional spaces.

Meanwhile, retrofit of historical structures should be such that it does not alter their structural behaviour harshly and should be reversible (Chiozzi et al., 2015). This assertion leads to the emergence of innovative protection systems like base isolation and energy-dissipation devices, such as viscous dampers and shapes memory alloys to enhance the resilience against the effects of earthquakes and excessive out-of-plane loading. These methods would mitigate the rocking response of block-like elements during earthquakes (Chiozzi et al., 2015). However, the number of technical details and resources required for these techniques make them a complex method of retrofitting. Also, heavy non-structural objects like dampers, which are placed on top or inside old URM buildings in these approaches, present a severe hazard for both human lives and cultural heritage in the event of structural failure (Ismail and Ingham, 2016).

The application of composite materials, such as epoxy and fibre reinforced polymers (FRPs) mostly based on carbon, glass, and aramid fibre, offers promising retrofitting possibilities for masonry buildings (Nanni and Tumialan, 2003; Corradi, et al., 2015). They present several well-known advantages over existing conventional techniques. They do not alter the configuration of the building on which they applied. Most studies have highlighted that FRP makes less ingress into functional space to achieve a reasonable increase in structural capacity (Nanni and Tumialan, 2003; Willis et al., 2010; Alkhrdaji, 2013). FRP composites have then arisen to be an auspicious construction material for retrofit of historic structures (Varum et al., 2014; Gattesco and Boem, 2017), even if there are many doubts on the solution. Other drawbacks of FRP applications are the relatively high cost of the material, technical requirement for the installation and limited knowledge about the ageing properties of the material. More so, some experimental tests showed that FRP is not compatible with masonry due to the differences in stiffness, strength and thermal coefficient (Varum et al., 2014). In reality, the application of FRP on masonry surfaces showed a poor bond to the substrate. This is due to the type of substrate material and irregularity of the masonry surface, which may induce debonding, and thus reduce the proclaimed effectiveness of FRP in retrofitting URM structures (Varum et al., 2014).

A different approach is the retrofit of adobe masonry building using canes (Varum et al., 2014) and rammed earth using timber posts (Silva et al., 2013) as external reinforcement. The improvement recorded in the tensile strength of rammed earth through the fixing of timber posts behind the wall indicates that a timber panel might also significantly improve the structural capacity of old URM walls. Consequent to this reason and the increasing campaign for sustainable design, construction and retrofit, this study investigates the performance of oriented strand board (OSB) timber panels in retrofitting URM walls. This study considers timber-based techniques because the material is economical, can be easily sourced around the globe and can be considered as a sustainable material. The introduction of this retrofit approach using OSB timber panel will add to the existing masonry retrofit techniques and also provide practitioners the opportunity to choose an appropriate retrofit technique for URM structures from the available pool.

Indeed, timber-panels are currently being used for energy retrofit of old URM buildings, but their application in structural retrofitting of URM structures is still not been thoroughly studied. To the authors' knowledge, an experimental study (Sustersic and Dujic, 2014) was the first study on the application of timber panels as strengthening system for existing buildings against seismic actions. The in-plane behaviour of URM walls retrofitted with Cross Laminated Timber (CLT) panel was studied, and the results showed that there is a considerable increase in strength and ductility of URM walls. In this case, a 100% increase in ductility was observed when the CLT panel is connected to URM walls with a specially developed steel connection at the top and bottom of the wall (Sustersic and Dujic, 2014). Here, in contrast, OSB panels connected to the URM walls by threaded dry rod connections and injectable chemical adhesive anchor readily available in the European market are investigated.

In this paper, a four-point bending test on small scale masonry prisms is presented to evaluate the flexural performance (out-of-plane load capacity and deflection) of URM prisms retrofitted with OSB timber panel. The experimental works involved subjecting both plain and timber retrofitted URM prisms to out-of-plane loading using a quasi-static (monotonic) loading scheme. The reasons for selecting quasi-static loading scheme is that the test will be able to replicate the behaviour of URM wall when subjected to cycles of loadings through an hydraulic actuator which is similar to what is expected from the effect induced by wind, explosion or earthquake. Quasi-static loading has been widely accepted and implemented in previous studies in the absence of shaking table facilities (UMINHO, 2006; Costa et al., 2014). Meanwhile, this research is not exclusively applicable to earthquakes but to generate knowledge and understanding of whether timber panels can improve the out-of-plane capacity of URM walls against excessive out-of-plane loading in general.

The following sections present the summary of the proposed retrofit technique followed by the details of the materials used and methodology. In a subsequent section, the results of the experimental works are presented, and the paper ends with conclusions and recommendations for future works.

Proposed Retrofit Technique: Timber Panels

Timber is one of the oldest structural materials used in many parts of the world. Timber frame structures were the most standard type of housing in the USA, Canada, Turkey and New Zealand until approximately 1960s when reinforced concrete and masonry buildings became preferred (Tobriner, 1999). Timber structures are known for their aesthetic and environmental benefits. Timber also has relatively higher strength to weight ratio and high tensile strength along the grain. Timber has been mainly used in masonry structures for floors and roofs, as well as inside masonry walls as finishing. Despite these obvious advantages and strength of timber, the literature review shows that the potential of timber has not been fully utilised for retrofitting old masonry building. Although, several researchers (Pan et al., 2016; Langenbach, 2007) have acknowledged that the seismic performances of brick-timber structures are better than URM structures and that traditional timber-framed masonry constructions have also fared well in large earthquakes, and better than URM structures in the same area.

Therefore, this work proposed securing OSB type 3 timber-panels properly behind masonry walls (Fig. 1). In this study, 18mm thick OSB board has been connected to URM prisms using Ø8mm/L50mm threaded anchor rods together with an option of plastic plug or injection mortar (see the material section for details).

Materials

Brick Unit

Engineering class B fired clay solid bricks with UK standard size 215 x 102.5 x 65mm were used to construct all test specimens (Fig. 2a). Prior to the construction of the test specimens, six samples of brick units were randomly selected from a stack of 400 bricks [34]. They were tested to determine the conformity of the physical properties of the unit to the manufacturer's specification. The characterization test was also made to determine the suitability of the brick samples for the proposed experimental campaign. In total, six brick units were tested for dry density(γ_{du}), water absorption (W_u), compressive strength (f_b), modulus of elasticity (E_b), and Poisson's ratio (μ_b) according to relevant standards, and the details of the testing were reported in (Dauda et al., 2018, inpress). The obtained brick properties were compared to the values declared by the manufacturer in table 1 to determine the quality of the brick. Generally, the results indicate that bricks are of good quality and conform to the specification, making them acceptable for the proposed experiment study.

Mortar

Type N (general purpose) mortar mix with a ratio of 1:1:6 (Type II cement: aerial lime: sand) by volume was used to construct the specimens with 10mm thick nominal mortar joint. The fresh mortar sample was tested for consistency. Samples of 40 x 40 x 40mm cube were prepared and tested to determine the compressive strength (f_m) of the hardened mortar (Dauda et al., 2018, inpress). The fresh mortar has a dropping value of 10.2mm and the corresponding mean flow value of 167mm. The consistency of mortar is good as this agreed with the ideal flow value (150-175mm) for bedding masonry (Haach et al., 2007). The mortar has an average compressive strength of 7.1N/mm^2. The combination of mortar with a strong brick unit (f_b of 87.9N/mm^2) is similar to what is expected in old masonry units (strong unit-weak mortar joint). Hence, the materials are suitable for the proposed study.

Oriented Strand Board (OSB)

An 18mm thick OSB type 3 (Fig. 2b) which is a load-bearing engineered wood-based panel for use in humid conditions was selected for this study. The OSB is manufactured from strands of wood which are bonded together with a synthetic resin. The strands are pressed together in layers. From the manufacturer's specification, the board has an average density of 650kg/m^3, internal bond strength of 0.3N/mm^2, and modulus of elasticity of 3500N/mm^2 and 1400N/mm^2 for both bending in major and minor axis, respectively. OSB can achieve a Euro class D fire rating. OSB panel can resist a small flame attack without substantial flame spread for a long period (Anon, 2018). In addition, they are also capable of undergoing thermal attack by a single burning item with sufficiently delayed and limited heat release.

Connections

Two types of connections were tested in this study. The OSB panel was securely connected behind the masonry prism using anchor systems selected by considering masonry as the base material, manual cleaning procedures of holes drilled, economy, the recommended design tensile resistance (N_{rd}) and configuration of the anchors. The selected connections were all made of A4 (1.4401 or 316) stainless steel. The criteria for selecting these connection types are guided by the requirements of European Technical Approval (ETAG 029, 2013) which ensure that the selected anchorages are fit for use in solid masonry subjected to either static or quasi-static loading which was tested in this study. The strength of both the masonry unit and mortar were considered in the selection of the anchor diameter. The spacing of the anchors are provided to meet the minimum allowable spacing and edge clearance as specified in the ETAG 029. The selected connections are classified as follows;

I – Connection Type 1 (C1): This is an adhesive anchor connection system herein refers to as C1. It is a combination of styrene-free vinylester-hybrid injection mortar and A4 anchor rod. The styrene-free vinylester-hybrid mortar is a high-performance injection mortar which is approved for fixings in both perforated and solid brick. The diameter of the anchor rod is 8mm with a permissible tensile load of 1.29kN.

II – Connection Type 2 (C2): This is a mechanical connection system classified as C2 in this study. C2 is a combination of frame fixing plastic plug made of high-quality nylon and A4 anchor rod. The diameter of the anchor rod is 8mm with a permissible tensile load of 1.39kN. The plastic anchor selected has an overall length (l_d) of 60mm and an embedment depth (h_{nom}) of 50mm as shown in figure 2c.

Table 1. Mechanical properties of masonry brick units

Property	Experiment	Manufacturer	Requirement
γ_{du} (kg/m^3)	2200	2310	shall not be less than 2079kg/m^3 i.e. 90% of specified density (BSI, 2000)
W_u (%)	3.9	≤ 7	shall not be more than manufacturer limit (BSI, 2011b)
f_b (N/mm^2)	87.9	75	shall be not less than the declared strength (BSI, 2011a)
E_b (N/mm^2)	32470	≤ 34000	between 3500 and 34000 (Haach et al., 2007)
μ_b (-)	0.26	0.2-0.5	the range for clay masonry unit

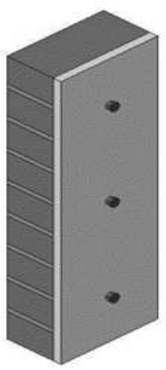


Figure 1. Timber panel secured behind URM

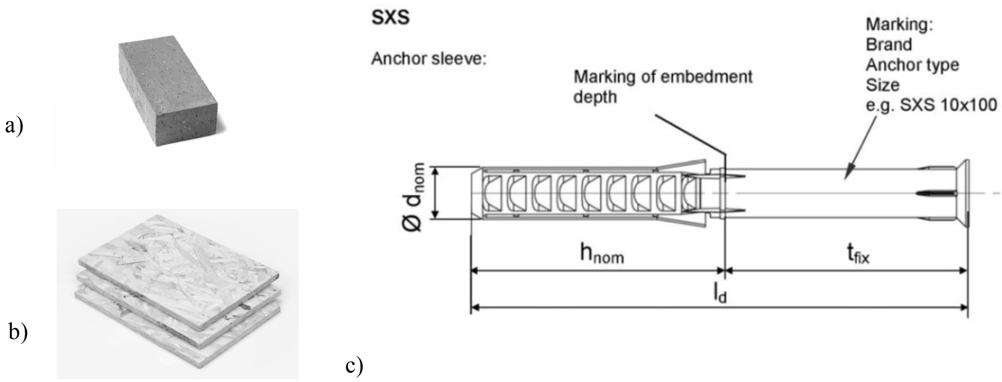


Figure 2. Materials.
(a) Brick unit (b) OSB panel (c) Plastic anchor

Experimental Program

The work carried out aimed at investigating the effectiveness of OSB timber panels for the retrofit of URM walls by assessing the improvement in the out-of-plane behaviour. The experimental campaign was articulated into three main stages:

(i) Material characterisation to determine the mechanical properties of masonry brick units, mortar and masonry assemblage (Dauda et al., 2018).

(ii) Small-scale test to perform out-of-plane flexural bond strength tests in form of four-point bending test on masonry prisms explained in detail in this paper. The flexural bond strength test was carried out on masonry prisms with relevant guidance (ASTM, 2015a, 2015b). The purpose of this test is to provide a simplified means of gathering data on the flexural strength of plain URM prisms and URM prisms retrofitted with 18mm thick OSB timber panel and the two selected connection types. The test was carried out prior to the larger-scale experiment to help in understanding the behaviour of masonry and the connection between masonry prism and OSB timber panel (Dauda et al., 2019). The test provided an insight on the effectiveness of OSB panel on flexural behaviour of masonry prisms, and it also enabled the design and implementation of the larger-scale test to be straightforward.

(iii) Larger-scale test to perform an out-of-plane flexural strength test on single leaf, double wythe solid (1115 x 1115x 215mm) URM walls (Dauda and Iuorio, 2019).The details of the larger-scale test are not in this paper, but some general comments on the extent of work carried out and the performance of the "large-scale specimen were given. For the larger-scale test, two similar specimens were tested as plain, one-sided retrofitted and double-sided retrofitted walls. The plain wall was tested with both constant and variable pre-compression load to represent high in-plane compression usually present in URM walls. The retrofitted walls were constructed using OSB type 3 and adhesive anchor connection type (C1) that offer the most improvement in the flexural bond strength of masonry prisms identified from the small-scale test. The test program has ensured that loading has been applied on wall retrofitted with OSB timber on only tension face and on both tension and compression face of the masonry wall. This is because the type of application we are proposing is the application of the OSB panel on the internal surface of exterior URM walls so that external historic appearance of the building is preserved. The other configuration where we have the OSB on both sides were for application on both surfaces of internal partition walls. So, specimen with OSB on the compression face only was not tested because the application of the technique on the external surface is not envisaged.

Test Program

Nine single leaf masonry prisms (MP) were tested in the laboratory under four-point bending test using a quasi-static monotonic loading scheme. The experimental campaign (Table 2) involved testing: (a) three samples as plain MP to serve as reference to measure the effectiveness of the proposed retrofit techniques, (b) three samples each retrofitted with 18mm thick OSB using adhesive anchor connection (C1) and (c) three samples retrofitted with 18mm thick OSB using mechanical connection (C2).

Table 2: Test program specimen identification

Specimen Label	Description	Connection Type	Quantity
MP00-1			1

MP00-2	Plain specimen	-	1
MP00-3			1
MPOSBC1-2			1
MPOSBC1-2*	Retrofitted specimen	C1	1
MPOSBC1-3			1
MPOSBC2-1			1
MPOSBC2-2	Retrofitted specimen	C2	1
MPOSBC2-3			1

MP stands for Masonry Prisms
OSB stands for Oriented Strand Board panel
C1 stands for Connection type 1 i.e. adhesive anchor connection
C2 stands for Connection type 2 i.e. mechanical connection

Test Specimen Set up and Instrumentation

Test specimens were constructed as nine courses stacked bonded prisms, 215 x 102.5 x 665mm with mortar joints of 10 ± 1.5mm thickness (Fig. 3). This allowed the specimens to meet the minimum height of 460mm required (ASTM, 2015a) and avoided cutting brick units in height. The test specimens were constructed using English bond consisting of alternate rows of headers and stretchers, which is the oldest form of brick bond popular in the United Kingdom (Anon, 2009). For the specimens that were retrofitted with OSB timber panel, the brick units were pre-drilled in the predetermined connection location to avoid disturbing the specimen after construction which might have caused the failure of the joint before testing. Afterwards, the first course of the prism was set on a flat 10mm thick metal plate with the use of mortar. Subsequently, all the remaining eight courses were laid on top of each other with a full-face mortar bed on all units without furrowing. During the construction of all test prisms, the vertical face of each prism was aligned using level. In all cases, the test specimens remained in construction position for 21days after construction to avoid disturbing the setting of the specimens. The standard curing procedures adopted was wrapping them with a polythene sheet for 14 days and thereafter store them in the laboratory air for further 14 days. For the purpose of monitoring the quality control, samples of mortar cubes were taken from each set of prisms and cured under the same condition with the test prism. For the retrofitted prism, the timber panel was fixed to the masonry prism (Fig. 4) after 21days to allow for curing of the connection for further 7days before testing. The specimens were all tested at 28days.

a) b)

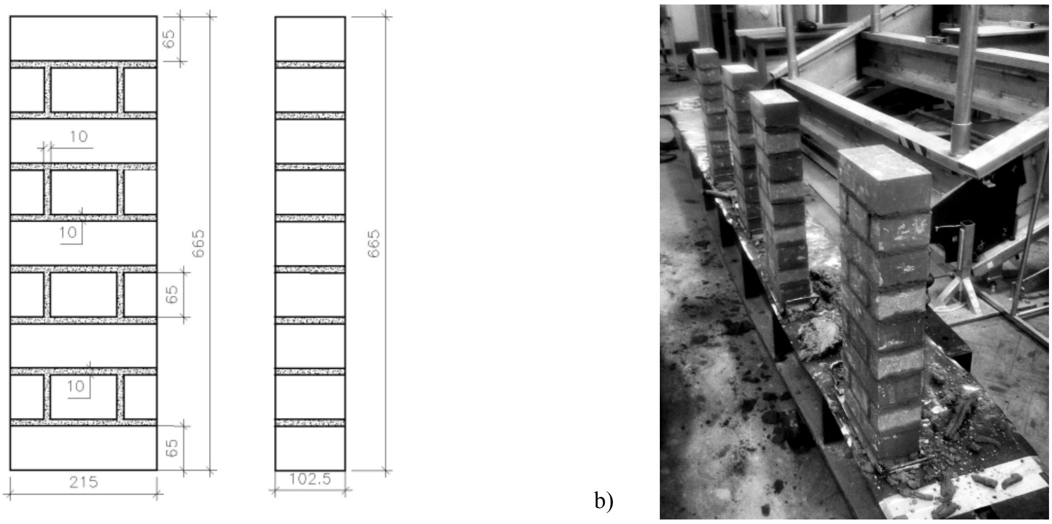


Figure 3. Plain Masonry Prism: (a) Drawing (front and side view), (b) As-built specimen

a)

b)

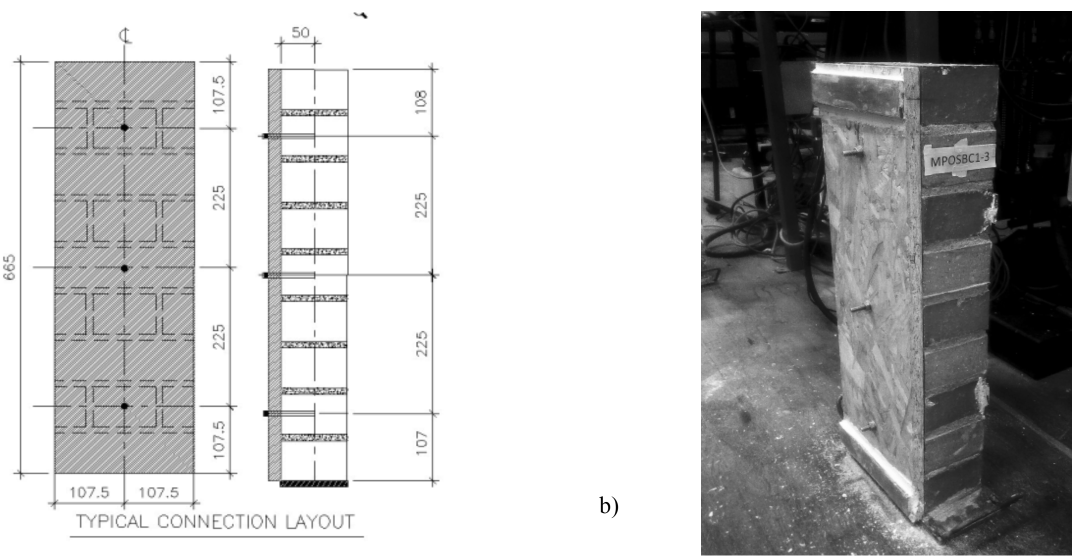


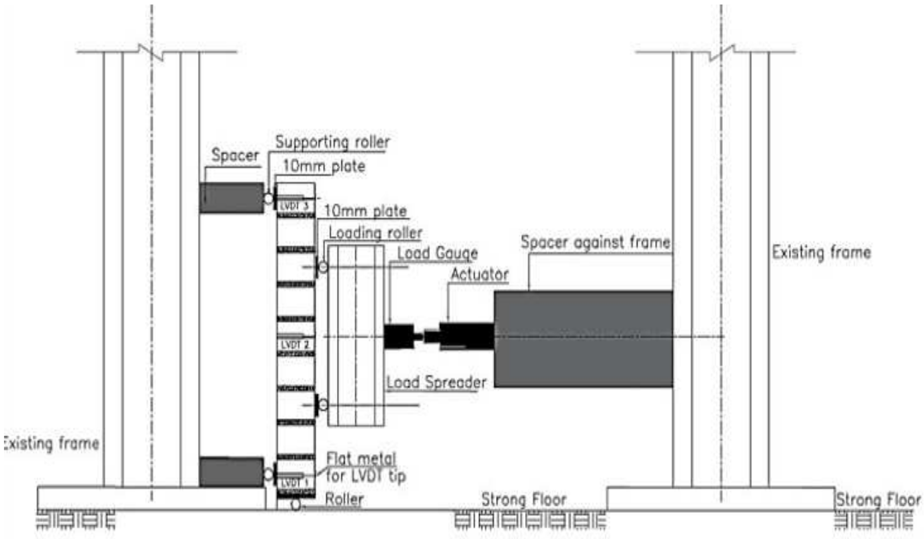
Figure 4. Retrofitted Masonry Prism: (a) Drawing (front and side view), (b) As-built specimen

Test Set-up

The MP specimens constructed on the 10mm thick steel plate were carefully moved into the test rig (Fig. 5 & Fig. 6)). The specimens were tested with simply supported boundary condition and no vertical pre-compression load. The specimen on steel plate rested on 25mm diameter cylindrical roller with the axis of the roller parallel to the face of the specimen to allow it to freely rotate around its base while deflecting out-of-plane and prevent restrained end condition. At the back of the specimen, 25 x 5mm thick metal plate was fixed across the middle of the top and bottom brick unit each. This 5mm thick plate provided smooth contact for the Ø25mm supporting rollers fixed on an existing steel reaction frame in the laboratory. On the front side of the specimen, two others 25 x 5mm thick metal plates were fixed at 1/4th and 3/4th of the height of the specimen to provide a contact for which the loading roller rest. The loading is such of a four-point testing arrangement where the loads were applied on the specimen using a Hi-force hydraulic jack and distributed through a spreader beam. The spreader beam spanned between two Ø25mm cylindrical rollers placed across 1/4th of the height from top and bottom support of the test prism. The direction of the load application is perpendicular to the MP specimen surface.

The values of the applied load on the prism were monitored using a 200kN capacity ring load cell. Simultaneously, four linear variable displacement transducers (LVDTs) were used to record the deflections of the test specimen along the wall centre, mid-top and bottom. The locations of these gauges were as shown in figure 7. The LVDTs used during the test were fixed on an independent steel tripod stand, which was not connected to the test rig.

The force and the displacements were real-time monitored by connecting the measuring equipment (load cell and LVDTs) to an electronic acquisition unit interfaced with a computer. The test was load controlled, and the loading scheme was such that an initial load of 200N increments at every two minutes up to the occurrence of first cracks was applied. Thereafter, there was a continual increment of load up to the cracking of MP specimens.



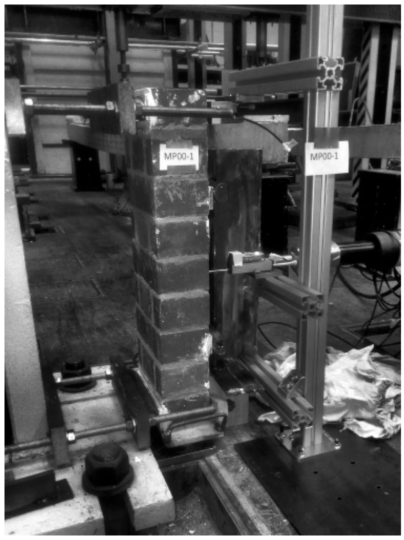


Figure 5. Test setup (drawing)

Figure 6. Test setup (As built)

Experimental Results

Results Estimation

The test specimens were tested to failure (cracking) with the loads and corresponding out-of-plane displacements monitored. The experimental results were then expressed in term of load-displacement curve, which represents the relation between the applied out-of-plane loads and the net out-of-plane displacement in the mid-height of the test specimen.

Out-of-plane Displacement

In order to estimate the net out-of-plane displacement in the specimen mid-height, the average absolute value of horizontal displacement at the top and bottom of the specimen was removed from the mean value of the displacement measured at its mid-height using equation 1.

$$\delta_{net} = \left(\frac{\delta_1 + \delta_2}{2}\right) - \left(\frac{\delta_3 + \delta_4}{2}\right) \qquad \text{Equation 1}$$

Where; subscript 1, 2, 3 & 4 refers to position of LVDT as shown in figure 7.

The average displacement at top and bottom deduced from the average displacement at the mid-height of the specimen accounts for the unexpected little displacement at the top and bottom of the prisms. A typical load-displacement curve showing the displacement measured by the four LVDTS is presented in figure 8. It can be observed that the top and bottom of the prism (LVDT 3 & 4) displaced in the opposite direction to the mid-height of the prism (LVDT 1 & 2).

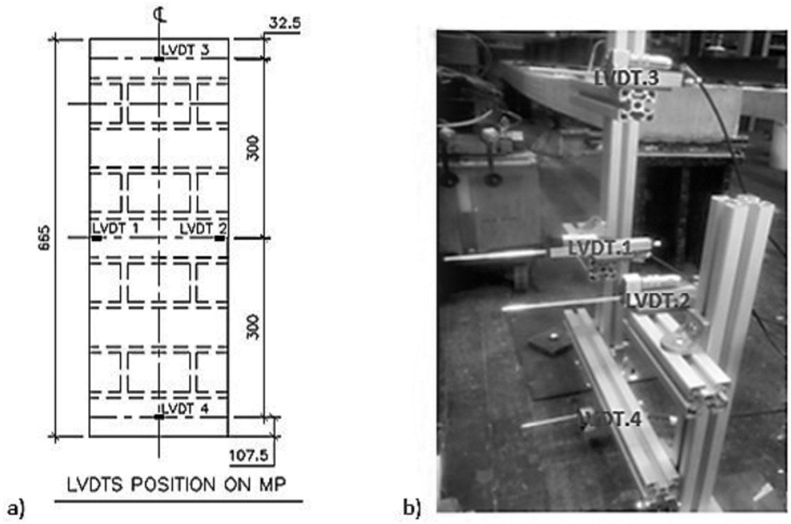


Figure 7. LVDTs position on MP specimen

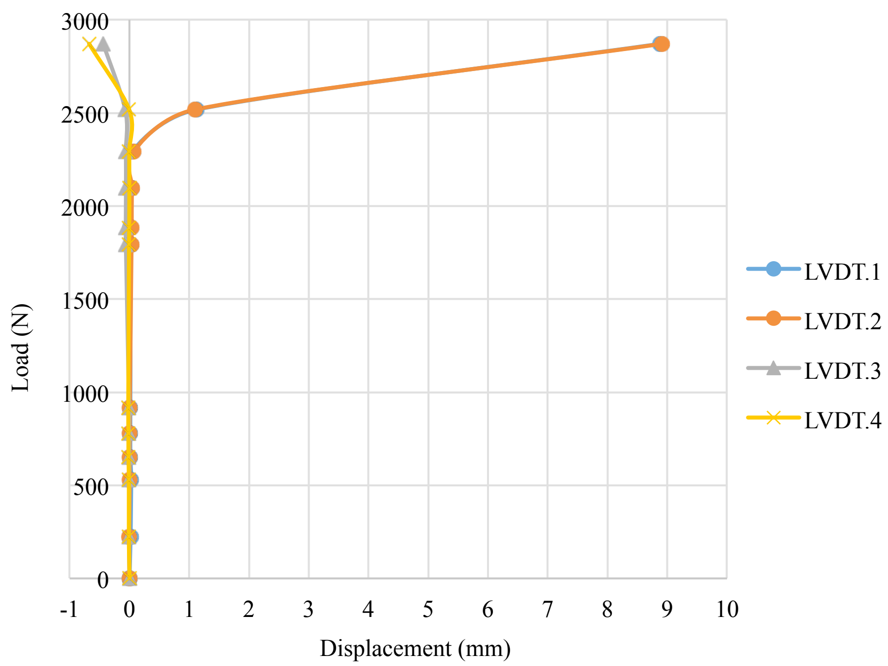
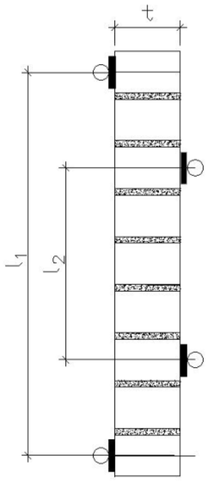


Figure 8. Typical load displacement curve

Flexural Strength

The flexural strength of the masonry prisms (Fig. 9) was determined using Equation 2 below:

$$f_x = \frac{3P_{max}(l_1 - l_2)}{2bt^2} \qquad \text{Equation2}$$



Where;

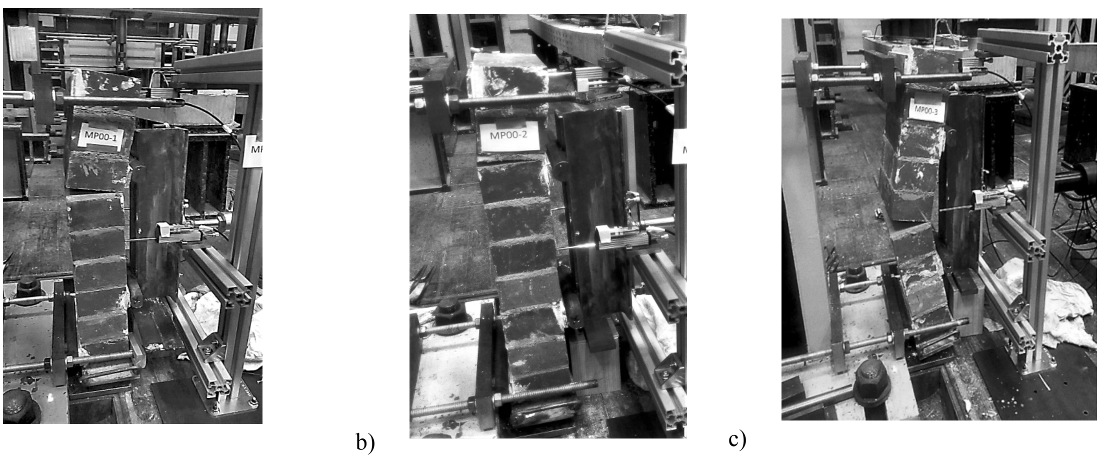
f_x	:	Flexural strength of masonry prism
P_{max}	:	Maximum load applied to the specimen
l_1	:	Distance between the top and bottom supports (outer bearing)
l_2	:	Distance between the loadings supports (inner bearing)
b	:	Width of specimen
t	:	Thickness of specimen

Figure 9. Dimension on prism

Failure Pattern of Plain MP

The failure mode of the plain specimen is quasi-brittle with plain MP showing little or no deformation prior to the separation of the brick unit from the mortar. After the crack appeared in the unit/mortar interface, the deformation measured in LVDT 1 & 2 jumped up significantly. Failures were sudden and always started with the formation of crack opening in one of the bed joints at the tensile face of the specimen (i.e. the side opposing the loading face). Subsequently, the crack that occurred in single bed joint propagated throughout the sample thickness so that the unit-mortar interface was completely separated in all cases. The failure occurred within the loading span (i.e inner bearing) for all tested specimens except for MP00-2 (Fig. 10b). Thus, the result of MP00-2 was discarded because one of the acceptability criteria of the test is that the failure must occur within the inner bearing (BSI, 1999; ASTM, 2015a, 2015b).

Having discarded MP00-2, the load-displacement curve for MP00-1 and MP00-3 is shown in figure 11. Fig. 11 shows that the specimens remain undamaged for up to 80% and 85% of the average failure load (2857N) for MP00-1 and MP00-3 respectively. However, as the loading increment continued, the specimen peak load and corresponding out of plane displacement at the mid-height was then recorded as (2871N, 8.34mm) and (2843N, 9.62mm) for MP00-1 and MP00-3 respectively. A new specimen to replace MP00-2 was not constructed because the results of MP00-1 and MP00-3 compared fairly well.



a) b) c)

Figure 10. Failure pattern of (a) MP00-1 (b) MP00-2 (c) MP00-3

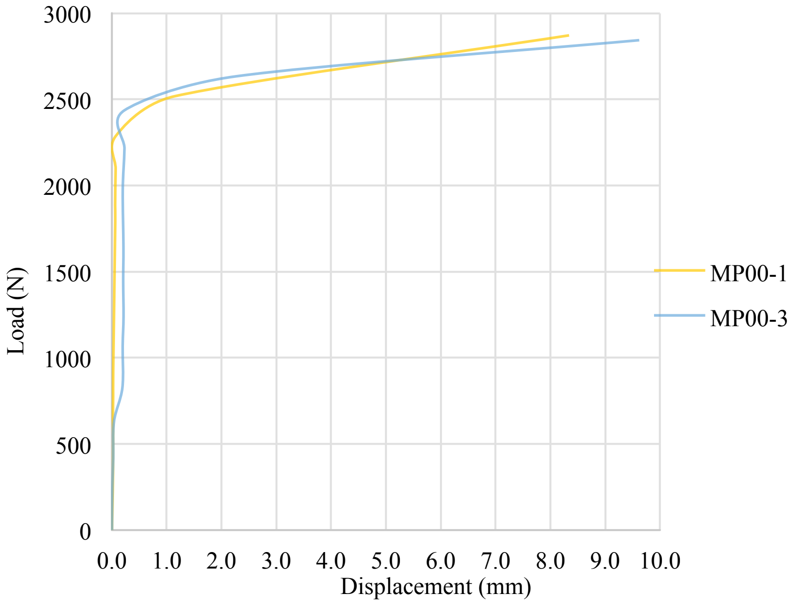
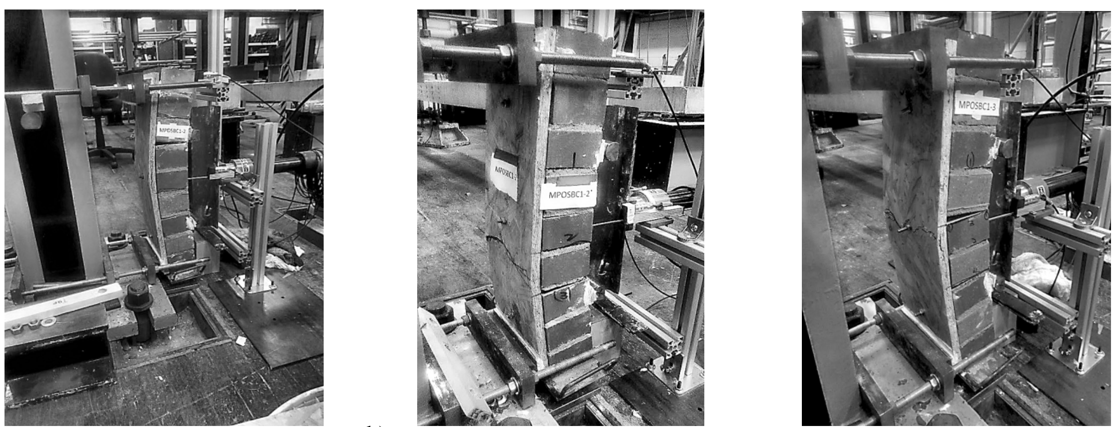


Figure 11. Load displacement curve for plain specimens

Failure Pattern of Timber Retrofitted MP

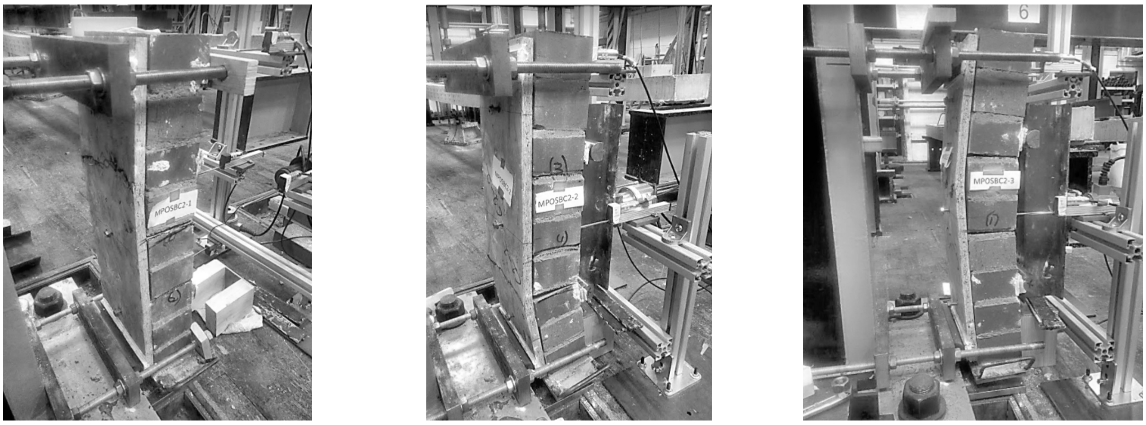
Similar to the plain MP, the retrofitted specimen showed little or no deformation prior to the appearance of the first crack, which is also in the bed joint within the inner bearing. This first crack appeared at an average load of 3640N and 3590N for MP retrofitted with adhesive anchor connection (C1) and mechanical connection (C2) respectively. As the loading continued, other cracks appeared in the bed joints parallel to the first crack still within the inner bearing (Fig. 12 & 13). As the applied load increased, the first crack to appear failed completely at an average load of 5330N for C1 and 5280N for C2.

After the first crack appeared, the application of OSB timber panel at back of the MP specimens caused formation of others cracks in the specimens before reaching the ultimate load. In order to ensure that the maximum load capacity of the retrofitted specimen is obtained, the loading continued until the timber panel at the back failed (broken). At this failure point, the corresponding load vs displacement for all specimens including the plain ones were plotted for comparison (Fig. 14). On the load-displacement curve (Fig. 14), the point at which cracks developed is identified with numerals corresponding to the ones labelled on the specimens during testing. The average maximum load and corresponding displacement at failure are (21068N, 18.74mm) and (14407N, 15.24mm) for MPOSBC1 and MPOSBC2 respectively.



a) b) c)

Figure 12. Failure pattern of (a) MPOSBC1-2 (b) MPOSBC1-2* (c) MPOSBC1-3



a) b) c)

Figure 13. Failure pattern of (a) MPOSBC2-1 (b) MPOSBC2-2 (c) MPOSBC2-3

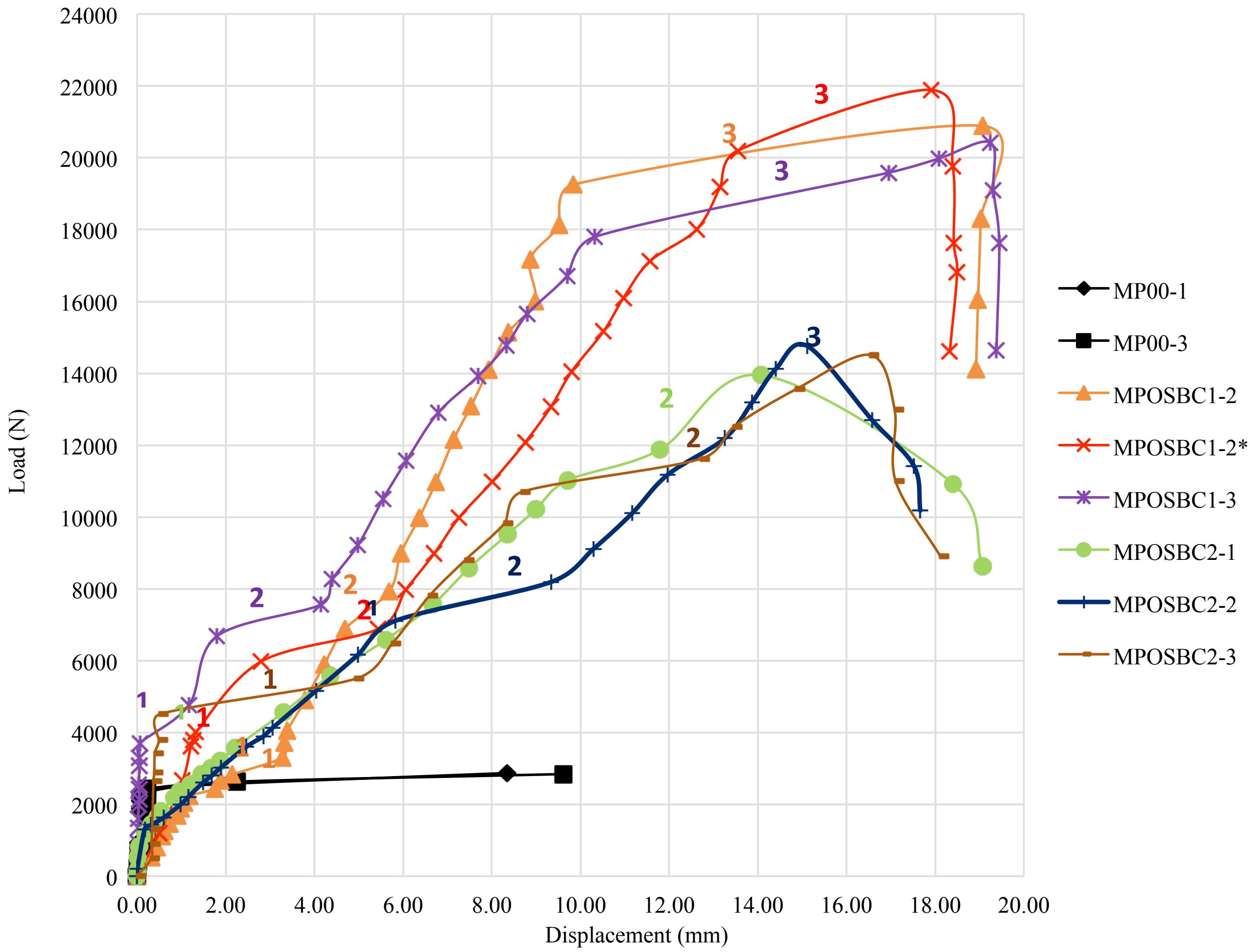


Figure 14. Load displacement curve for plain and retrofitted specimens

Evaluation of Performance of the Proposed Retrofit Technique

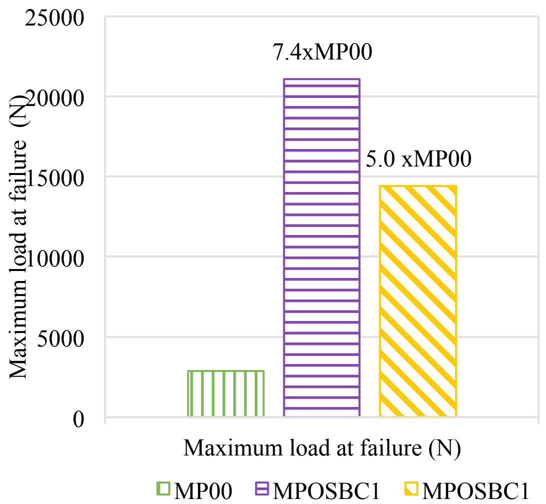
Table 3: Summary of experimental results

Specimen Label	Maximum load at failure (N)	Flexural strength (N/mm^2)	Characteristic flexural strength (N/mm^2)	Maximum Displacement at failure (mm)
MP00-1	2871	0.54	0.36	8.34
MP00-3	2843	0.53	0.36	9.62
Average	**2857**	**0.54**	**0.36**	**8.98**
MPOSBC1-2	20889	3.85	2.57	19.07
MPOSBC1-2*	21890	4.04	2.69	17.91
MPOSBC1-3	20424	3.83	2.56	19.24
Average	**21068**	**3.91**	**2.61**	**18.74**
MPOSBC2-1	13950	2.57	1.72	14.07
MPOSBC2-2	14760	2.72	1.81	15.12
MPOSBC2-3	14510	2.68	1.78	16.54
Average	**14407**	**2.66**	**1.77**	**15.24**

Note: MP00-2 failed outside the inner bearing (Result is not acceptable)

Table 3 above summarised the results from the flexural strength experiment (four-point bending test) in term of the maximum load and corresponding displacement at the failure of the test specimens. In order to evaluate the performance of the proposed retrofit technique, the average value of each property was found for each group of specimens (i.e. MP00, MPOSBC1 and MPOSBC2). Subsequently, two comparison charts were developed as shown in figure 15. The comparison shows that the maximum load and flexural strength that can be attained in MP when retrofitted with OSB timber panel is about 7.4times and 5.0times that of plain MP when connection type C1 and C2 are used respectively (Fig. 15a). Therefore, adhesive anchors perform much better for this application.

Furthermore, figure 15b revealed that the retrofitted specimens were able to take more loads by displacing more without sudden failure (collapse). The increased out-of-plane displacement has been estimated in timber retrofitted specimens as about 2.0times that of plain MP.



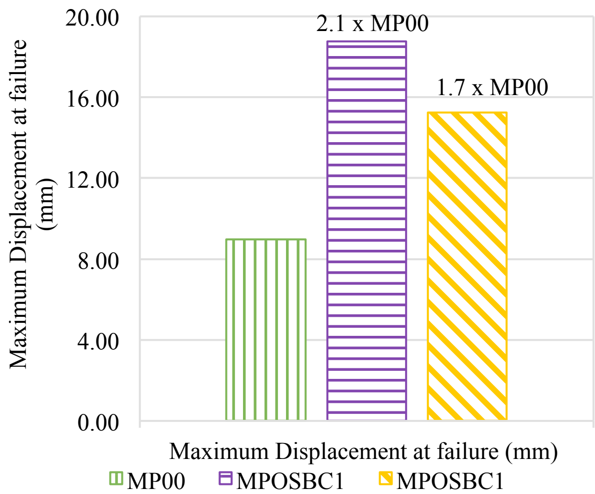


Figure 15. Performance in term of (a) Load Capacity (b) Displacement

Conclusion

A small-scale experimental campaign has been presented to investigate the use of timber panels in retrofitting URM wall. Precisely, the experiment evaluates the out-of-plane performance of OSB panel in retrofitting URM prisms by comparing the flexural strength, out-of-plane load capacity, and displacement of both plain and OSB-retrofitted masonry walls. In this research, flexural strength test in form of four-point bending test was performed on nine MPs, three of which were tested as plain to establish a baseline for comparison. Two groups of three specimens each retrofitted with OSB panel using two different connection typologies C1 (adhesive anchor: a threaded dry rod with an injectable chemical adhesive) and C2 (mechanical connection: a threaded dry rod with a plastic anchor). The focus of this research is to generate knowledge and understanding of whether OSB panel can improve URM walls capacity against excessive out-of-plane loading.

Based on the obtained test results, the application of OSB panel at the back of MP greatly influenced its out-of-plane behaviour. In plain specimen (MP00), the collapse was sudden with the evolution of crack opening in single mortar bed joint within the inner bearing of the specimen. The failure (cracking) of the masonry prism specimen was abruptly occurred between the interface of the mortar joint and brick unit. While, in the retrofitted specimen (MPOSB), the OSB panel improved the flexural response of the specimens such that the failure was much more ductile. For the failure to occur, there are occurrences of crack openings in the interface of mortar and brick units on multiple bed joints within the inner bearing. This proposed retrofit technique increased the initial crack load on the retrofitted specimens. Compared to the plain one, the OSB retrofitted MP not only demonstrated higher load capacity but also improved ductility and integrity of the MP. This is to the extent that even after the cracking of OSB panel, the damaged specimens remained as a unit which prevents the sudden collapse of the specimens unlike plain MP. An inference from this is that timber panel might not prevent the ultimate failure of URM wall, but it improved the performance to at least collapse prevention. This will ensure that sudden failure is avoided and thus minimised the high risk of mortality and substantial damages that comes with the sudden collapse of URM wall.

Indeed, the retrofitted MP is able to offer flexural strength to resist out-of-plane load almost 7.5times greater than plain MP in case of adhesive anchor and 5.0times greater when a mechanical connection was used. Adhesive anchors performed thus much better for the envisaged application. Consequently, the out-of-plane displacement showed in retrofitted MP is almost 2.0times greater than that of plain MP. This is because there is limited tensile strength in plain MP and the failure (collapse) is sudden. But the addition of OSB panel offered additional tensile strength and ductility in retrofitted specimens, and thus they were able to displace gradually before the timber failed. The performance of the proposed retrofit technique recorded might have been amplified due to the fragility of the plain specimen, which is not a true representative of the real working condition of URM walls. This observation is sustained by the results of the larger-scale specimen where an increase of about 300% load capacity was achieved in a retrofitted larger wall specimen compared to about 500% increase recorded in the small-scale specimen reported in this study.

Conclusively, the performance of adhesive anchor (C1) is better than the mechanical connection (C2). C2 is not totally effective due to poor bonding between the OSB panel and MP. The reason for this poor bonding was observed to be the inability of plastic anchor to expand in the high dense brick unit. Although the results presented herein were based on initial tests on small specimens, the inferences from the results were promising. As such, a larger-scale experimental campaign on 1115x 115 x215mm single leaf, double wythe solid URM walls is ongoing to study the proposed technique in detail.

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