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The out-of-plane behaviour of wall panels reinforced with Titanium rods

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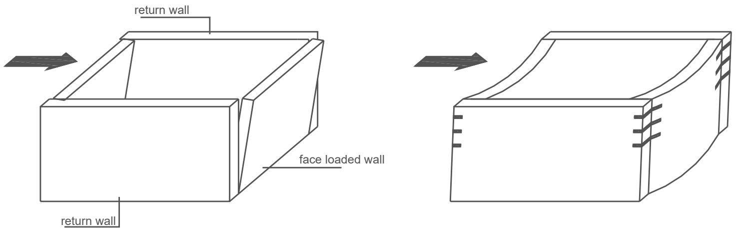
Abstract. Titanium has exceptional durability, high specific strength, low thermal expansion and its cost has reduced significantly over the last decades. Important requirements in masonry conservation are the durability of the reinforcement materials and the reversibility of interventions: the use of titanium rods in combination with inorganic matrices meets these requirements and has recently sparked the interest of researchers. Since 2000s, titanium has been used to repair important masonry and archaeological monuments. Out-of-plane collapse mechanisms are common during earthquakes, especially when the level of connection between adjacent wall panels is weak. This paper presents the results of an experimental campaign on the use of titanium threaded rods to connect wall panels against out-of-plane loading. Two reduced-scale brickwork structures (C-shaped masonry specimens) have been assembled at the Structures laboratory at Northumbria University and reinforced with titanium rods, embedded in the horizontal mortar joints: the aim was to prevent or delay the out-of-plane mechanism of the face-loaded wall by connecting it to the return lateral walls. The structural performance of the masonry specimens under out-of-plane loading is also discussed, in terms of failure modes, deformation and load capacity. It is finally demonstrated that titanium threaded rods can be effectively used to improve the wall-to-wall level of connection and increase the masonry bending strength.

Keywords: Brickwork masonry, earthquake engineering, retrofit, titanium.

1 Introduction

Earthquakes often produce significant damage to masonry heritage buildings. Masonry is considered a zero tensile-strength material and the seismic forces generates tensile stresses resulting in cracks and collapses [1-2].

One of the most dangerous failure modes of masonry structures is the rocking (out-of-plane) mechanism of a load bearing wall. Its activation could easily lead to the collapse of a whole masonry building due to the domino effects (Figs. 1 and 2). In fact, the rocking collapse of a single wall can cause a series of related collapse events, one following another, of the structural members of a building. To avoid the out-of-plane collapse of single walls, structural engineers adopt the principle of the “box” structure [1]. By effectively connecting all structural members it is possible to increase the resisting capacity of a masonry building, avoiding the collapse of the face loaded walls.



(a) (b)

Fig. 1. The level of wall-to-wall connection has a significant effect on the structural response of a masonry building under the effect of an earthquake: (a) unconnected wall panels: in this situation the out-of-plane collapse of face loaded walls is likely to occur, (b) well-connected wall panels: loads are transferred to return walls, able to resist better to the seismic action, thus increasing the seismic capacity of the building.

Fig. 2. Examples of out-of-plane collapse mechanisms of masonry buildings.

In this experimental work, titanium threaded rods have been used to reinforced face-loaded walls. Titanium is rarely used for civil applications, its use is limited to orthopedic products (such neurosurgical prosthesis), spectacle frames, military, marine and aerospace structural members.

These structural members are typically made of a titanium alloy. There are several types and grades of titanium alloys, but the most common type is Ti 6Al-4V (Grade 5). This exhibits excellent ultimate strength (1100-1400 MPa) and yield strength (1000-1100 MPa) and low weight density (4400-4500 kg/m^3), high elongation at break (10-12%), low Young`s modulus (110-120 GPa) making it an interesting solution in earthquake engineering, where lightness and deformation capacity are important characteristics. However, the most interesting characteristic of a titanium alloy is its durability, without the common problems of carbon steel.

The use of titanium in conservation engineering is very limited [3-4]. Corradi et al. proposed to use titanium rods in bed joint reinforcement of shear walls [5]. Titanium ties have been used to contain the thrust of the vaulted masonry structure of the belltower of Milan Cathedral [6]. More recently, titanium has been extensively used in reinforcement of monuments and archeological structures. In the most part of these applications, titanium wraps are installed to confine marble columns. Titanium elements have been used to restore the continuity of marble statues, to connect large stone blocks to prevent sliding phenomena [7-10].

To increase the wall-to-wall level of connection several methods have been proposed in the past [11-13]. In the 1990s, several researchers proposed several solutions. A common method of strengthening masonry walls is to wrap the walls with composite materials (FRP, Fiber Reinforced Polymers) or to tie the walls with metal rods.

In the late 1990s, the use of FRPs was proposed as a viable retrofit method for historic masonry structures. Numerous studies have been conducted to evaluate the retrofitting effect of masonry structures wrapped with FRPs [14-16].

However, recent studies have also highlighted the poor durability of FRPs exposed to environmental ageing. Mechanical degradation, masonry detachment and cracking were observed only a few years after application [17-18]. Another major drawback of FRPs is its low shear and tensile strength (and the direction perpendicular to the composite). FRP usually has very high tensile strength along the fiber direction, but in monument protection, the fibers are not easily attached in such a way that the load on the reinforced masonry activates only the tensile strength of the composite reinforcement. Small-scale shear stresses can cause premature cracking in composites, especially when used in the form of FRP strips and panels.

2 Materials

Mechanical tests were initially conducted to characterize the properties of the materials (masonry, bricks, mortar and titanium reinforcements) used in this experimental investigation.

2.1 Bricks

Compression tests on the solid bricks (brick dimensions 215 x 103 x 65 mm) used to build the "C" shaped walls were carried out at Northumbria Structures Laboratory. For the testing process, the following steps were followed: 1. As part of the preparation of bricks according to BS EN 771-1:2003 [19], the bricks were immersed in a water bath at 20°C ± 5°C for at least 15 hours and allowed to drain for 15-30 minutes after removal from the tanker. 2. The bricks were then placed between two pieces of plywood in the press machine to help with load distribution, placed in the center of the machine. 3. A compressive loading rate of 15 kN/s was employed in the tests using 2000kN press machine. Compressive brick strength was determined in the parallel direction of vertical loading (i.e. bricks were loaded perpendicularly to the longest brick dimension).

The failure mode was consistent with the one typically observed in this type of tests: vertical cracks formed in the bricks starting from the peripheric area (near the borders), while in the inner brick core, more laterally confined, remained partially undamaged. The type of failure observed appears to be non-explosive with the vertical crack progressively developing in the bricks. Table 1 shown the result of the compressive tests. An average compressive strength of 28.37 MPa was obtained with a coefficient of variation (CoV) of 14.3%.

Table 1. Results of the compressive tests.

Weight density (kg/m^3)	1723.8
Max load (kN)	636
Compressive strength (MPa)	28.37
Moisture content (%)	7

2.2 Mortars

Two types of mortar were used in this experiment: a low-strength mortar was used for the construction of the walls, in order to reproduce a “historic” mortar typically used in masonry constructions. The mix of mortar was designed as follows: sand to lime in a volume ratio of 6:1, resulting in a natural M4 mortar [20-21], as per relevant standard. A second type of mortar, with high compressive strength and cement-based (M12), was used to repoint the bed joints where titanium rods had to be installed.

Flexural and compression tests were performed to characterize the mortar. Mortar samples with dimensions 160 x 40 x 40 mm were first tested for bending according to the procedure given in EN 1015-11 [22]. The resulting halves were subjected to a compression test. For the mortar used in wall construction, the average compressive strength was 2.8 MPa with a CoV of 23.2%. The flexural strength was 0.68 MPa (CoV 19.3%). These results are consistent with the mechanical properties of a historical mortar (Tab. 2).

Table 2. Flexural and compressive strengths of the mortar. CoV % values in ( ).

	Mortar used in construction	Repointing mortar
Density (kg/m^3)	1.84	1.96
Compressive strength (MPa)	2.82 (19.3)	26.1 (15.1)
Flexural strength (MPa)	0.68 (23.2)	3.8 (25.1)

2.3 Titanium

6.35mm threaded titanium rods were tested in tension for mechanical caracterization. Rods exhibits a linear weight density of 144.35 g/m (Fig. 4). However, the thread has been removed before testing and the diameter of the rods reduced to 5 mm. This was necessary to measure the rod cross sectional area with accuracy and to induce failure in the rod gage length. When reducing titanium rods to sample size, precautions were taken to avoid surface work hardening and heating of the material, which would change the mechanical properties of the material.

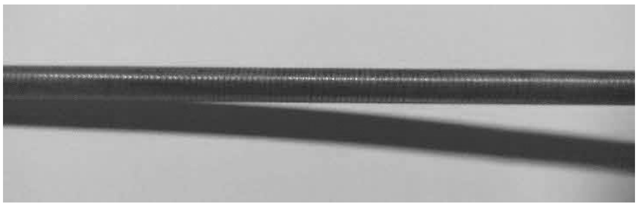


Fig. 4. Detail of threaded titanium rod (diameter 6.35 mm)

The thread was removed to produce a consistent diameter across the length of the sample. Table 3 shows the test results: tensile and yielding strengths are 1012.6 and 923 MPa, respectively.

Table 3. The average results of titanium rods tensile tests. CoV % values in ( ).

Diameter of the titanium rod (mm)	5
Tensile strength (MPa)	1012.6 (9.1)
Failure load (N)	46415
Yield strength (MPa)	923 (7.3)
Young’s modulus (GPa)	111.7 (5.1)

3 Construction of the walls

Masonry C-shaped specimens were made of solid bricks, to form a double wythe wall (wall thickness 215 mm). Initially, a first course of bricks has been laid above the asphalt, after having levelled this with a cement screed (thickness about 40 mm). Two C-shaped brickwork structures were constructed and tested. The “English” bond pattern has been used in construction: this is made of alternate courses of staggered layers of stretchers and headers.

Each C-shaped specimens is made of 3 separate wall panels (2 “return” walls 900x2200x215 mm, and a “face-loaded” wall 2015x2200x215 mm). These are all made of 29 courses of bricks. To reproduce a situation of “weak-connection” between wall panels, sometimes common in historic constructions, only 3 bricks have been used as connectors (at the 14th, 26th and 28th brick course) (Figs. 4 and 5).

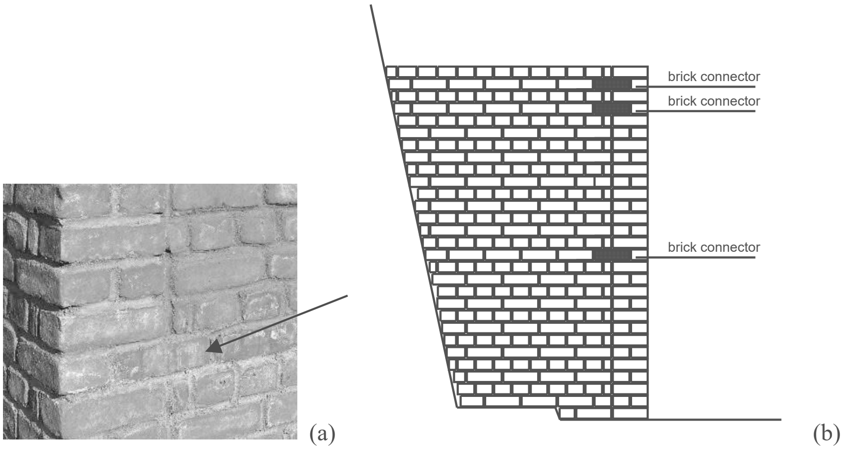


Fig. 4. (a) Detail of brick used as wall-to-wall connector, (b) location of the brick connectors.

Both vertical and horizontal (bed) mortar joints have a thickness of about 10-11 mm, the same as on conventional building sites. Construction of the walls was made by experienced local bricklayers. Return walls were connected to the reinforced concrete wall using steel brackets.

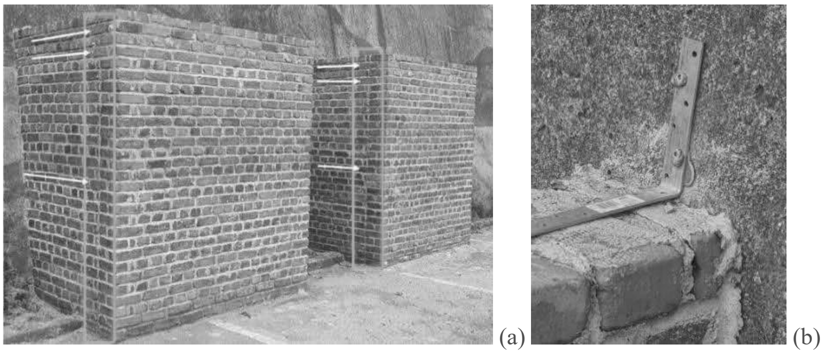


Fig. 5. (a) The two C-shaped walls panels and the location of brick connecters (white arrows), (b) steel bracket used to connect return walls to reinforced concrete wall.

4 Reinforcement of the Walls

Titanium threaded rods were used in this work to reinforce a C-shaped masonry structure. This retrofitting method is interesting because of its characteristics in terms of reversibility [23] and the durability of the reinforcement materials (titanium). In fact, the retrofit can be removed with very limited or no damage to the pre-existing masonry structure. Figure 6 shows the titanium rod used for reinforcement: this has a U-shape with a length 2010 mm in one direction, and 1000 mm in the other.

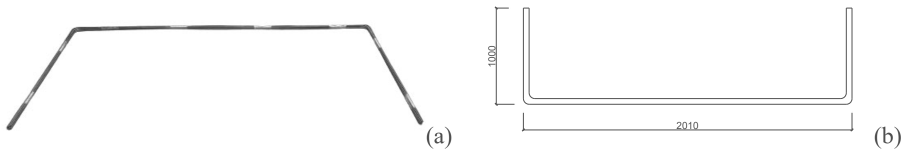


Fig. 5. (a) U-shaped titanium threaded rods, (b) dimensions**.**

The C-shaped masonry structure was made of 29 courses of solid bricks. Two titanium rods have been installed below the 26th and 24th brick course. A high-strength cement mortar was used to repoint the bed joint where the rods have been embedded.

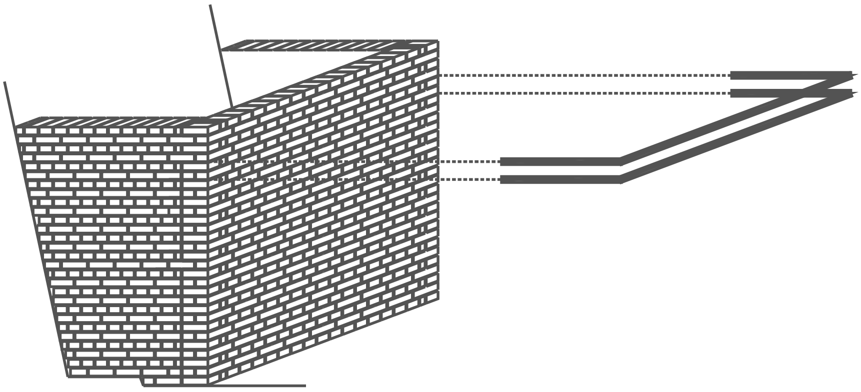


Fig. 6. Reinforcement method. Two titanium rods have been installed below the 26th and 24th brick course.

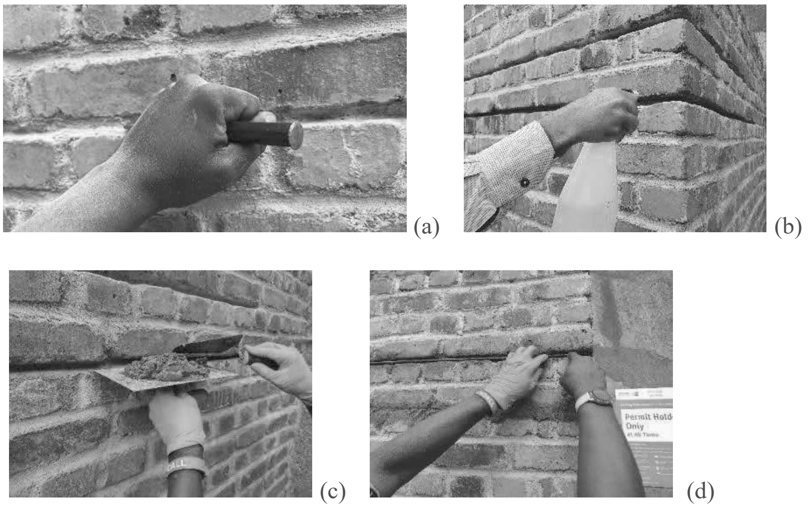


Fig. 7. Main phases of the rod installation (a) Cut a slot into the horizontal bed joint (b) Wetting using spray water, (c) Filling the joint with new cement mortar, (d) Installation of the titanium threaded rod.

Figure 7 shows the installation method of the reinforcement: 2 threaded titanium rods have been installed in the horizontal bed joints of the face-loaded wall, and in the return walls. The reason for doing this is to improve the wall-to-wall level of connection and to increase the bending capacity of the face-loaded wall.

The installation phases of the threaded titanium rods include: 1. Select a suitable bed joint, 2. Ensuring that the bricks around the bed joints to reinforced are sound, 3. Cut a 20mm slot into the selected bed joint, 4. Cleaning the joint using compressed air, 5. Wetting the joint with a water spray, 6. Application of a first (15 mm thick) layer of cement mortar, ensuring that this mortar is in contact with pre-existing masonry and it is right to the back of the slot, 7. Push the titanium threaded rod into the fresh mortar such that it surrounds the rod, 8. Repoint the front of the slot with a second layer of the same cement mortar, previously used (Fig. 8).

5 Test Method

The low level of wall-to-wall connection is often the cause of wall rocking during earthquakes. This project aims at studying the effectiveness of titanium connectors between load bearing faced-loaded and return walls. A new retrofitting method, consisting in the use of titanium rods fully embedded in the mortar horizontal bed joints will be studied. An experimental investigation using full-scale brickwork specimens will be therefore conducted to assess the walls' structural response when these are subject to out-of-plane loads.

A hydraulic cylinder, placed inside the C-shaped specimen (Fig. 9), will be used to apply the out-of-plane cyclic load which permit it, on the one hand, to act directly on the faced-loaded wall, while on the other hand, of resulting connected to a reaction wall.

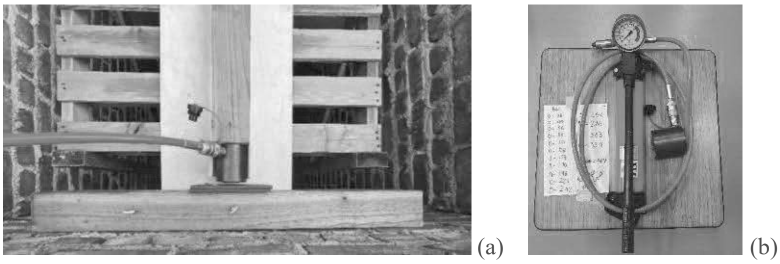


Fig. 9. (a) Hydraulic jack placed inside the C-shaped wall (plan view), (b) Manual pump.

Figure 9(a) shows detail of the load (horizontal plan): this is applied with hydraulic cylinders and distributed horizontally with a 100x100x1000 mm timber beam.

Load applied in cycles of 4 kN using our manual pump (Fig. 9(b)) for each cycle, the maximum load level is maintained for approximately 30 seconds before being completely removed. Then, allow the wall to remain unloaded for an additional 30 seconds before applying the next load cycle. Movements of the wall during testing with be measured using our LVDTs.

6 Test Results

6.1 Unreinforced C-shaped masonry structure

The level of wall-to-wall connection of the first C-shaped structure was low. Only few bricks were used to connect the face-loaded wall to the return (side) walls. The aim was to reproduce the situation of a historic building where walls are often poorly connected each other: extensions and partitions of existing buildings, demolitions and reconstructions are common in historic centres of European cities where buildings have been in use for centuries.

The horizontal load was applied to the face-loaded wall in cycles: failure occurred when the load reached 28.7 kN. This produced a sudden vertical crack (Figs. 10 and 11) that separated completely the return walls from the face-loaded one. The few solid bricks used to connect the walls provided a significant resisting effect: this can be demonstrated by the fact that the crack, in the area near the connecting bricks, also involved the return walls (shear diagonal cracks).

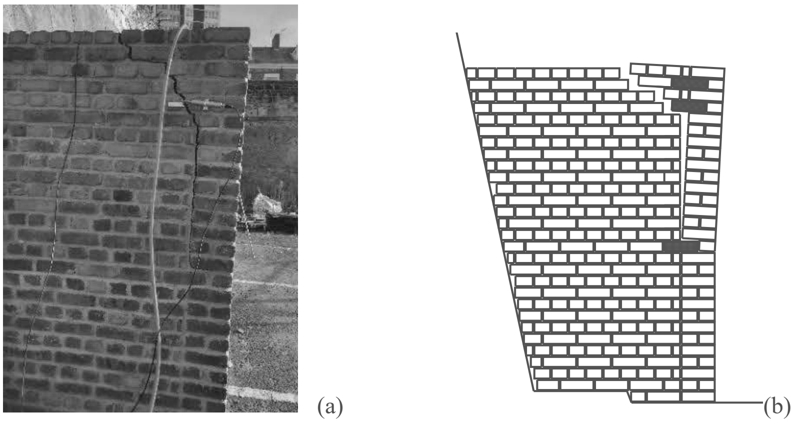
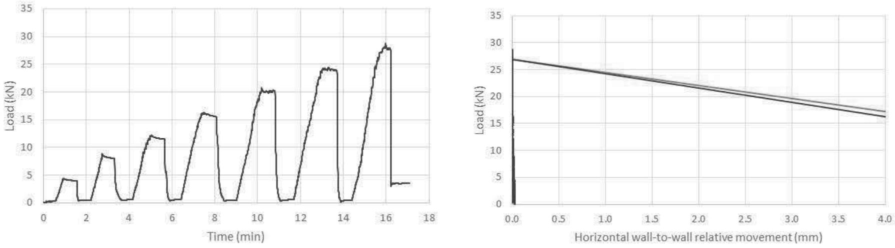


Fig. 10. (a) Failure mode of unreinforced C-shaped structure, (b) Schematic representation of the mechanism. The brick connectors were effective in preventing the out-of-plane mechanism of the lower part of the face-loaded wall. Only the upper part collapsed (rocking mechanism). In addition, the two brick connectors near the top were able to "transfer" the out-of-plane load to the return walls. To be noted the diagonal shear cracks in the return walls.

6.2 Reinforced C-shaped masonry structure

The second C-shaped masonry structure was tested after reinforcement. Two titanium wraps were installed to increase the wall-to-wall level of connection and bending strength of the face-loaded wall.



(a) (b)

Fig. 11. Unreinforced structure (a) Out-of-plane load history (load cycles), (b) Out-of-plane load vs horizontal relative movement between return and face-loaded walls at the top of the C-shaped structure.

The failure mode of the reinforced specimen differed significantly from the one observed in the unreinforced one: while in the unreinforced C-shaped structure failure was due to separation of the face-loaded wall from the return walls, in this experiment the walls remained effectively connected and no detachment or separation was recorded. This is a significant indication about the effectiveness of the titanium rod in connecting the walls. Figure 12(a) shows the failure mode: it can be observed that the failure basically involves only the face-loaded wall.

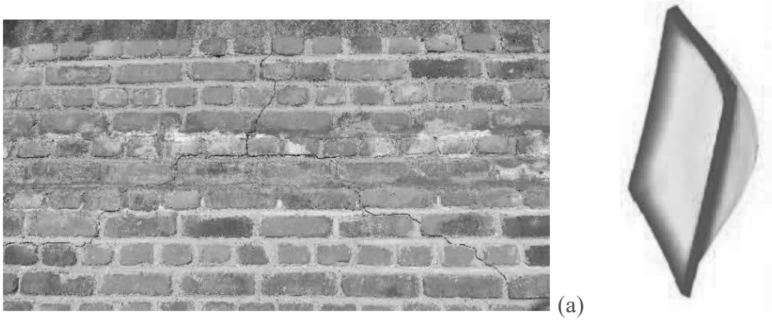

(a) (b)

Fig. 12. (a) Failure mode of reinforced C-shaped structure: a Y-shaped crack developed in the face loaded walls. To note this crack did not develop in the bed joints where titanium rods were installed, (b) Schematic and simplified representation of the deformed shape of the face-loaded wall.

The face-loaded wall failed because of a combination of horizontal and vertical bending produced by the out-of-plane load applied horizontally. The crack is Y-shaped, made of three branches, intersecting near the point of application of the point load (using the hydraulic cylinder). Figure 12(b) shows a schematic and simplified representation of the deformed shape of the face-loaded wall. The titanium rods and the lateral constraints of the face-loaded walls prevented a horizontal displacement near the return walls (vertical sides) and near the wall foundations. Only the upper horizontal edge of the wall can freely deform this can be graphically represented with a dome-shaped configuration.

Figure 13 shows the out-of-plane load vs horizontal relative movement between return and face-loaded walls at the top of the C-shaped structure measured with the contact instrumentation (LVDTs) fixed to the return walls: it can be noted that relative horizontal movement is very small (maximum 0.05 mm), and only after cracks develop in the face-loaded wall, LVDTs recorded small horizontal movement (0.4-0.5 mm). Titanium rods were effective in preventing separation of the face-loaded wall from return walls.

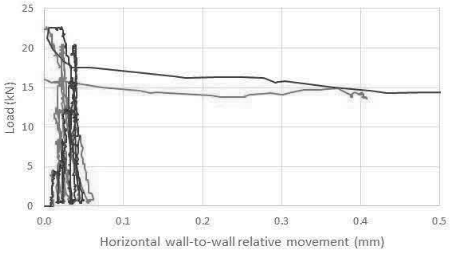


Fig. 13. Reinforced structure: Out-of-plane load vs horizontal relative movement between return and face-loaded walls at the top of the C-shaped structure.

7 Conclusions

Out-of-plane collapse (rocking mechanism) of face-loaded walls is common in historic buildings under the action of an earthquake. This is mainly the consequence of a low level of connection between walls, and the low bending strength of masonry.

In this paper the out-of-plane behaviour of masonry structures reinforced with titanium threaded rods embedded into the mortar bed joints is investigated. Two large brickwork structures (C-shaped, made of three wall panels) have been constructed at the Northumbria structures laboratory. For both of them the wall-to-wall level of connection was, on purpose, weak.

The first results of this experimental campaign indicates that the application of threaded titanium rods using a high strength, cement mortar is able to significantly increase the level of wall-to-wall connection, preventing the rocking mechanism. While the unreinforced masonry structure collapsed because of rigid out-of-plane rocking of the face-loaded wall, the reinforced one resisted until a bending mechanism developed in the face-loaded wall, with the wall-to-wall connections fully operational during out-of-plane loading.

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