



## LARGE-SCALE TESTING PROGRAM FOR THE SEISMIC CHARACTERIZATION OF DUTCH MASONRY WALLS

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### Abstract

The evaluation of the seismic response of unreinforced masonry buildings is a popular topic all over the world. In recent years, also the Netherlands started to face seismic risk, since the induced seismicity in the north of the country considerably increased (the gas extraction started in 1963, and earthquakes have occurred since the early '90s, with the highest magnitude equal to 3.6 on the Richter scale experienced near Huizinge in 2012). This phenomenon has a wide impact on the built environment, which is mainly composed by unreinforced masonry. These buildings were not designed for seismic loading, and present specific characteristics such as very slender walls (a ratio height/thickness equal to 25), limited cooperation between walls and floors, and use of cavity walls, often connected by weak and corroded ties.

To predict the behaviour of unreinforced masonry buildings, the use of numerical models and simple analytical design methods is required. These approaches necessitate the characterisation of the masonry at both material and structural level. An extensive large-scale testing program was performed at the Delft University of Technology to create benchmarks for the validation of the numerical and analytical models. The attention was mainly devoted to a terraced house typology, which was widely adopted for housing in the period 1960-1980. These houses were characterised by loadbearing walls of calcium silicate bricks and walls of clay bricks as outer leaves.

In this framework, the paper presents an overview of the cyclic pushover tests performed on full-scale walls under either in-plane or out-of-plane loading.

Seven full-scale unreinforced masonry (URM) walls were tested under in-plane loading. Two different series of solid brick masonry walls were considered: four specimens (COMP-0a, COMP-1, COMP-2, and COMP-3) were characterized by a high aspect ratio ( $H/B = 2.5$ ), whereas three specimens (COMP-4, COMP-5, and COMP-6) had low aspect ratios ( $H/B = 0.6$ ). Also two different configurations were considered, according to the provided boundary conditions at wall ends: cantilever walls, and double clamped walls.

Five full-scale URM walls were tested in the out-of-plane direction by applying cyclic loading using a system of airbags. Two different geometries of brick masonry walls were considered: two specimens (COMP-0b and COMP-7) were characterized by a high aspect ratio and tested in a one-way spanning configuration; other three specimens (COMP-10, COMP-11, and COMP-12) had low aspect ratios and were tested in a two-way spanning configuration. All the walls were composed by solid calcium silicate masonry, except specimen COMP-10 which was made of perforated clay brick masonry. Sample COMP-12 contained a window opening, so that two asymmetric piers were determined at the sides of the window.

For both the in-plane and the out-of-plane tests a description of the material properties, of the employed set-ups, and of the loading procedures is provided. An overview of the main results is presented.

*Keywords: Unreinforced masonry structures; Experiments; Cyclic tests; In-plane behaviour; Out-of-plane behaviour.*



## 1. Introduction

In the last years, the Netherlands started to face seismic risk, due to induced earthquakes caused by gas extraction in the province of Groningen, with the highest magnitude equal to 3.6 on the Richter scale experienced near Huizinge in 2012; in the region, the majority of the built environment is composed by unreinforced masonry. Buildings were not designed according to any seismic design criteria and are characterised by very slender walls, absence of reinforcement, the use of cavity walls, and little cooperation between walls and floors. To assess the behaviour of the existing unreinforced masonry (URM) buildings, the use of numerical models as well as analytical design methods is required, whose validation should be performed against well-defined benchmarks. In order to provide benchmarks for the Dutch masonry, a comprehensive experimental campaign has been performed at the Delft University of Technology in 2015. The campaign focused on a terraced house typology, which was widely built during 1960-1980. This typology of building is characterised by slender cavity walls, composed of an inner leaf in calcium silicate masonry and an outer leaf in clay masonry connected by masonry wall ties, concrete floors and timber roof. Experimental tests were carried out at various scales in order to characterise the masonry material [1], the connection [1], the vulnerable elements [2], [3] and the structural behaviour [4], [5]. This experimental campaign was included in an integrated testing program, part of which was developed also at the European Centre for Training and Research in Earthquake (Eucentre) [6].

In the present work, the experimental outcomes of the cyclic tests performed at a component level on full scale masonry walls tested under in-plane and out-of-plane loading are presented. Initial stiffness, resistance, ductility, hysteresis loops, and crack pattern were investigated. In the literature various benchmarks can be found on the seismic behaviour of URM walls for the in-plane (e.g. Ref. [7]-[12]) structural behaviour. In recent years, wide attention has also been devoted to the out-of-plane for both one-way (e.g. Ref. [13]-[15]) and two-way spanning (e.g. Ref. [16], [17]) structural behaviour. This paper investigates specifically the behaviour of Dutch masonry. Section 2 describes the material properties. Sections 3 and 4 contain a detailed description of the specimens and of the test setup, of the material properties and of the testing procedure for the in-plane and out-of-plane tests, respectively. An overview on the experimental findings, which have been used to validate the numerical models [18], is also presented. Section 5 reports the main concluding remarks.

## 2. Material properties

The material properties of the tested masonry were selected to represent the typical URM buildings of the period 1960-1980 in the Groningen area, on the base of the information defined in a previous experimental campaign, in which masonry samples were extracted from existing building and tested in laboratory [19]. All the tested specimens, except one sample tested in the out-of-plane direction, were made of masonry composed of calcium silicate bricks and general purpose mortar in the M5 strength class; perforated clay bricks were used for specimen COMP-10 (described in Section 4). Calcium silicate bricks and perforated clay bricks had nominal dimension of 210x71x102 mm and 201x51x102 mm, respectively; the declared mean compressive strengths were 16 MPa and 25 MPa, respectively. The thickness of both head- and bed-joints was set to 10 mm with possible variation between 9 to 12 mm. A running bond was adopted for every specimen.

A dedicated experimental campaign was performed for the characterisation of the replicated masonry used for the construction of the walls. Table 1 lists the obtained material properties, derived according to standardised tests. A complete description of the performed test campaign is provided in Ref. [1].

## 3. In-plane tests

### 3.1 Description of test set-up and test specimen

Seven full-scale URM walls were built and tested at the TU Delft testing Stevin laboratory to study the in-plane behaviour of pier walls in URM buildings. Two different series of solid brick masonry walls were considered:

specimens COMP-0a, COMP-1, COMP-2, and COMP-3 were characterized by a high aspect ratio  $H/B = 2.5$  (1.1 m long and 2.75 m high), and will be hereinafter referred to as “short walls”, whereas specimens COMP-4, COMP-5 and COMP-6 had a low aspect ratio  $H/B = 0.6$  (4 m long and 2.75 m high), and will be referred to as “long walls”. Also two different configurations were considered according to the provided boundary conditions at wall ends: four cantilever walls, having a shear ratio  $\alpha_v = M/(V \cdot H) = \text{moment at end section} / (\text{shear} \times \text{panel height}) = 1$  (as defined in e.g. Ref. [20]), and three double clamped walls ( $\alpha_v = 0.5$ ).

The frame set-up was designed in order to provide both a uniform vertical pressure (throughout four actuators, having each a capacity of 100 kN) and a horizontal imposed displacement (via a horizontal actuator with a capacity of 400 kN) on the top of the walls. The top and bottom brick course of each specimen was glued to a steel beam with a high performance glue to prevent sliding shear failure and tension failure at the steel-masonry contact layer. The bottom steel beam was connected to the cross-beams of a steel frame anchored to the floor, whereas a load-spreading beam was bolted on the top steel beam and connected to the horizontal actuator. The vertical actuators connected the cross-beams at the base of the wall to the load-spreading beam on the top, and they were controlled pairwise (on the front and back of the wall) to ensure that the load of each actuator in a pair was the same. Out-of-plane displacements and rotations of the top beam were prevented by a steel frame. Given the large distance between the two couples of vertical actuators in the long walls, two extra steel beams were added above the load spreading beam to ensure a uniform spreading of the vertical load on the top of the masonry wall.

A scheme of the test set-up employed for the short and the long walls is displayed in Fig. 1a and b, respectively. A summary of the main features of the tested specimens is reported in Table 2.

Table 1 – Material properties of adopted replicated masonry

Material property			Calcium silicate masonry	Clay masonry
Compressive strength perpendicular to the bed joints	$f'_m$	MPa	5.9	14.7
Compressive strength parallel to the bed joints	$f'_{m,h}$	MPa	7.5	7.5
Elastic modulus perpendicular to bed joints evaluated between 1/10 and 1/3 of the maximum compressive stress	$E$	MPa	2746	8156
Elastic modulus of masonry parallel to bed joints evaluated between 1/10 and 1/3 of the maximum compressive stress	$E_h$	MPa	2081	4676
Out-of-plane flexural strength parallel with the bed joint	$f_{x,1}$	MPa	0.21	0.40
Out-of-plane flexural strength perpendicular to the bed joint	$f_{x,2}$	MPa	0.76	1.12
Initial shear strength	$f_{v0}$	MPa	0.14	0.15
Shear friction coefficient	$\mu$	MPa	0.43	0.87

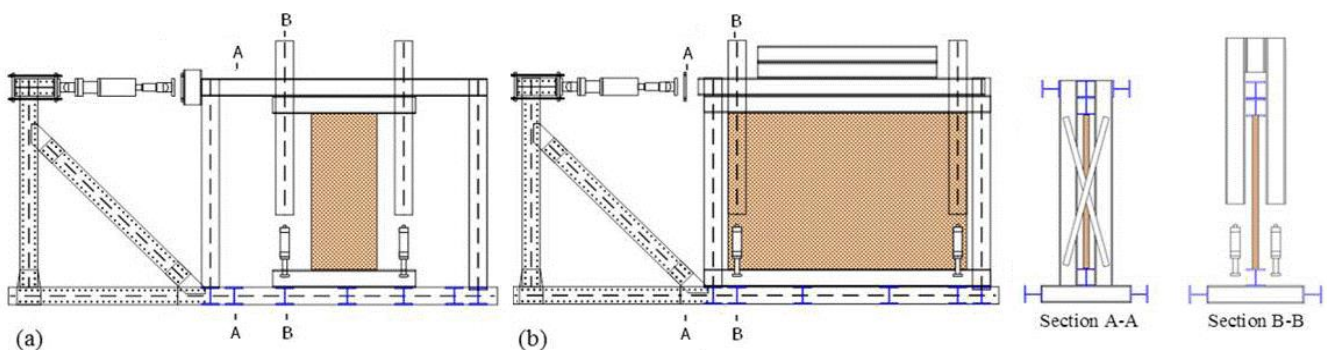


Fig. 1. Scheme of the test set-up used for the in-plane tests on short (a) and long (b) walls.

Table 2 – Dimension and features of the in-plane test samples

Sample name	Type of masonry	Dimensions	Vertical pressure (MPa)	Shear span $L_v$
		L (m) x H (m) x t (m)		
COMP-0a	Calcium Silicate	1.1 x 2.76 x 0.102	0.7	0.5
COMP-1	Calcium Silicate	1.1 x 2.76 x 0.102	0.7	1
COMP-2	Calcium Silicate	1.1 x 2.76 x 0.102	0.5	1
COMP-3	Calcium Silicate	1.1 x 2.76 x 0.102	0.4	0.5
COMP-4	Calcium Silicate	4.0 x 2.76 x 0.102	0.5	0.5
COMP-5	Calcium Silicate	4.0 x 2.76 x 0.102	0.3	0.5
COMP-6	Calcium Silicate	4.0 x 2.76 x 0.102	0.5	1

### 3.2 Testing procedure

A quasi-static cyclic pushover test was performed on each wall. The tests were performed in displacement control. In the preparation phase, the vertical loads were applied throughout four actuators. The total applied vertical load remained constant during the test, whereas the load in each single pair of actuators depended by the provided boundary conditions. For the cantilever walls the load was maintained constant in each actuator, whereas for the double clamped walls the forces in the actuators were dynamically updated according to a “kinematic” criterion, which assumed that the distance between the steel beams, glued at top and bottom of the specimens, remained constant (i.e. the actuator elongations were the same during the whole test).

During the test, horizontal imposed displacements were applied to the top of the samples by controlling the horizontal actuator, with cycles of increasing amplitude; each cycle was composed of three runs, where a run was defined as the time needed to apply the maximum positive and negative target displacement starting and ending at zero displacement. The speed of the imposed horizontal deformations was chosen for every cycle such that every cycle lasted about 10 minutes. The number of applied cycles differed from test to test and depended either on the failure of the specimen, or on limitations of the loading frame. Fig. 2 shows the adopted loading scheme. The net horizontal displacements presented in the following sections were measured directly on the samples. Consequently, the elastic deformations of the loading frame determined small differences between positive and negative measured displacements, as well as between the different tests.

### 3.3 Overview on the experimental results

In this section, a short overview on the obtained results is presented in terms of capacity curves (Fig. 3) and crack patterns (Fig. 4) at the end of the tests. It should be noted that, except for specimen COMP-0a and COMP-6, tests ended before a real failure of the specimens occurred.

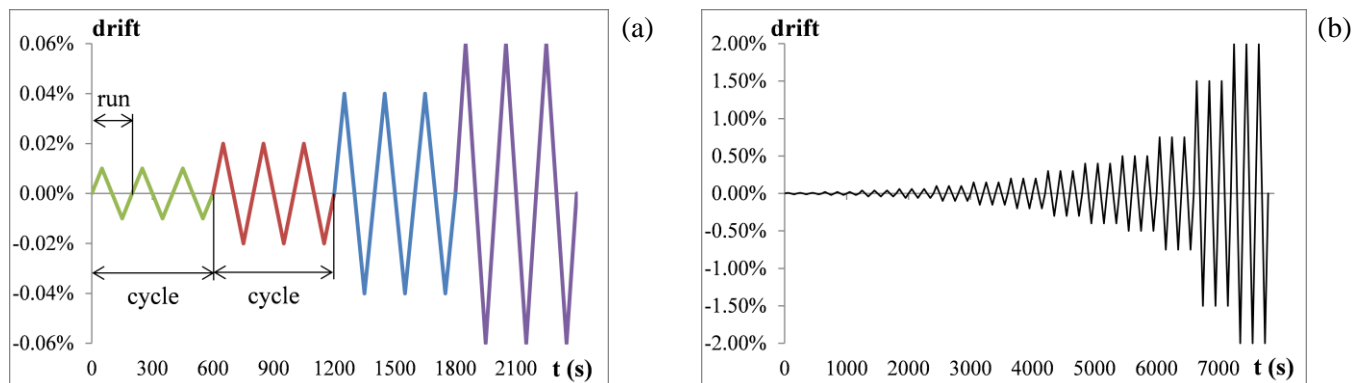


Fig. 2. Loading scheme for the in-plane tests: (a) detail of the first cycles and (b) complete scheme.

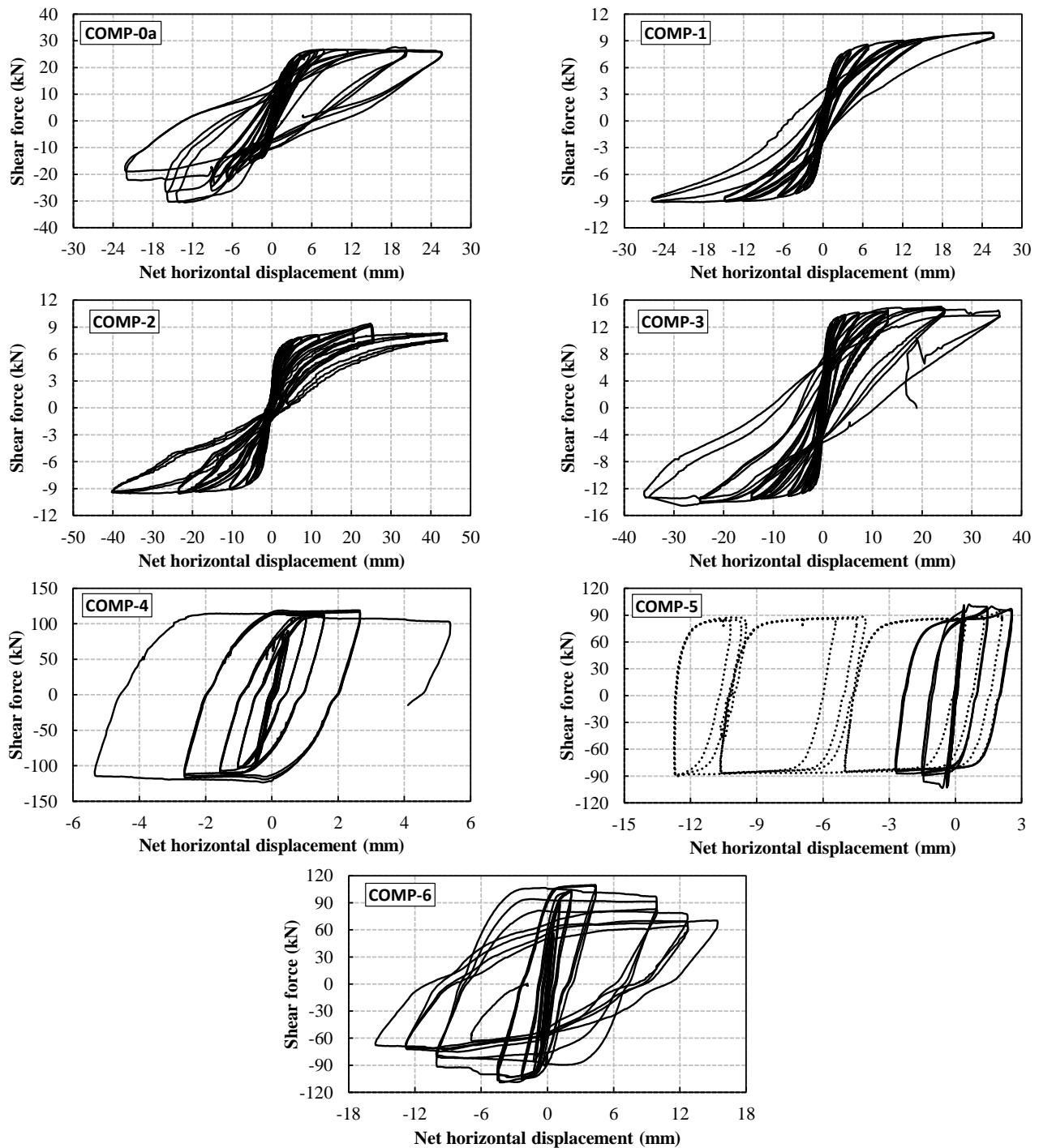


Fig. 3. Shear force vs Measured net displacement of the walls tested under in-plane loading.

The prevailing failure mode depended mainly on the shear ratio: flexure determined the failure of the short specimens, whereas shear failure occurred for the long specimens. Also the level of pre-compression affected the results: large overburdens determined toe crushing in the short specimens and defined the crack pattern (diagonal stair-stepped cracks instead of horizontal cracks) in the long specimen. The initial stiffness of the walls (measured as the secant stiffness between the extreme displacements of the first cycle in the force-displacement graph) were consistent with the properties listed in Section 2. The resistances and failure modes

were in line with the values predicted by codes and the literature (e.g. [20], [21]), except for sample COMP-1, whose resistance was lower than the predicted value. Specifically, the calcium silicate masonry showed remarkable compression crushing at toes (short specimens) or along the diagonal strut (long walls); this is consistent with the results of the compression tests performed at material level [1], which showed significant non-linearity from small compressive stresses. Finally, residual sliding accumulated cycle after cycle along the main stair-stepped cracks of the long specimens, so that the final crack opening was much larger than the maximum imposed top displacement; this phenomenon limited the maximum drift of the wall, even if the sliding mechanism is locally rather ductile.

A summary of the obtained results is reported in Table 3.

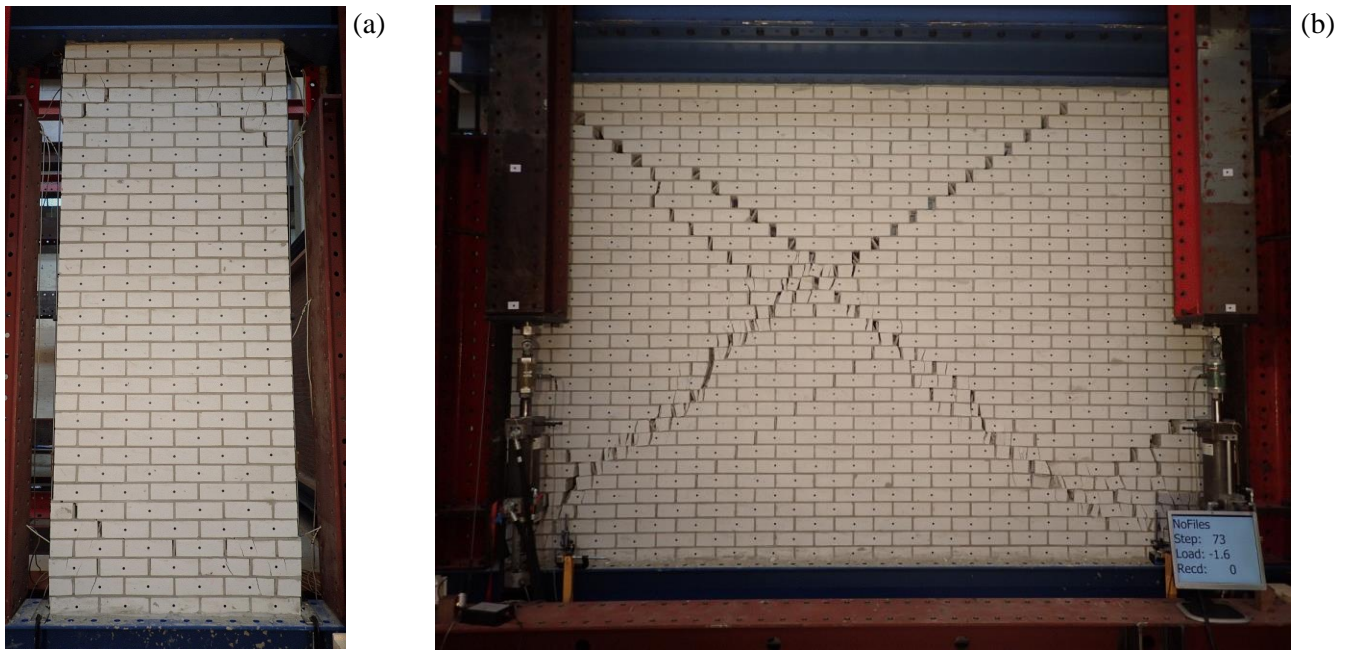


Fig. 4. Examples of the obtained crack patterns at the end of the tests: (a) short COMP-0a and (b) long COMP-6 specimens.

Table 3. Principal results of the performed in-plane tests

Specimen	BC	$\sigma_v$	$K_{in}$	$V^+$	$V^-$	Prevailing failure mode
		(MPa)	(kN/mm)	(kN)	(kN)	
COMP-0a	DC	0.7	25.8	27.7	-30.6	Combined (flexure with toe crushing, and sliding).
COMP-1	C	0.7	7.2	9.94	-9.11	Combined (flexure with toe crushing, and sliding).
COMP-2	C	0.5	7.7	9.40	-9.57	Combined (flexure and sliding).
COMP-3	DC	0.4	22.4	15.0	-14.2	Combined (flexure with toe crushing, and sliding).
COMP-4	DC	0.5	223	119	-123	Shear diagonal cracks along joints.
COMP-5	DC	0.3	288	102	-103	Sliding along the bottom mortar joint.
COMP-6	C	0.5	125	110	-109	Shear diagonal cracks along joints and toe crushing.

Where BC = boundary conditions; DC = double clamped wall; C = cantilever wall;  $\sigma_v$  = vertical pressure;  $K_{in}$  = initial stiffness (measured as the secant stiffness between the extreme displacements of the first cycle);  $V^+$ ,  $V^-$  = shear strength for positive and negative displacements, respectively.



## 4. Out-of-plane tests

### 4.1 Description of test set-up and test specimen

Five full-scale URM walls were built at the TU Delft testing Stevin laboratory and tested in the out-of-plane direction by applying cyclic loading using a system of airbags. Two different geometries of solid brick masonry walls were considered: specimens COMP-0b and COMP-7 were characterized by a high aspect ratio  $H/B = 1.9$  (2.75 m high and 1.44 m long) and tested in a one-way spanning configuration (hence they will hereinafter referred to as “one-way walls”); specimens COMP-10, COMP-11 and COMP-12 had a low aspect ratio  $H/B = 0.68$  (2.75 m high and 4 m long) and were tested in a two-way spanning configuration (hence they will hereinafter referred to as “two-way walls”). All the walls, except specimen COMP-10, were made of calcium silicate masonry; sample COMP-10 was composed of clay brick masonry. Sample COMP-12 contained a 1786 mm x 1630 mm window opening (positioned at 650 mm from the left side and 570 mm from the base) with a 2000 mm x 160 mm prefabricated concrete lintel above the opening; two piers (of dimensions 650 mm x 1630 mm and 1550 mm x 1630 mm) were identified at the side of the opening.

The frame set-up was designed in order to provide a uniform vertical pressure throughout four springs (two on each side, one on the front and one on the back), having each a stiffness of 50 kN/m. The top and bottom brick course of each specimen was glued to a steel beam with a high performance glue to prevent sliding shear failure and tension failure at the steel-masonry contact layer. The bottom steel beam was attached to cross-beams and connected to a steel frame anchored to the floor. The springs were guided by columns placed on the bottom beam and connected to the top beam by steel bars with a diameter of 12 mm. A load cell was placed in between the steel bars and the springs to control the compression force applied to the specimen.

The quasi-static tests were performed by employing a system of coupled airbags on both sides of the wall to apply a uniform pressure, as recommended by ASTM standards [22]. The airbags were contrasted by a timber reaction frame. The total load transferred to the reaction frame was measured by four load cells on each side, and the difference between the loads measured on both sides is the total net force acting on the wall. For specimens COMP-10 and COMP-11 four airbags were applied on each side of the wall. The two central airbags had dimensions of 500 mm x 2600 mm; the two lateral airbags had dimensions of 1400 mm x 2600 mm. For specimen COMP-12 the airbags were positioned in correspondence of the two piers only (one airbag of dimensions 1400 mm x 2600 mm and one of 500 mm x 2600 mm). For the one-way spanning walls only one outer airbag of dimensions 1400 mm x 2600 mm on each side was adopted.

The one-way spanning walls were supported at top and bottom; small finite out-of-plane rotational stiffness ( $C$ ) of the supports was obtained for sample COMP-0b, whereas larger stiffness were obtained for the other specimens, so that boundary conditions close to clamping were achieved. The two-way spanning samples were hinged on the vertical sides, by four steel rods welded on steel tubes of 120 mm x 80 mm x 6 mm; wood wedges were applied between the steel rods and the walls to prevent local damage of masonry and horizontal sliding.

A scheme of the employed test set-up (e.g. for the two-way spanning walls) is displayed in Fig. 5, and a summary of the main features of the tested specimens is reported in Table 4.

### 4.2 Testing procedure

In the preparation phase, the vertical load was applied by pre-stressing the four vertical springs. The total applied vertical load remained almost constant during the test, and only small variations depending on the vertical displacements were allowed.

During the test, a constant pressure was applied by the airbags on one side of the wall and a varying pressure by the airbags on the other side of the wall. The airbags on each side were inflated simultaneously to an equal pressure level. The control system allowed for a displacement controlled test: the pressure in the airbags on one side (active side) was adjusted to achieve the target deformation of a selected set-point; the pressure on the opposite side (passive side) remained constant during each test. Horizontal imposed displacements were applied

to the centre of the samples with cycles of increasing amplitude up to the 80% of the wall thickness; each cycle was composed of three runs, similarly to the in-plane tests. Fig. 6 shows the loading scheme adopted for the out-of-plane tests.

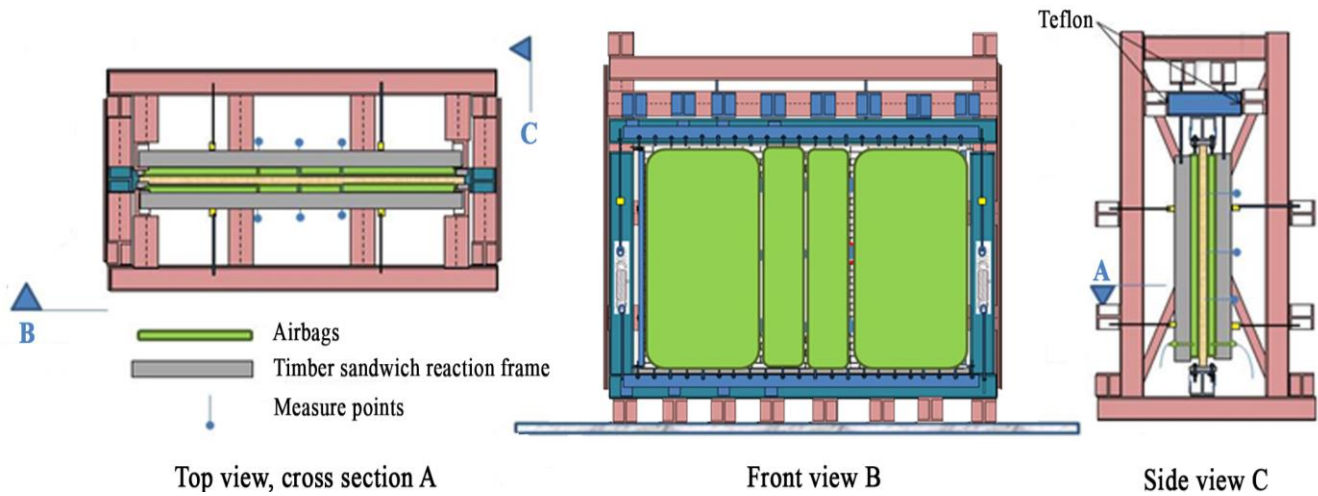


Fig. 5. Scheme of the test set-up used for the out-of-plane tests (e.g. two-way spanning walls).

Table 4. Dimension and features of the out-of-plane test samples

Sample name	Type of masonry	Type of out-of-plane test	Dimensions L (m) x H (m) x t (m)	Vertical pressure (MPa)	C (kNm/rad)
COMP-0b	Calcium Silicate	One-way	1437 x 2753 x 102	0.2	170
COMP-7	Calcium Silicate	One-way	1437 x 2750 x 102	0.2	2580
COMP-10	Clay	Two-way	4000 x 2751 x 102	0.05	2580
COMP-11	Calcium Silicate	Two-way	3874 x 2765 x 102	0.05	2580
COMP-12	Calcium Silicate	Two-way	3986 x 2764 x 102 (with opening)	0.05	2580

Where C is the rotational stiffness of the support as defined in the text.

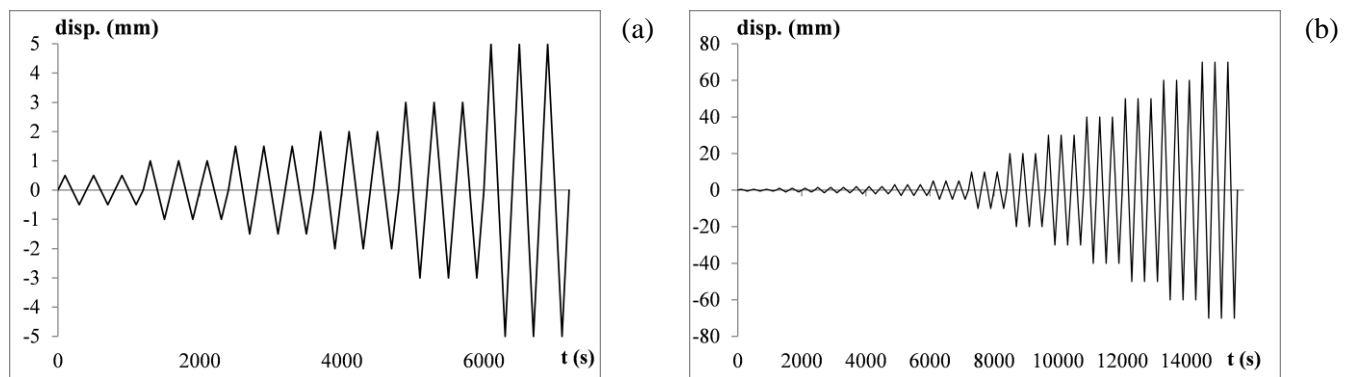


Fig. 6. Loading scheme for the out-of-plane tests: (a) detail of the first cycles and (b) complete scheme.



### 4.3 Overview on the experimental results

In this section, a short overview on the obtained results is presented in terms of capacity curves (Fig. 7) and crack patterns at the end of the performed tests (Fig. 8). The reported lateral force is the difference between the loads measured on the active side and on the passive side of the reaction frame (as described in Section 4.1-4.2).

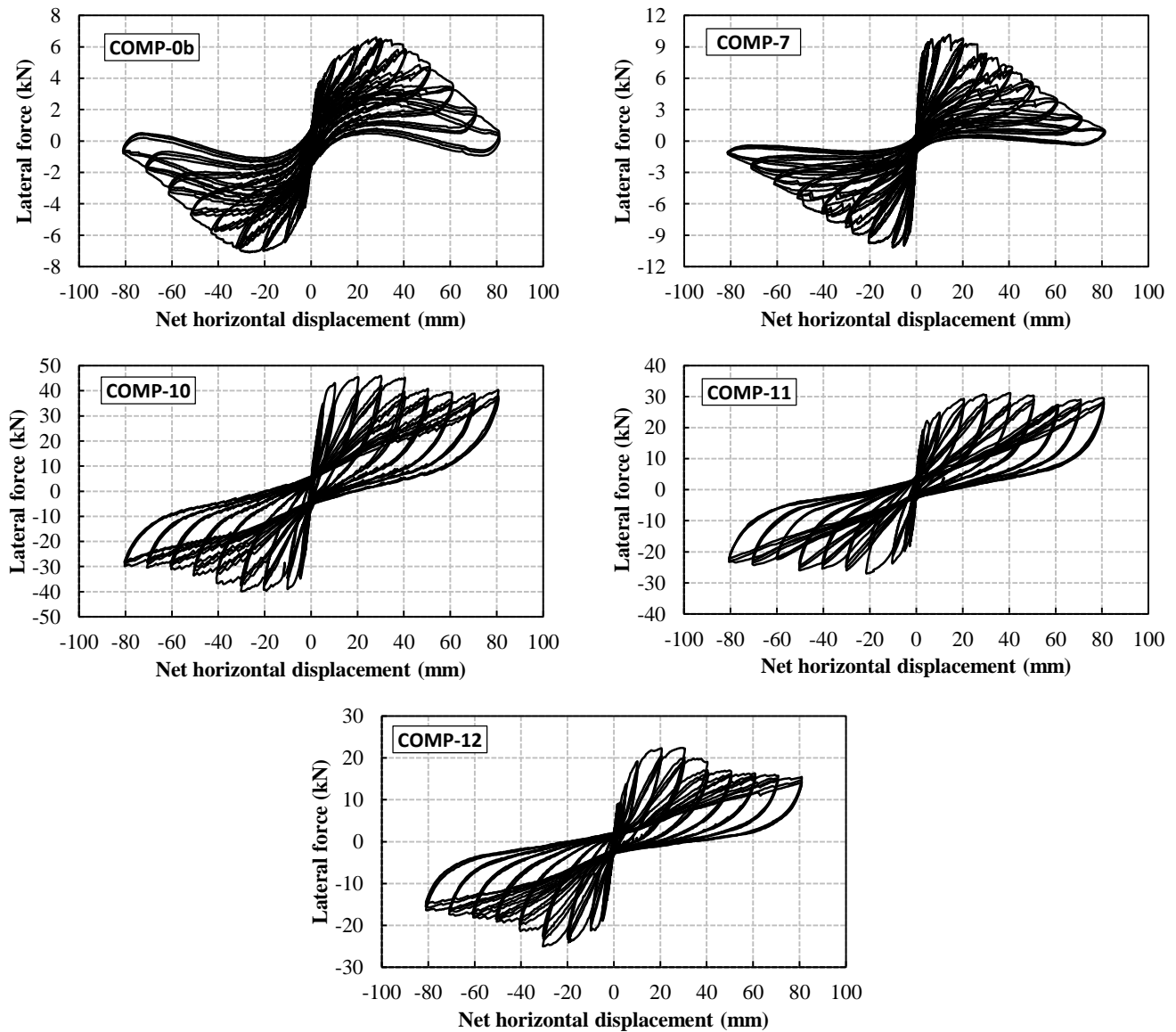


Fig. 7. Lateral force vs Measured net horizontal displacement of walls tested under out-of-plane loading.

In the described testing campaign, single wythe brick walls were tested; consequently, the failure mechanism was properly represented by the motion of rigid blocks connected along the cracks. The position of the cracks assumed a relevant role to determine the structural behaviour of the walls, which was mainly governed by geometry and boundary conditions rather than by the material properties.

In the one-way walls, cracks typically occurred at the wall base, at an intermediate height of about 0.5H above the wall base (spread on multiple mortar joints), and at the top of the wall. The different rotational stiffness of the supports determined remarkable differences in terms of initial stiffness and lateral resistance

between samples COMP-0b and COMP-7. The maximum resistance ( $F_H^\pm$ ) was in line with analytical computations based on the yield line analogy, often proposed in the literature (e.g. [16]). The post-peak behaviour showed that the walls were able to sustain out-of-plane displacements almost equal to the wall thickness; zero residual resistance was achieved at approximately 80% of the thickness of the walls.

The two-way walls without openings presented a crack pattern characterised by diagonal cracking from the wall edges to the centre of the panel, and horizontal cracks at the wall base, at an intermediate height, and at the top of the wall (Fig. 8a). The lateral resistance calculated in terms of applied pressure (that could be obtained by dividing the lateral force by the wall area) was similar to that of the one-way walls; however, no significant softening was detected after the peak for large displacements, giving a residual resistance for displacements of 80% of the wall thickness equals to 80-90% of the maximum load. A significant energy dissipation for large displacement cycles was measured.

In the two-way wall with an opening, cracks localised mainly in the long pier (Fig. 8b). The concrete lintel remained intact during the test (minor cracks could be observed at the supports) and maintained straight the upper spandrel; on the contrary, the bottom spandrel was heavily horizontally deformed, and cracks were observed. The short pier experienced significantly smaller displacements (approximately 10% of those of the long pier) and, consequently, was barely damaged. Similar to the other two-way walls without openings, specimen COMP-12 showed a stable post-peak behaviour (the residual resistance for displacements of 80% of the wall thickness was equal to approximately 60% of the maximum load).

A summary of the obtained results is reported in Table 5.

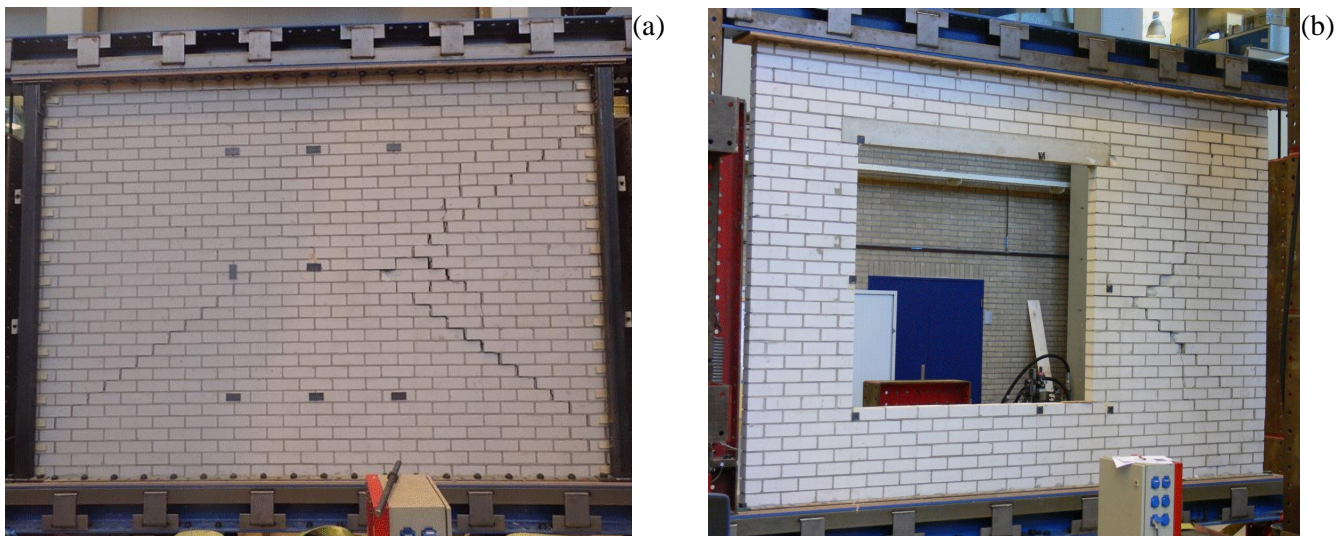


Fig. 8. Examples of the obtained crack patterns at the end of the tests: (a) COMP-11 and (b) COMP-12 samples.

Table 5. Principal results of the performed out-of-plane tests

Specimen	Type of test	$\sigma_v$	$K_{in}$	$F_H^+$	$F_H^-$
		(MPa)	(kN/mm)	(kN)	(kN)
COMP-0b	One way	0.2	1.65	6.61	-7.09
COMP-7	One way	0.2	4.50	10.15	-10.16
COMP-10	Two way	0.05	12.88	45.91	-39.88
COMP-11	Two way	0.05	12.00	31.16	-27.00
COMP-12	Two way with opening	0.05	6.5	22.40	-25.00

Where:  $\sigma_v$  = vertical pressure;  $K_{in}$  = initial stiffness in terms of lateral force (measured as the secant stiffness between the extreme displacements of each cycle);  $F_H^+$ ,  $F_H^-$  = lateral resistance for positive and negative displacements, respectively.



## 5. Concluding remarks

Due to the increasing induced seismic activity in the region of Groningen, the assessment of unreinforced masonry structures has acquired more and more relevance also in the Netherlands. A recent experimental campaign performed at the Delft University of Technology 2015 consisted of experimental tests carried out at various scales from the material level to the behaviour of a full-scale two-story high building subjected to cyclic pushover test.

In this framework, the paper presents an overview on the results of the cyclic tests performed on seven full size walls under in-plane loading, and on five full size walls under out-of-plane loading.

The outcomes of the in-plane tests were generally in line with tests on other masonry typologies described in the literature. The prevailing failure mode depended mainly on the shear ratio of the walls: flexure and toe crushing governed the failure for high shear ratios, whereas shear failure occurred for low shear ratios. Besides, also the level of vertical pre-compression had an influence on the results. Also resistance and ductility were governed by the geometry of the walls: long walls were able to withstand large loads, but they showed a rather limited ductility; short walls can bear much smaller forces but they are able to sustain larger displacements. With respect to other masonry typologies, specific attention should be devoted to the significant compressive crushing at toes (short walls) and along the diagonal struts (long walls) and to the large residual sliding observed in long walls, which determined at the end of the test cracks of the head joints much larger than the maximum imposed drift. Further investigations will be required to overcome setup limitations and test the specimens up to complete failure.

The results of the out-of-plane tests showed that the out-of-plane failure mechanism is mainly governed by the geometry and boundary conditions of the walls; besides, the good quality of the tested masonry allowed the walls to withstand large displacements, almost equal to the thickness of the walls. Specifically, the different post-peak behaviour detected for walls tested on one-way (i.e. when walls are supported only at top and bottom) and the two-way spanning (i.e. when walls are supported also on the side) is of high relevance, having shown the latter significantly greater residual resistance for large displacements. Even the presence of an opening strongly modified the peak resistance and crack pattern of the wall, but did not prevent a stable post-peak behaviour, with a large final residual resistance.

In conclusion, the performed experimental tests provided several benchmarks for characterising the in-plane and the out-of-plane behaviour of Dutch masonry walls. The obtained results can be used to validate numerical and analytical models, with particular devotion to the seismic assessment terraced houses built during 1960-1980 in the north of the Netherlands and nowadays subjected to induced seismicity.

## 6. Acknowledgements

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