Experimental Study of Remedial Actions for Non-Structural Masonry Walls in Earthquake Prone Areas

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ABSTRACT

Masonry non-structural walls serve as physical barriers between two spaces, fully span the storey height, and provide sound isolation. They are usually built from either clay solid and hollow blocks or autoclaved aerated concrete units (AAC). There are no special requirements for non-structural walls in the current seismic codes, however recent earthquakes revealed high vulnerability of these secondary elements even in the case of moderate seismic events. This problem is particularly evident for public buildings (e.g. schools, hospitals), where due to high stories, the slenderness of these elements could be a crucial parameter that may significantly amplify design parameters derived from storey response spectra of primary structure. The main aim of this experimental study was to increase resistance of these elements due to out-of-plane seismic actions in the process of regular refurbishment works.

A series of 18 large URM panels (316 x 195 x 12 cm) built from brickwork with lime mortar (representing old masonry - NF) and new AAC masonry panels (303 x 188 x 10 cm) were out-of-plane tested with four point bending cyclically displacement-controlled load. Each type of masonry was also strengthened with introduction of glass fibre mesh or fabric attached on both sides. For each configuration of masonry and reinforcement, three specimens were tested. In the strengthened state, both types of masonry had their maximum resistance increased by four times, while their ductility was doubled. A minimally invasive and cost-effective solution can be recommended for remedial actions on partition walls during regular refurbishment works.

KEYWORDS

out-of-plane test, non-structural walls, strengthening, glass mesh, brickwork masonry, autoclaved aerated concrete

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INTRODUCTION

Non-structural (partition) masonry walls are one of the most vulnerable elements in buildings when considering earthquake loading. This is especially relevant when they are located on higher floors, where the influence of dynamic floor response of the structure can be more pronounced. Consequently, in the case of longer earthquakes, the increase of seismic load to non-structural walls may occur due to the resonance effect. In recent post-earthquake reports from Croatia, Italy, and Turkey [1,2], it was revealed that the damages and collapses of non-structural masonry walls represent a huge share in economic losses. The failure of these elements mainly depends on the restraint boundary conditions, low out-of-plane resistance and their high specific mass.

For non-structural (partition) masonry walls there are no design provisions – neither for static nor dynamic loading. However, some requirements regarding maximum slenderness depending on their dimensions and restraints of the walls are stated in the Eurocode 6-3 [3] (Figure 1). In Central Europe (including Slovenia) before the introduction of drywall systems, partition masonry walls were usually built either from solid clay, hollow clay and concrete blocks, or, more recently, Autoclaved Aerated Concrete units (AAC). Thus, our study considers solid clay brickwork (Normal Format unit – NF) and AAC walls (in the paper referred to as YT). Brickwork specimens were composed of weaker mortar to represent typical historic masonry used in public buildings dated from the first half of the 20th century.

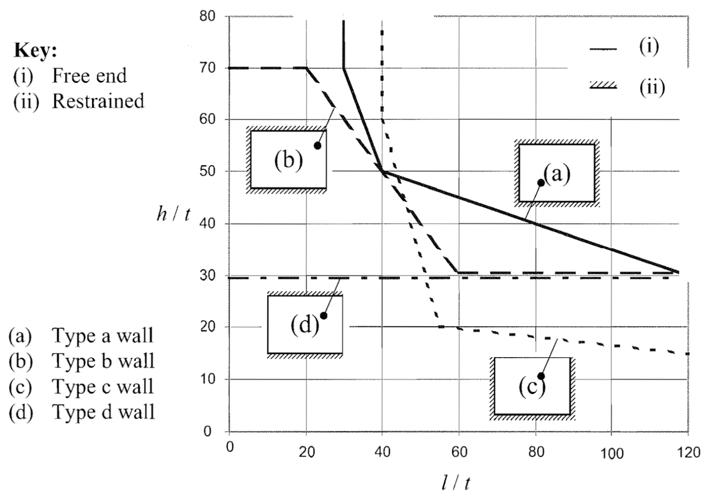


Figure 1. Geometry limitations for partition walls not subjected to vertical load (Eurocode 6-3 [3]).

There are numerous different types of masonry walls strengthening systems available on the market today. A review of existing strengthening methods using composite materials such as fiber-reinforced polymers (FRP) or fiber-reinforced cement matrix (FRCM), can be found in [1,2]. The reviews also proposed various simple and cost-effective methods for the out-of-plane strengthening of masonry partition walls. The main idea driving this experimental study was improving the resistance of these elements due to out-of-plane seismic actions in the process of regular refurbishment works and remedial actions on the building. In our work glass fiber-reinforcing fabric and glass fiber-rendering mesh were used. Both strengthening materials were applied to the surfaces of the partition wall using flexible polyurethane-based adhesive.

TEST ON CONSTITUENTS

Brickwork masonry (NF)

Compressive strength tests of 10 masonry units were conducted according to the standard EN 772-1 [4]. We found that an average compression strength of brick reached 36.3 MPa with a coefficient of variation of 15.5 %. Additionally, flexural and compressive strength tests of 66 mortar prisms with 40 x 40 x 160 mm, collected during the construction of non-structural wall specimens, were conducted according to the standard EN 1015-11 [5]. The mixing ratio of cement-lime mortar was made at ratios 1:3:9 (cement:lime:sand) by volume. The average flexural strength was 1.08 MPa, with a coefficient of variation of 23.3%, whereas the average compressive strength was 5.02 MPa, with a coefficient of variation of 9.6%. Moreover, the bond wrench tests were conducted according to EN 1052-5 [6] to evaluate an average bond strength of 61 specimens. An average flexural bond strength of 0.22 MPa was obtained with a coefficient of variation of 36%.

AAC masonry (YT)

The declared compressive strength of the AAC blocks was 3.0 MPa after 28 days of curing time. Nevertheless, additional compressive strength tests of 10 masonry units were conducted at our laboratory according to the standard EN 772-1 [4]. An average compressive strength determined with standard tests reached 3.6 MPa with a coefficient of variation of 6%. Additionally, flexural strength was determined in accordance with the standard EN 1351 [7], obtaining an average value of 0.48 MPa with a coefficient of variation of 8%. The mortar used for the construction is declared by the manufacturer as M10 class thin-layered mortar. With standard tests on 61 prism specimens, according to the standard EN 1015 [11], the declared values were confirmed with the obtained compressive strength of 10.3 MPa and a coefficient of variation of 10%. The average flexural strength of mortar reached 3.01 MPa, with a coefficient of variation of 23%.

OUT-OF-PLANE TESTS

The extensive experimental investigation, presented in this paper, was conducted at the Faculty of Civil and Geodetic Engineering at the University of Ljubljana [1]. The core of this research was an out-of-plane cyclic quasi-static experimental analysis of slender partition masonry walls made from brickwork and aerated concrete blocks with thin layered mortar. In the first part of the cyclic quasi-static out-of-plane tests, three full-scale specimens of each type of masonry were examined as-built. In the second part, two different strengthening glass fiber nets were applied on identical specimens as-built. Three repetitions were performed for each strengthening material.

Masonry wall specimens

Nine full-scale test specimens were built with regular solid bricks (250/120/65 mm) laid in cement-lime mortar and using a half bond pattern. The constructed specimens were 194 cm long and 316 cm high. They had a thickness of one full brick width (12 cm) and a slenderness of 26. The same number of specimens with a thickness of 10 cm, length of 187 cm, and height of 303 cm was prepared for AAC masonry specimens. The specimens were made with solid AAC blocks (625/100/200 mm) laid in prepared thin layered mortar using a half bond pattern and with a slenderness of 24.

Strengthening material

For this study two types of strengthening material were used – a glass fiber reinforcing fabric (RF) with a density of equal to 286 g/m^2 (Type A) and a glass fiber rendering mesh (RM) with a density of 145 g/m^2 (Type B). Both types were applied on the entire plane surface of the wall specimens on both sides. The glass fiber reinforcing fabric is part of a commercially available system for reinforcing masonry partition walls, whereas the glass fiber rendering mesh is ordinarily used for reinforcement of thin coat façade plaster. The tensile strength of RF and RM was equal to 92 kN/m and 34 kN/m, respectively. The RF is a bidirectional textile with a maximum elongation at rupture equal to 4%, while the RM is a bidirectional mesh with a square size of 4 x 4 mm and a maximum elongation at failure equal to 2%. Nevertheless, the RM appears to be more economical, since its price is up to 20 times lower in comparison to the RF.

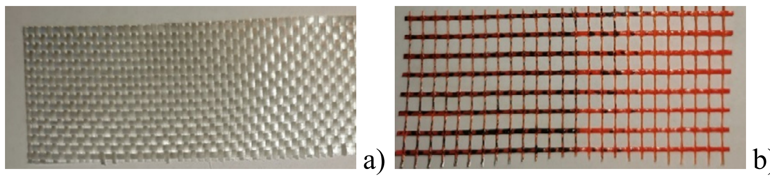


Figure 2. Applied reinforcing glass fiber fabric RF– a) and mesh RM – b) for strengthening specimens

Test set-up and experimental protocol

During the test, the non-strengthened and strengthened specimens were clamped into the rigid supporting frame fixed in the strong floor. The actuator was mounted on the rigid reaction wall. The top and the bottom support of the specimen was provided by rigid steel elements and a U shape profile, which were fixed on parallel frame columns – as can be seen in Figure 3. The upper U shape steel profile was placed on the top edge of the wall, without additional vertical compression load. The horizontal relative displacement in support was prevented by placing wooden wedges in the space between the U shape profile and specimen, as it is presented in Detail A and Detail B in Figure 3. During the investigation, seven LVDTs were attached to record the specimens' out-of-plane horizontal displacements along the height. One of the major goals of the cyclic quasi-static testing was to observe the out-of-plane behaviour and damage of non-strengthened partition walls and partition walls strengthened with proposed methods.

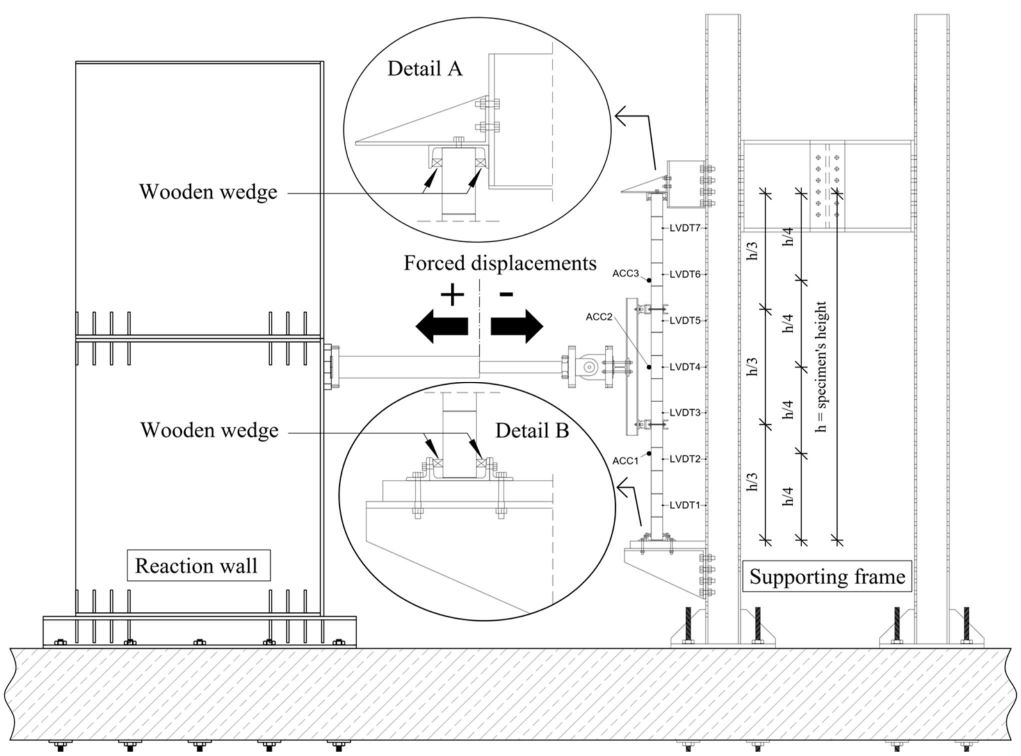


Figure 3. Experimental set-up.

The experimental investigation was controlled by horizontal load displacements, which were applied at one and two thirds of the specimen's height, following the protocol presented in Figure 4. Depending on the damage level of each individual specimen, the endpoint of the test was the near collapse limit state or when further testing was deemed too hazardous.

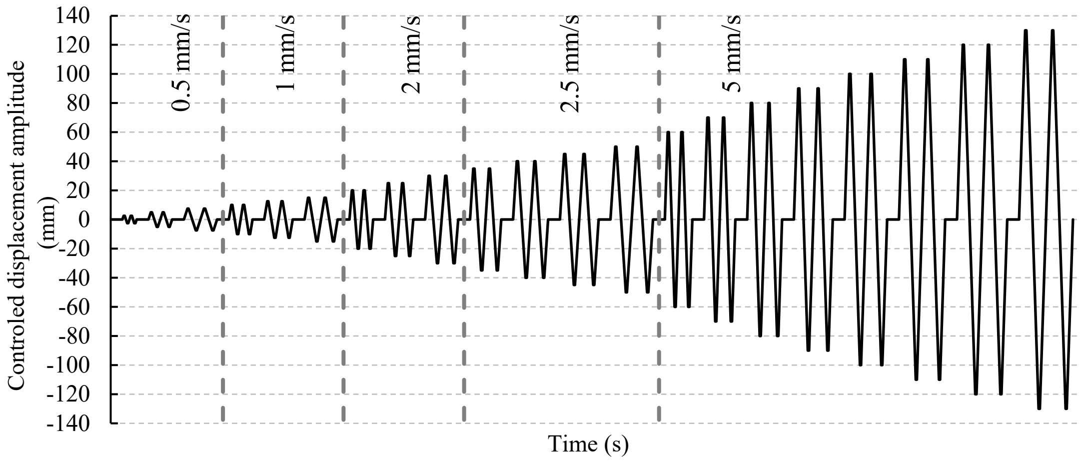


Figure 4. Loading protocol

EXPERIMENTAL RESULTS AND DISCUSSION

The rocking mechanism is a characteristic phenomenon of out-of-plane behaviour of slender walls, which is a consequence of a seismic action. In general, after reaching the masonry's flexural strength, the cracking pattern of three points occurred. The first was at the bottom support, the second at the upper support and the third somewhere in the mid-height area. The constant bending moment was between 1/3 and 2/3 of a specimens' height (Figures 5a and b). This cracking pattern forms the mechanism of three plastic hinges, where the energy dissipation is progressing while rocking. Unlike NF masonry, where we have a strong unit and weak mortar, YT masonry exhibits a strong thin bed mortar and much weaker units. Thus, the plastic hinges for NF masonry were mainly situated in bed joints while the cracks for YT were distributed within units.

For NF masonry, the out-of-plane resistances of the strengthened specimens with system A were similar, and the shapes of hysteresis were symmetric. The ultimate displacement was determined where instantaneous collapse occurred with debonding of the reinforcing glass fabric from the lower rows of the wall specimen (Figure 5f). The characteristic failure of the type B strengthening system can be attributed to exceeding the tensile strength of the rendering mesh (Figure 5g).

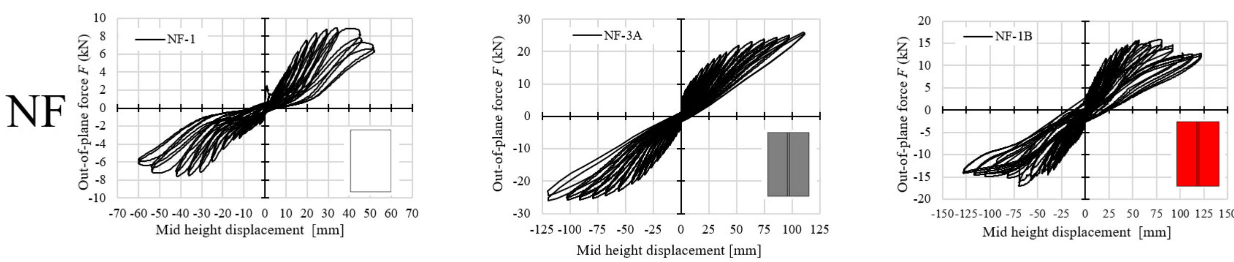
Figure 5. Failure modes and damage of NF specimens

After reaching the limit of elasticity, the as built YT masonry exhibited flexural cracks in AAC blocks within the constant moment area and crushing of AAC blocks at the supports. Increasing the horizontal displacement amplitude caused further crack openings and distinct crushing. After reaching the maximum out-of-plane capacity, intense crushing of AAC blocks in the compression zone of horizontal cross section was observed. While the AAC blocks were gradually crushing, the RF and RM prevented the AAC pieces from falling apart. Subsequently, the crushed material was confined between meshes and still had an impact on the out-of-plane capacity (Figures 6d and e).

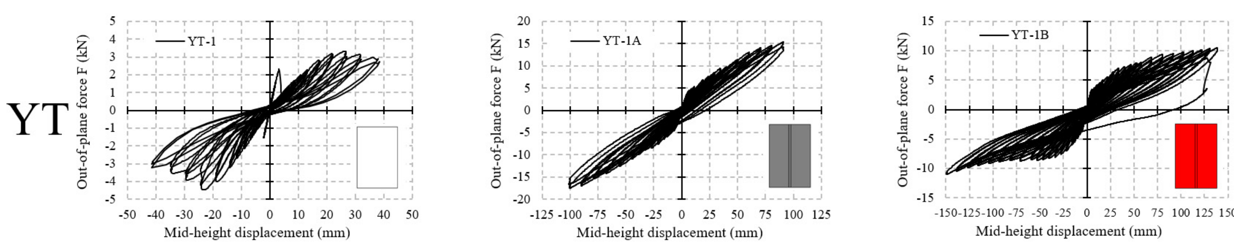
(a) (b) (c) (d) (e)

Figure 6. Failure modes and damage of YT specimens

Characteristic hysteretic load-displacement responses for each system are presented in Figure 7. Cyclic tests were generally conducted up to the out-of-plane displacement amplitude where the near collapse state of the specimen was reached.



a) NF unstrengthened b) NF strenghtened – Type A c) NF strengthened – Type B



d) YT unstrengthened e) YT strenghtened – Type A f) YT strengthened – Type B

Figure 7. Characteristic force-displacement hysteretic responses of: specimens without strengthening (a,d), with RF applied over entire surface (b,e) and with RM applied over entire surface (c,f).

Unstrengthened specimens have a characteristic elastic behaviour which was observed at the first two displacement amplitudes, up until reaching the elastic limit state. At that stage, a three-hinge mechanism was developed (two hinges at the support and the third one above the middle part of the specimen – see Figures 8a and d). The displacement amplitudes of cyclic loading were increased gradually until the end of a test, when the out-of-plane load resistance dropped by more than 30% in respect to its peak value, leading to heavy damage of the specimen. At that point it was determined that the near collapse limit state had been reached.

A comparison between out-of-plane deformed shapes at maximum resistance LS (Limit State) and near collapse LS can be seen in Figure 8 (blue line). From displacement profiles, regardless of the type of masonry (Figure 8a and d) specimens, it is evident that the maximum out-of-plane displacement appears at two thirds of the specimen's height, where the mid-height cracking has occurred. Strengthening systems A (Figure 8b and e) and B (Figure 8c and f) provide a significantly better connection of masonry components compared to non-strengthened specimens. This is the reason why the specimens' recorded horizontal displacement profile is highly regular and symmetric with the maximum out-of-plane displacement appearing exactly at the mid-height of the wall.

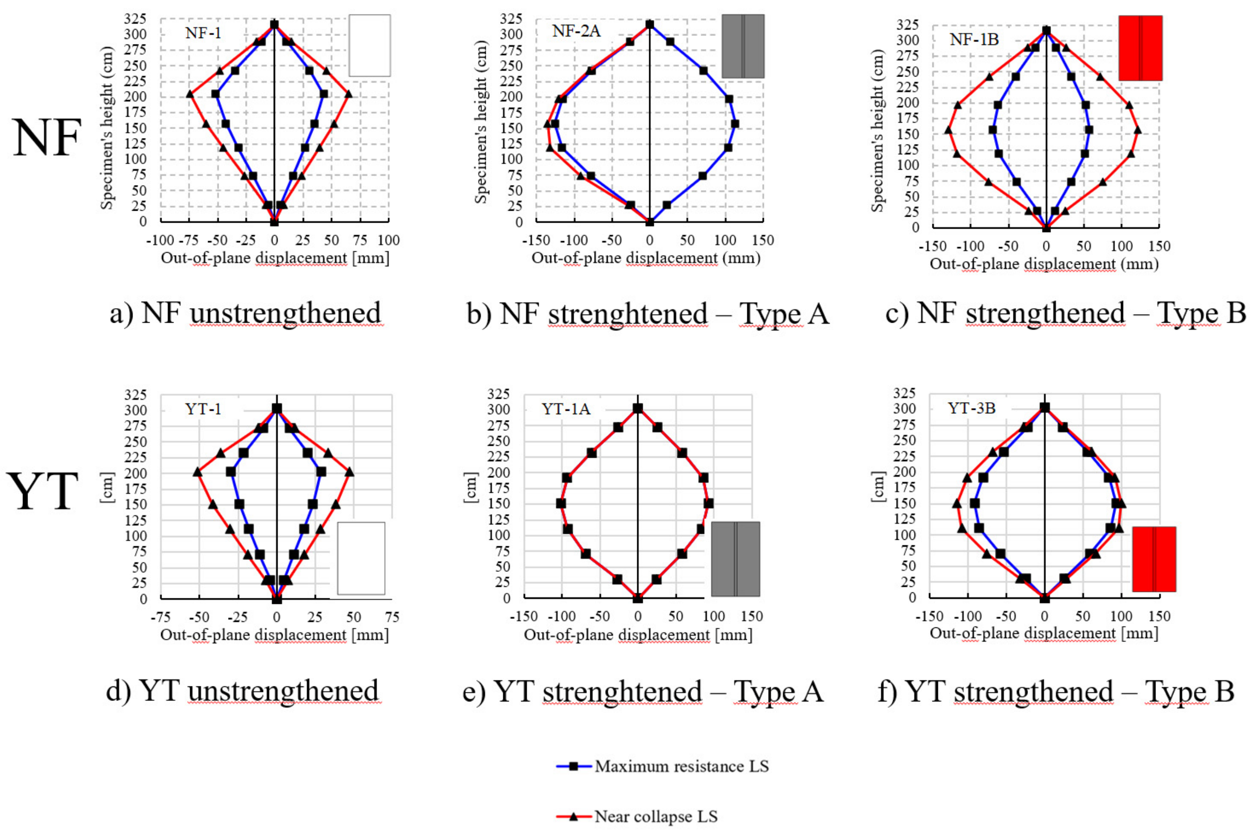


Figure 8. Horizontal displacements profiles along the heights of the specimens at maximum resistance LS and near collapse LS

Comparison of strengthening method efficiency for different types of masonry partition walls

The envelope curves of repeating hysteresis cycles for both loading directions were combined to form the average curves of a single specimens' group, to ensure clarity of the specimens' results comparison. Three limit states (LS) points based on the averaged envelope curves were defined as follows:

- First crack initiation LS: The new stability mechanism develops after the formation of plastic hinges.
- Maximum resistance LS: The maximum out-of-plane force resistance is achieved at the corresponding mid-height displacements.
- Near collapse LS: The test specimen is heavily damaged and a significant drop of force resistance occurs in the corresponding next displacement amplitude cycle.

To analyze the effectiveness of different strengthening systems, a comparison of the average hysteresis envelopes of the 2nd cycles in positive and negative loading direction for individual sets of test specimens was performed. Comparison of the specimens' average envelope curves is shown in Figure 9. In the case of the strengthening system A, the maximum resistance LS and the near collapse LS are remarkably close, both in terms of the limit displacements value and the out-of-plane resistance. For YT specimens, this trend holds for both types of strengthening. This is not the case with NF specimens strengthened with type B, where the curve slightly decreases to the near collapse LS after reaching the maximum out-of-plane capacity. A comparison of the average envelopes shows that the strengthening system A has the greatest impact on the maximum out-of-plane resistance.

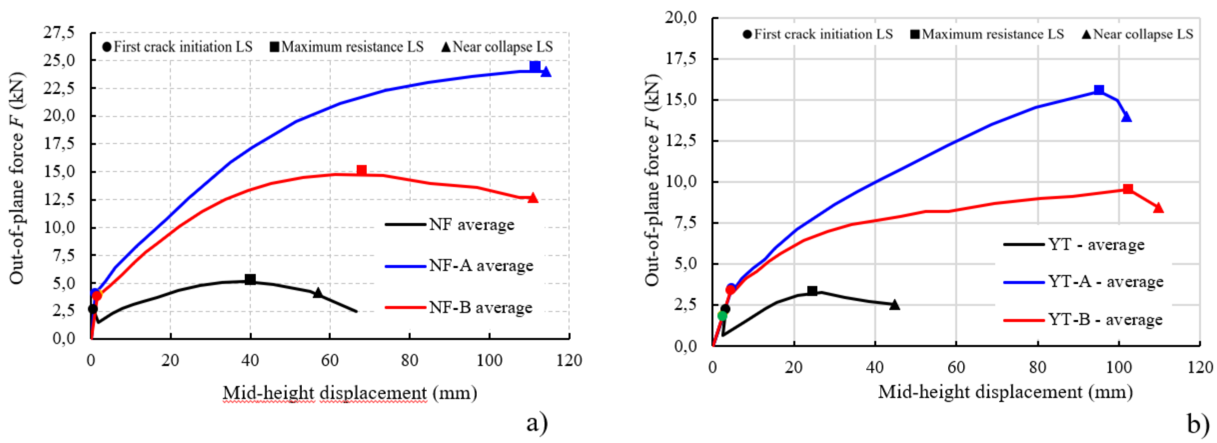


Figure 9. Average hysteresis envelopes of repeating cycles for NF (a) and YT (b) as built and strengthened specimens.

For a more detailed comparison, the average load capacities and limit displacements of individual test specimens' groups for each of the limit states were normalized in respect to average values of non-strengthened specimens. The relative comparison of different strengthening systems' efficiency at all three limit states for out-of-plane force resistance and mid-height displacement are shown in Figure 10.

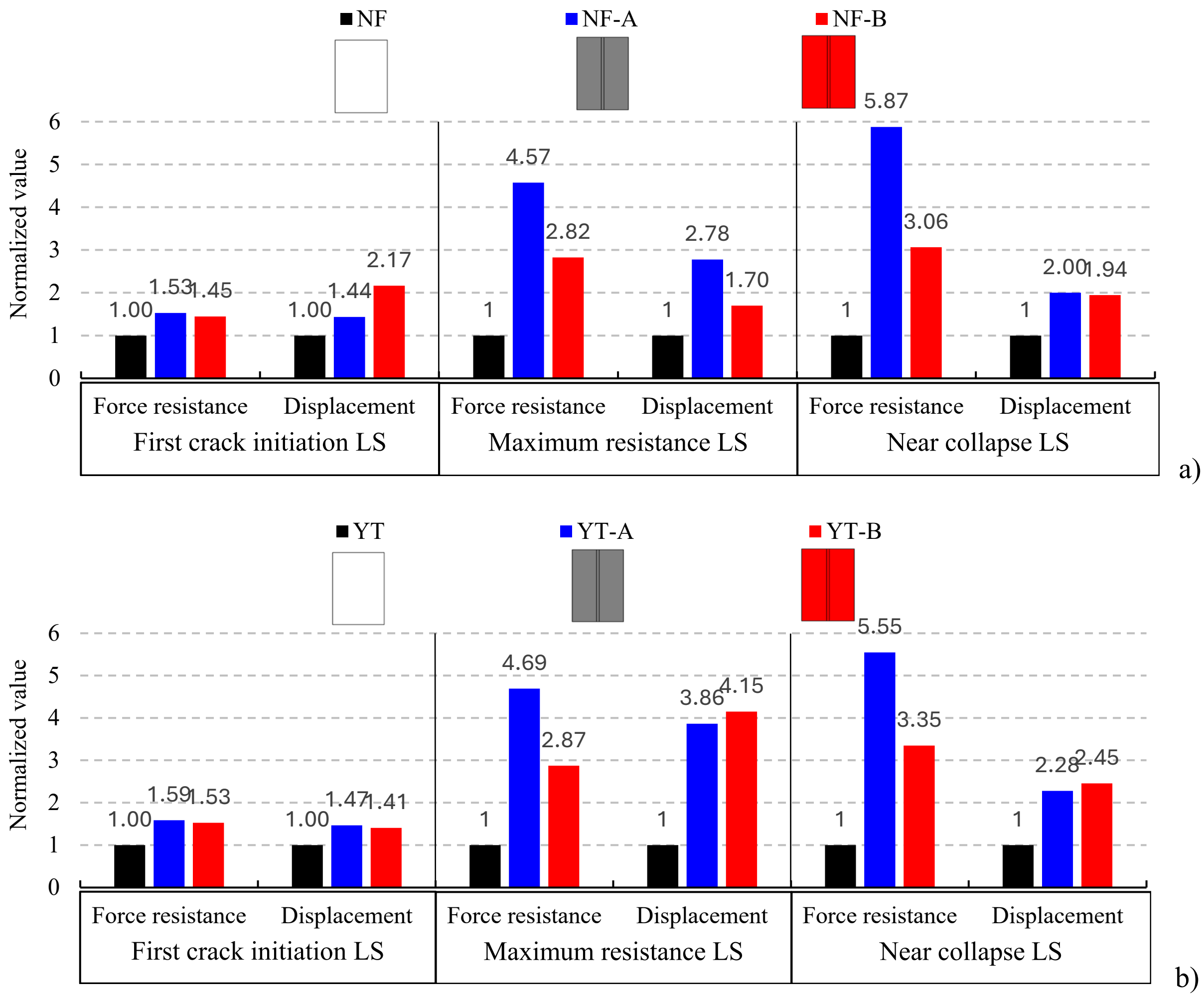


Figure 10. Efficiency of tested strengthening systems for all three observed limit states in regard to out-of-plane resistance and displacements corresponding to different LS for NF masonry (a) and YT masonry (b).

In terms of out-of-plane force resistance, it is obvious that the most significant improvement at maximum resistance LS shows strengthening method A over the method B. When comparing the out-of-plane force resistance of strengthened and non-strengthened specimens for NF masonry, it can be seen that by applying the strengthening system A, the resistance at first crack initiation LS is increased by 53%, the maximum resistance LS by 357% and the near collapse LS by 487%. For system B, the out-of-plane resistance improvement was halved, namely, 45%, 182% and 206% for each of the limit states respectively. At maximum resistance LS, the corresponding limit mid-height displacements for specimens with strengthening system A increases by as much as 178% and by 70% with system B,

The same trend can be observed in YT masonry, where for the first crack LS the out-of-plane force resistance is improved by 59% and 53%, for A and B method respectively. The limit mid-height displacements are higher by 47% and 41%, respectively. Despite the fact that the resistance with method B reached 60% of the resistance with method A, the performance of both methods is similar in terms of limit out-of-plane displacements. At maximum resistance LS, methods A and B increase out-of-plane displacements by 286% and 315%, respectively.

CONCLUSIONS

This study reinvestigated and compared new out-of-plane strengthening techniques for the prevention of the non-structural masonry partition walls collapse. The same strengthening methods were tested on full-scale specimens made from solid brickwork masonry with weak mortar and for AAC partition walls. Three of them were tested as-built, three were fully surface strengthened with RF (type A) and three fully surface strengthened with RM (type B). Both fabric and mesh were attached to the masonry surface by using a flexible polyurethane-based adhesive. The main conclusions can be summarized as:

1. The out-of-plane displacement profile of partition wall specimens became uniformly continuous along the height with application of all presented strengthening methods. The same effect of strengthening systems was observed on both types (NF and YT) of masonry partition walls.
2. The out-of-plane force resistance of non-structural walls, strengthened with method A, was significantly increased by 357% and 369% for NF and YT masonry, respectively.
3. The low-cost method B, where the full surface covering on both sides of the specimens was provided, achieved half of the resistance of the commercially available strengthening method A. It preserved the same displacement capacity in the case of YT masonry (286% vs. 315% for A and B type respectively). In NF masonry it resulted in a significantly lower increase of displacement capacity (178% vs. 70% for A and B type respectively). This is manly the consequence of the confinement effect, which was much more effective for weaker units used for YT masonry.
4. Regardless of the type of masonry, the ultimate out-of-plane force resistance is increased with the application of strengthening methods A and B. Type A has a much better performance of its strengthening fabric, as no rupture of fibres occurred.

From the obtained experimental results, it can be concluded that simple, minimally invasive and cost-effective strengthening methods (type B) can be effective on AAC partition walls and on regular solid brick partition walls to significantly improve the out-of-plane behaviour during the seismic excitation.

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