QUASI-STATIC OUT-OF-PLANE TESTING OF UNREINFORCED MASONRY WALLS INSTRUMENTED WITH OPTICAL MEASUREMENTS

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ABSTRACT

Masonry buildings have existed in Sweden since the Middle Ages. The use of brick masonry as a construction material was pivotal until the beginning of the 20th century. Unreinforced masonry walls (URM) are massive and act as a protective system, yet they have limited capacity against explosions. When exposed to blasts, they experience out-of-plane failure, which engenders flying debris inside the building and may affect the stability of the building. Knowledge pertaining to the design and strengthening of URM walls against blasts has been identified as insufficient, on a Swedish context, to answer the current threats. In this paper, the results from quasi-static out-of-plane tests performed on URM walls made of clay bricks and lime-based mortar are presented. The tests were performed at RISE Research Institutes of Sweden by applying an incremental out-of-plane displacement, while applying an axial load at the wall's top edge. RC slabs were affixed over and below the walls to simulate the contact condition of a typical system. Two different types of support were tested for the upper slab: a) where the slab could slide along the vertical direction, and b) where this was prevented, leading to an arching action inside the wall. The results were generated as a part of an initial experimental stage of a project investigating URM walls loaded laterally by static and blast loads with optical measurements. Ultimately, the results will be used to verify existing models and/or develop a new model for the load-deformation relationship.

KEYWORDS: *masonry, out-of-plane action, testing, blast, optical measurements*

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INTRODUCTION

Masonry buildings have existed in Sweden since the Middle Ages. Bricks imported from Germany and the Netherlands started to be used as foundation material during the 17th century. Massive walls were built using brick bonding, i.e., bricks were placed in rows (courses). During the 18th century, the production of brick was rationalized, which was motivated by the shortage of timber and devastating consequences of fire in cities [1]. Consequently, brick became an important building material for housing in Sweden until the beginning of the 20th century [2]. The existing building stock in Sweden, made up of load-bearing masonry walls, is generally protected and preserved due to its underlying historical value.

A load-bearing masonry wall acts as an autonomous load carrying element able to resist gravity and applied loads. Most prevalent are unreinforced masonry walls (URM), which are massive and act as a natural protective system, yet they are known to have a limited capacity against explosions. When exposed to blasts, they experience out-of-plane failure mechanisms, which engender flying debris inside the building and may affect the overall stability of the building. It is unclear which boundary conditions develop during blast actions [3]. Earlier studies [4] [5] show that upon out-of-plane actions, a so-called arching develops in the masonry wall which, as long as deformations are small, gives a relatively large contribution to the load bearing capacity. With increasing deformation, the arching effect successively loses its function until collapse occurs. Knowledge pertaining to the blast capacity of masonry walls on a Swedish context has however been identified as insufficient to answer the current threats, design and strengthening requirements.

In this paper, the results from quasi-static out-of-plane pushover tests performed on URM with single and double wythes are presented. This type of test yields the resistance curve, i.e., a diagram relating the resultant force to the displacement of a control point of the wall. Moreover, the stiffness, force and displacement capacity of the wall derived from the results of the tests can be compared to results from blast tests, such that the wall's static behaviour can be related to its dynamic response. The tests were performed at RISE Research Institutes of Sweden by applying incremental displacement perpendicular to the wall's plane while simultaneously applying an axial load at the wall's top edge. A reinforced concrete slab was affixed below and over the URM walls to simulate the contact condition between a typical system. Confined and unconfined support conditions, which exist between the wall and the floor/roof slab, were tested. Visualization and determination of deformation characteristics and crack distribution were obtained using an optical full-field deformation measurement system based on Digital Image Correlation (DIC).

The results presented herein are a part of an initial experimental stage of a project investigating the behaviour of URM loaded laterally by out-of-plane static and blast loads. Further experiments are planned to investigate additional geometric properties, materials, boundary conditions and loading scenarios. Finally, the results will be used to verify existing theoretical models and/or develop a modified model for the load-deformation relationship for a given masonry wall typology.

EXPERIMENTAL PROGRAM

URM wall specimens were constructed in this initial study according to the following description.

Test specimens

Three specimens were configured as unreinforced walls without a cavity (see Figure 1). One wall was built with one wythe and two walls with two wythes. The dimensions of the specimens were 1500 x 780 mm^2 with a thickness of either 125 mm or 250 mm. Each wall was constructed between two reinforced concrete (RC) slabs (980 x 500 x 75 mm^3) to simulate similar contact conditions to that found in existing buildings, where masonry walls are directly in contact with the RC floor slabs.

Figure 1: Exemplification of Test Specimens

Materials

Standard solid red bricks with the dimensions of 250 x 120 x 62 mm^3 were used along with a hydraulic lime mortar. The choice of mortar was motivated by the estimated time of when load-bearing masonry walls in Sweden were typically constructed, as well as its enhanced workability compared to standard lime mortar. The average compressive strength of the masonry was determined to be 4.0 MPa (COV 9%) from uniaxial compression tests performed on three wallets (510 x 390 x 250 mm^3).

EXPERIMENTAL SETUP

Quasi-static pushover tests were performed on the URM wall specimens. The experimental setup developed is presented along with the prescribed test protocol and applied measurement methods.

Quasi-static pushover test

Pushover tests consist in applying a displacement perpendicular to the wall's mid-plane, and whose magnitude increases slowly and incrementally. A pushover test setup was constructed at RISE Research Institutes of Sweden (see Figure 2), combining vertical loading and horizontal four-point bending of a wall specimen. The test rig is adjustable and different wall element heights, up to approximately 3 m, can be tested. The horizontal load was applied by means of a hydraulic actuator (capacity of 500 kN), which was displacement-controlled to be able to reproduce the entire resistance curve. The actuator was bolted to a rigid load frame. A system of steel beams was attached to the actuator to transfer the horizontal load by two half-moon shaped load lines located at 1/3 and 2/3 of the wall height, such that four-point bending loading was applied to the wall specimen. The load lines were mounted on a linear bearing, allowing them to follow the vertical uplift of the wall during testing. The axial force was applied at the top of the wall by means of a hydraulic actuator (capacity of 1 MN). This actuator can be operated in displacement-, stiffness- and force-control modes, thus allowing for testing of three different support conditions at the top of the wall, respectively: fixed support, flexible support and sliding support. The flexibility in specimen size and being able to modify the boundary conditions are novelties of such experimental test setup.

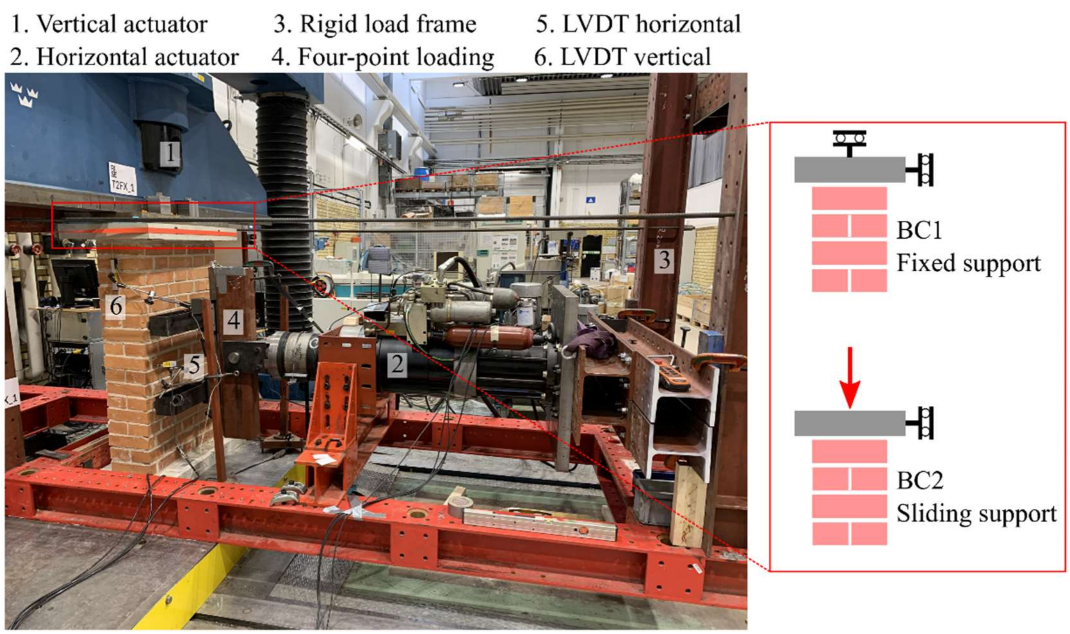

Figure 2: Overview of Pushover Test Setup

The following measurements were taken during the pushover testing according to the locations indicated in Figure 2:

- (1) Vertical load (overburden) from actuator denoted as O and measured in kN.
- (2) Total horizontal load from actuator, denoted as Q and measured in kN.
- (6) Vertical displacement measured by an LVDT, denoted as v and measured in mm.
- (5) Horizontal displacement measured by two LVDTs, denoted as u and measured in mm.

In addition, deformation characteristics and crack distribution were obtained using an optical full-field deformation measurement system based on Digital Image Correlation (DIC).

Test protocol

The wall specimens were subjected to quasi-static pushover tests according to the parameters listed in Table 1. The bottom concrete slab of the wall was placed directly in contact with the load table of the machine, while two different boundary conditions were explored for the slab placed at the top edge of the wall: a) BC1 – fixed support and b) BC2 – sliding support. These boundary conditions are presented in the American manual for blast resistant design of masonry components UFC 3-340-02 [6].The fixed support allows for arching to develop in the wall, due to the presence of a vertical reaction force that increases at the base of the wall to contrast the prevented wall elongation. The behaviour of these walls is known to be largely affected by the compressive strength of bricks and mortar [7] [8]. In contrast, walls subjected to the sliding top support do not develop arching action. It is known that the behaviour of these walls is mainly governed by the elastic modulus of masonry and the level of applied axial load [9]. Only marginally will they be affected by the masonry compressive strength.

A vertical pre-stress, σ_v, of 0.2 MPa was applied to the top of the wall, which corresponds to an axial load ratio (ALR) of 5%. The ALR is the ratio between the axial load applied initially on the top of the wall and the compressive strength of the masonry. The prescribed ALR can influence crack patterns, failure mechanisms and deformation of the wall obtained during the application of the out-of-plane load. The initial vertical load applied to the top of the wall to achieve this initial stress condition is presented in Table 1. The vertical load was constant for the sliding (unconfined) condition but increased due to the arching effect developed in the case of the fixed (confined) condition as horizontal load was being applied.

Firstly, the vertical load was applied at a rate of 10 kN/min until the initial vertical load was reached. Then the vertical top boundary condition was set to be controlled as fixed displacement for BC1 (T2-1) or as fixed load for BC2 (T1-1 and T2-2). Finally, the horizontal load was applied with a displacement rate of 1 mm/min. During the later part of the post-peak behaviour, the displacement rate was successively increased to 4 mm/min.

Table 1: Test Matrix for Initial Study

Specimen ID	**Description**	**Measured geometry [H x L x t, mm]**	**Top boundary condition**	**Axial load ratio [%]**	**Initial vertical load [kN]**
T1-1	Unreinforced, Single wythe	1500 x 790 x 115	BC2 - Sliding	5	18.2
T2-1	Unreinforced, Double wythe	1500 x 770 x 245	BC1 - Fixed	5	37.7
T2-2	Unreinforced, Double wythe	1500 x 780 x 245	BC2 - Sliding	5	38.2

Optical Measurements

The behaviour of the URM walls was analysed by optical full-field deformation measurements based on Digital Image Correlation (DIC). Both planar two-dimensional measurements using a four single-camera set-up (2D DIC) and three-dimensional measurements using a stereoscopic camera set-up (3D DIC) were used, as shown in Figure 3. The basic idea of DIC is to measure the displacement of a specimen under testing by analysing the deformation of a surface speckle pattern in a series of digital images acquired during loading. This is accomplished by tracking the position of discrete pixel subsets of the speckle pattern within the images.

The 3D DIC measurement was performed using the optical system ARAMIS 12M by GOM [10]. The system configuration was calibrated for a measuring volume of approximately 1500 x 1200 x 1200 mm^3, covering most of the wall surface, except a smaller area at the lower part, which were unsighted by the support beam (see Figure 3b). The images were captured with a frequency of 0.5 Hz. For this configuration, the displacement resolution was approximately 0.005 mm for both x- and y-displacement (in-plane) components and approximately 0.010 mm for z-displacement (out-of-plane), determined as the standard deviation between two static images of the specimen before loading. The out-of-plane 3D DIC measurement of the wall surface allows the visualization and determination of deformation characteristics and crack distribution, as depicted in Figure 4.

The images from the 2D DIC measurements were taken along the height of one side of the wall element, mainly to determine the crack propagation through the wall thickness (see Figure 3a). The imaging system was set up as four individual 2D measurements, with three of the cameras covering a third of the wall height each (measuring area 560 x 470 mm^2), with a small overlap, and the fourth camera focusing on the upper concrete slab. The images were acquired with a frequency of 0.5 Hz and evaluated by DIC technique using the software GOM Correlate [10]. For this configuration, the displacement resolution was approximately 0.003 mm for both x- and y-displacement components (in-plane).

(a) (b)

Figure 3: DIC Measurement Setup: 2D (a) and 3D (b)

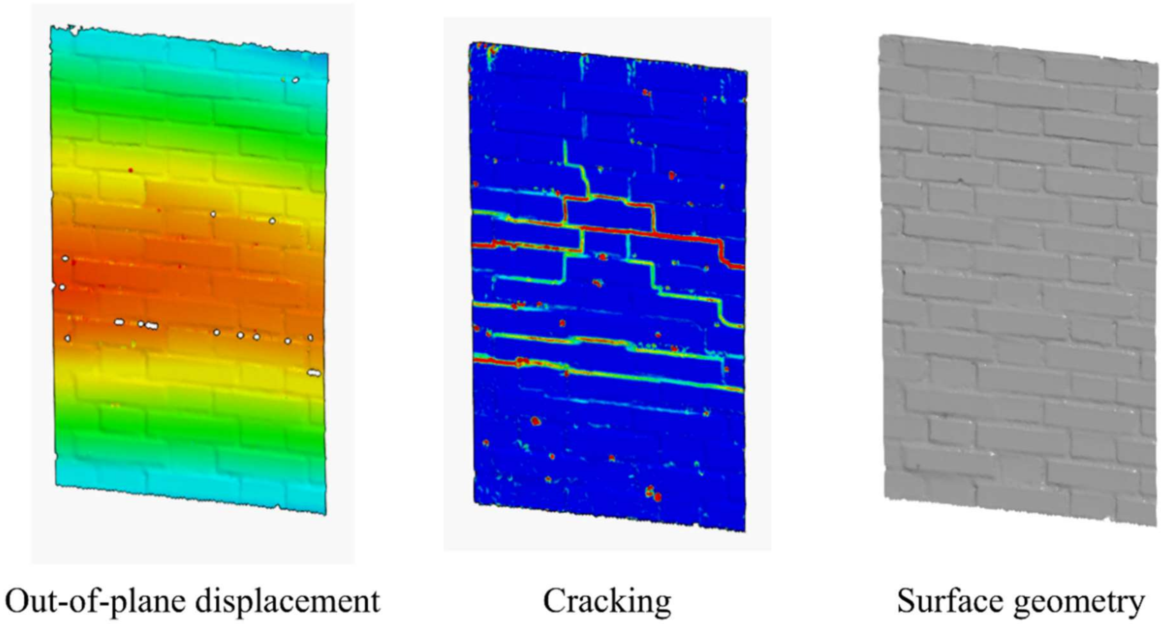

Figure 4: Exemplification of 3D DIC Measurement Results

TEST RESULTS

The quasi-static pushover test results are summarized in Table 2 for all specimens. The load capacity of the wall corresponds to the peak horizontal force, Q_{max}.

Table 2: Summary of Pushover Results

Specimen ID	Top boundary condition	Initial vertical load [kN]	Load capacity Q_{max} [kN]	Horizontal displacement u at Q_{max} [mm]	Arching action O_{max} [kN]
T1-1	Sliding	18.2	9.6	6.9	No arching
T2-1	Fixed	37.7	88.7	10.8	113
T2-2	Sliding	38.2	37.8	13.9	No arching

Single wythe with sliding support (T1-1)

Figure 5a shows that the horizontal force was nearly zero upon reaching the maximum displacement. Moreover, Figure 5b shows that the axial load remained relatively constant as the horizontal displacement increased, thus indicating that no arching effect was present. T1-1 underwent a gradual wall uplift during loading, as shown in Figure 5c. Specimen T1-1 reached a displacement close to collapse, as a three-hinge mechanism was formed. After reaching the displacement capacity of T1-1, the horizontal force was slowly removed, and the wall returned to its initial position.

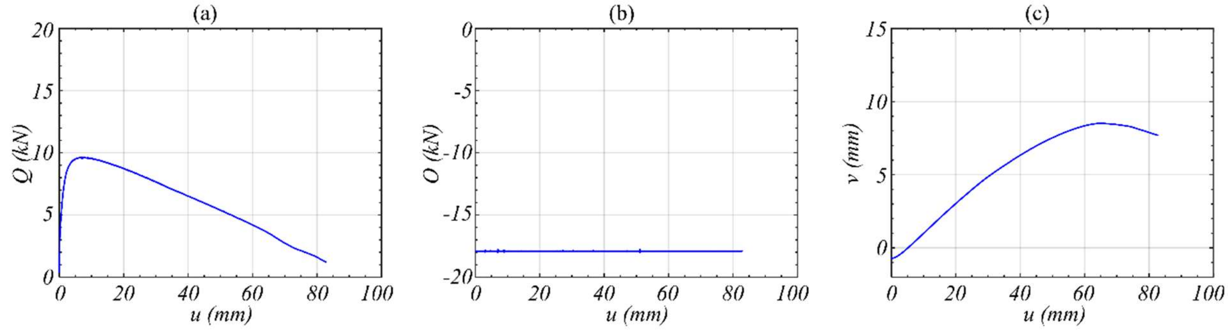

Figure 5: T1-1: Out-of-plane Behaviour (a), Arching Effect (b), Wall Uplift (c)

Double wythe with fixed support (T2-1)

The increase in load capacity was notably observed for T2-1, as an effect of arching, in comparison to T2-2, see Figure 6a. The load capacity was reached at nearly the same displacement as the maximum arching, shown in Figures 6a-b. Moreover, a displacement close to incipient collapse was nearly reached, such that the upper and upper-central hinges were almost aligned. The wall failed following a so-called flexural shear failure, with the formation of four hinges, two at the line loads and two at the supports. It was observed that the two internal hinges were approaching the two external ones, which was confirmed by the fact that the arching action was steadily increasing, as depicted in Figure 6b.

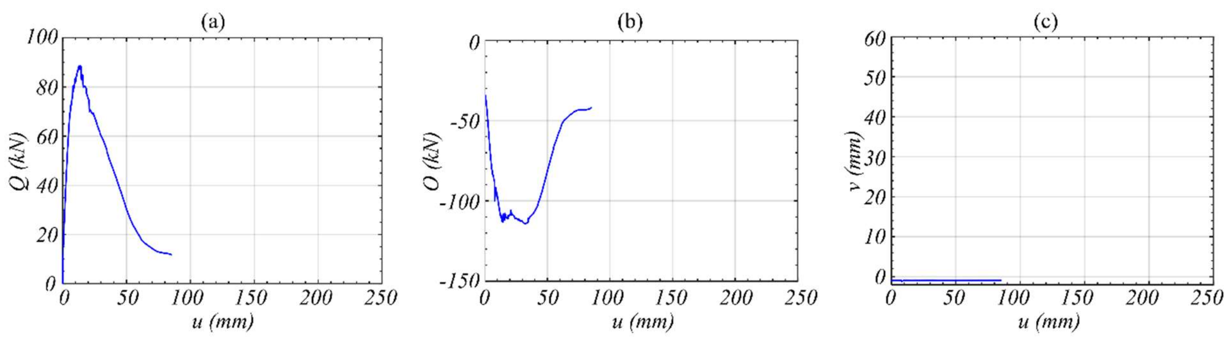

Figure 6: T2-1: Out-of-plane Behaviour (a), Arching Effect (b), Wall Uplift (c)

Double wythe with sliding support (T2-2)

The yielded load capacity for T2-2 was approximately 40% of that obtained for T2-1 (see Figure 7a) due to the prescribed sliding boundary conditions. The axial load was constant as the horizontal displacement increased, as shown in Figure 7b, which means that no arching took place. The vertical displacement versus horizontal displacement, shown in Figure 7c, indicate an inflection towards the end of the test. For this reason, the test was terminated at about 2 kN. Upon unloading, it appeared that the wall was returning together with the actuators, as a reaction force was present. Specimen T2-2 reached a displacement close to collapse, as a three-hinge mechanism was formed.

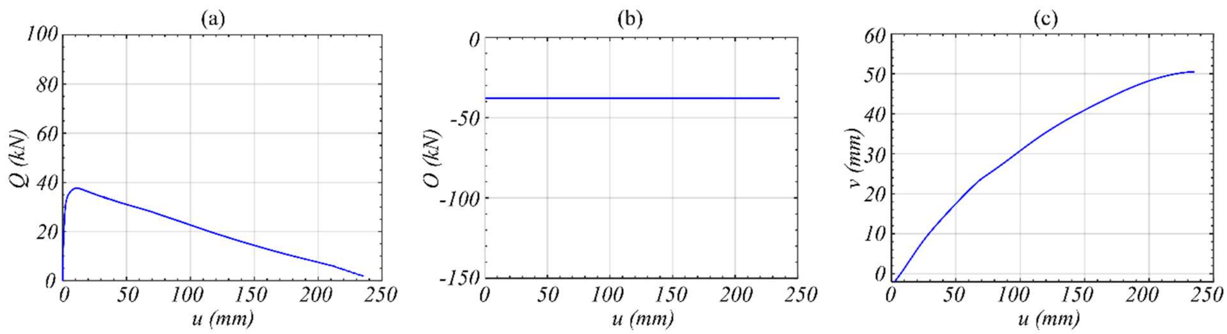

Figure 7: T2-2: Out-of-plane Behaviour (a), Arching Effect (b), Wall Uplift (c)

OBSERVATIONS

Selected DIC results are presented herein to show deformation characteristics and crack distributions of the tested specimens. The peak Q_{max} and final Q designate the load capacity and load just before collapse/unloading, respectively.

Single wythe with sliding support (T1-1)

A narrow three-hinge mechanisms for the wall was formed during this test, as observed in Figure 8. Some crushing was also observed during the test on the compression side, such that mortar was falling from the joints. On the tensile side, damage localizes into several cracks which opened progressively upon wall deflection. Upon removing the top slab after the test, it was observed that the uppermost masonry joint was completely detached, such that failure occurred at this interface.

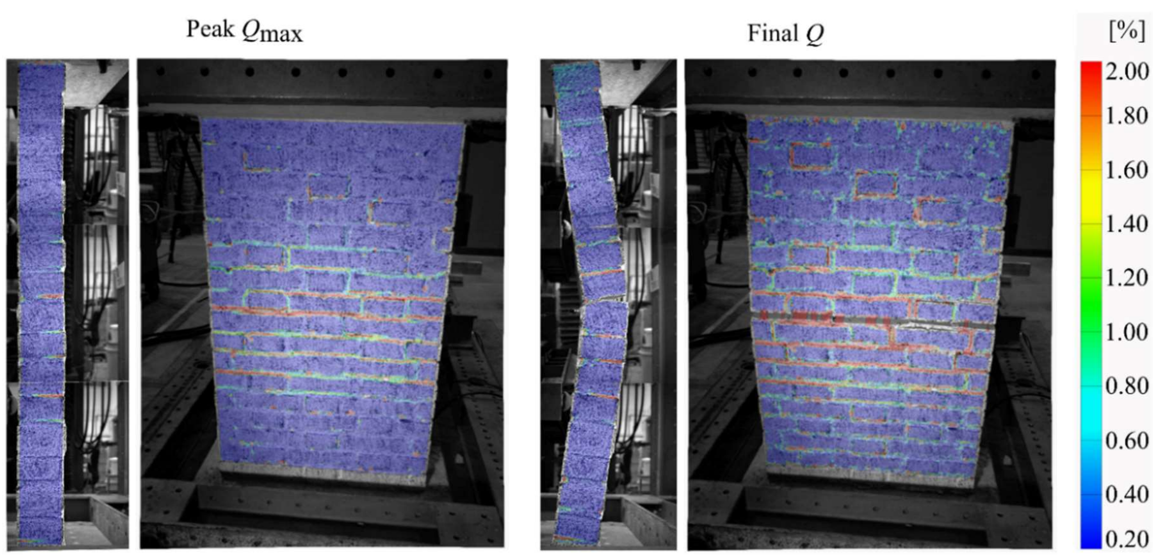

Figure 8: T1-1: DIC Results for Peak and Final Horizontal Loads

Double wythe with fixed support (T2-1)

The initiation of splitting can be observed between and through the bricks as shown in Figure 9. This failure mechanism propagated through the bricks that were running entirely through the wall thickness. The wall failed following a so-called flexural shear failure, with the formation of four hinges, two at the line loads and two at the supports. The increase of arching action engendered the compression failure of the wall portions involved in the mechanism accompanied by the splitting of the two wythes.

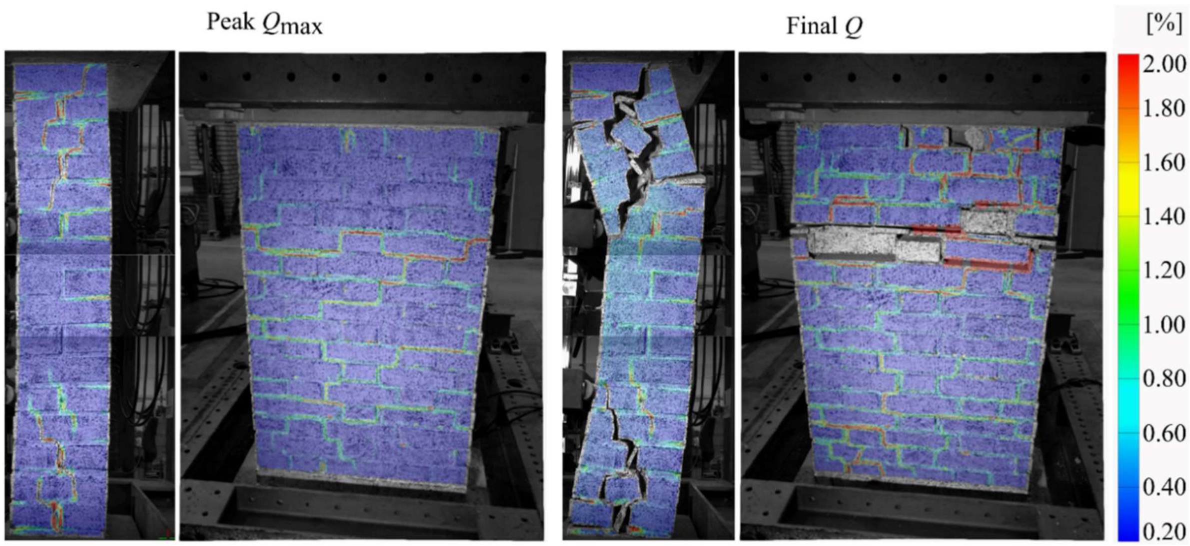

Figure 9: T2-1: DIC Results for Peak and Final Horizontal Loads

Double wythe with sliding support (T2-2)

The wall experienced a three-hinge mechanism as shown in Figure 10. Two mid-cracks, located at the same distance from the supports, formed. The upper middle crack eventually closed while the lower middle crack was opened forming the middle hinge. Given the thickness of the wall, a large amount of crushing was observed. Shear sliding at the wall supports, in combination with bending, was also noted.

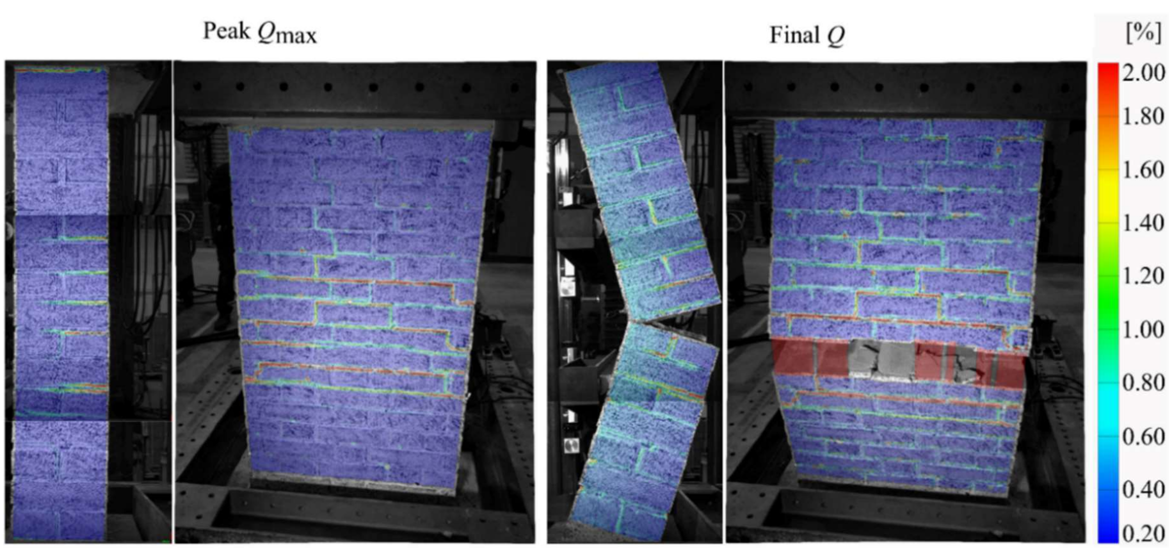

Figure 10: T2-2: DIC Results for Peak and Final Horizontal Loads

CONCLUSIONS

The quasi-static pushover test results indicate that URM wall capacity is largely influenced by its boundary conditions, which was verified in the case of the double wythe configuration. Due to the arching action arising inside the masonry as the wall deflected, the load capacity increased. Optical full-field deformation measurements, based on DIC, were obtained during the testing, both in 2D and 3D. The measurements were used to visualize and determine deformations and to show the crack pattern development. Further experiments are planned to investigate additional geometric properties, materials, boundary conditions and loading scenarios. More specifically, a flexible support boundary condition at the top of the wall with different stiffness values will be explored. Ultimately, the results will be used to verify existing models and/or develop a modified model for the load-deformation relationship for a given masonry wall typology.

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