Out-of-plane tests on replicated masonry walls

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OUT-OF-PLANE TESTS ON REPLICATED MASONRY WALLS

Authors: Geert J.P. Ravenshorst, Francesco Messali


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Table of Contents

1 Description of test set-up and test specimen ............................................................. 3
  1.1 General overview ........................................................................................................ 3
  1.2 Boundary conditions ................................................................................................. 6
      1.2.1 Boundary conditions at top and bottom wall ends .............................................. 6
      1.2.2 Vertical springs .................................................................................................. 8
      1.2.3 Supports on the sides ......................................................................................... 8
  1.3 Description of the measurement system .................................................................... 9
  1.4 Load application ....................................................................................................... 12
  1.5 Loading protocol ...................................................................................................... 12

2 Primary results ............................................................................................................. 14

3 Crack patterns and remarks for every single tests ....................................................... 21
  3.1 TUD_COMP-0b ....................................................................................................... 21
  3.2 TUD-COMP-7 ......................................................................................................... 24
  3.3 TUD_COMP-10 ....................................................................................................... 28
  3.4 TUD_COMP-11 ....................................................................................................... 32
  3.5 TUD_COMP-12 ....................................................................................................... 36

4 Conclusions .................................................................................................................. 44

References ....................................................................................................................... 46

APPENDIX A - Comparison with values proposed by the Eurocodes .............................. 47
  A.1 One way out-of-plane .............................................................................................. 47
  A.2 Two way out-of-plane ............................................................................................. 47
  A.3 One-way out-of-plane: TUD-COMP-0b and TUD-COMP-7 ................................ 48
  A.4 Two way out-of-plane: TUD-COMP-10 and TUD-COMP-11 ............................... 49
  A.5 Comparison between the code predictions and the measured resistances .......... 49

APPENDIX B - Predictions based on the yield line analogy .......................................... 50
  B.1 One-way out-of-plane test ....................................................................................... 50
  B.2 Two-way out-of-plane test ..................................................................................... 50
  B.3 Comparison between the analytical predictions and the measured resistances .... 51
1 Description of test set-up and test specimen

1.1 General overview

The experimental set-up for the out-of-plane cyclic tests was designed making use of the steel-frame assembling system at the TU Delft. To apply uniform horizontal loads a system of coupled airbags was used on both sides of the tested walls. The airbags put themselves off from a timber reaction frame. Load cells on the timber reaction frames on both sides provided the activated loads on both sides. The difference between the loads measured on both sides is the net force taken up by the wall.

A system was developed that allowed for a displacement controlled test. A set-point for the deformation is given and the pressure in the airbags is adjusted to achieve the desired deformation. During the test most of the walls were not visible, so the crack pattern had to be visually examined after the test.

Two types of specimen were tested, short walls (1.4 m in length) that were tested one way out-of-plane, and long walls (4 m in length) that were tested two way out-of-plane. The test specimen were glued on wooden strips with “Sikadur 30” that were bolted to a bottom steel beam. The same procedure was followed for the top beam. The top beam and bottom beam were connected by 4 springs (2 on each side, one on the front and one on the back) which a spring stiffness of 50 kN/m each. The springs were guided by columns placed on the bottom beam. The springs were connected to the top and bottom beam by steel bars with a diameter of 12 mm. A load cell was placed between the steel bars and the springs to measure the compression force that was applied to the specimen.

![Figure 1. Graphic representation of the test specimens used for the out-of-plane tests: short (a) and long (b) walls.](image)

A scheme of the preparation of the short and the long walls before they were positioned in the test is displayed in Figure 1a and b, respectively.

A summary of the main features of the tested specimens is reported in Table 1. Specimen TUD-COMP-0b was used to test the system and determine the measures necessary to achieve as much out-of-plane clamping as possible for the boundary support at the top and bottom of the wall.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Dimension</th>
<th>Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUD-COMP-0b</td>
<td>1.4 m x 2.4 m</td>
<td>Attached to wooden strips with “Sikadur 30”</td>
</tr>
<tr>
<td>TUD-COMP-0a</td>
<td>4.0 m x 2.4 m</td>
<td>Attached to wooden strips with “Sikadur 30”</td>
</tr>
</tbody>
</table>

Table 1. Dimension and features of the test samples.
<table>
<thead>
<tr>
<th>Sample name</th>
<th>Type of masonry</th>
<th>Type of Test</th>
<th>Dimensions Length x height (mm)</th>
<th>Vertical pressure (MPa)</th>
<th>Test date</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUD_COMP-0b</td>
<td>CS</td>
<td>One way OOP</td>
<td>1437 x 2753</td>
<td>0.2</td>
<td>16-7-2015</td>
</tr>
<tr>
<td>TUD_COMP-7</td>
<td>CS</td>
<td>One way OOP</td>
<td>1437 x 2750</td>
<td>0.2</td>
<td>02-9-2015</td>
</tr>
<tr>
<td>TUD_COMP-10</td>
<td>Clay</td>
<td>Two way OOP</td>
<td>4000 x 2751</td>
<td>0.05</td>
<td>20-10-2015</td>
</tr>
<tr>
<td>TUD_COMP-11</td>
<td>CS</td>
<td>Two way OOP</td>
<td>3874 x 2765</td>
<td>0.05</td>
<td>29-9-2015</td>
</tr>
<tr>
<td>TUD_COMP-12</td>
<td>CS</td>
<td>Two way OOP with opening</td>
<td>3986 x 2764</td>
<td>0.05</td>
<td>17-12-2015</td>
</tr>
</tbody>
</table>

Figure 2 shows the test set-up of the sample TUD-COMP-0b. Figure 3 shows the test set-up of the sample TUD-COMP-7. Figure 4 shows the test set-up of the samples TUD-COMP-10, TUD-COMP-11 and TUD_COMP-12 that were tested two way out-of-plane.

Figure 2. Scheme of the test set-up used for the out-of-plane test on short wall TUD-COMP-0b with unstiffened clamping boundary conditions at the top and the bottom.
Figure 3. Scheme of the test set-up used for the out-of-plane test on short wall TUD-COMP-7 with stiffened clamping boundary conditions at the top and the bottom.

Figure 4. Scheme of the test set-up used for the out-of-plane tests on long walls TUD-COMP-10, TUD_COMP-11 and TUD-COMP-12 with stiffened clamping boundary conditions at top and bottom and hinges at the sides.
The position of the airbags is given in Figure 5.
The dimensions of the airbags are (airbag configuration on both sides):
- The two centre airbags have a dimension of width x height of 500 mm x 2600 mm
- The two outer airbags have a dimension of width x height of 1400 mm x 2600 mm

For the short walls only one outer airbag of 1400 mm x 2600 mm on each side is used. For TUD-COMP-12 on each side two airbags are used: on airbag of 1400 mm x 2600 mm and one airbag of 500 mm x 2600 mm.

1.2 Boundary conditions

1.2.1 Boundary conditions at top and bottom wall ends

The boundary conditions applied in the different tests are summarised in Figure 6.

![Figure 6. Boundary conditions of TUD-COMP-0b (a), TUD-COMP-7 (b) and TUD-COMP-10, TUD-COMP-11 and TUD-COMP-12 (all c). Explanation of boundary conditions (d) ](image)

The mechanical scheme in the vertical cross section of the wall is given in Figure 7a. In Figure 7b and 7c the details of the bottom steel beam with the crosswise foundation beams are given.
Given the real supports (Figure 7b, c), the masonry walls cannot be regarded as fully double-clamped; hence, a rotational stiffness $C$ out of the plane of the wall can be associated. The rotational stiffness associated to detail (b) is governed by the bending of the web of the steel HEB 300 beam (in blue) on which the plywood strips (on which the masonry is glued on) are bolted.

In detail (c) the bending of the web is prevented by adding steel plates and steel angles. This provision increases the rotational stiffness $C$ significantly, but still a perfect clamping cannot be achieved.

To determine the value of $C$, the following procedure was followed.

- the horizontal deflections were measured at three positions over the height of the wall (points p1, p2, p3);
- The deflection at midspan (p2) is compared with the differential deflection between the outer measuring points and midspan [(p2-(p1+p3)/2);
- If the clamping moment at the top and bottom of the wall is expressed as $M_c = \alpha q l^2$, the factor $\alpha$ can be determined according to structural mechanics equations (the Young’s modulus is assumed equal to 3500 N/mm$^2$) with use of the deflection at midspan and the differential deflection;
- Knowing factor $\alpha$, the rotational stiffness can be calculated according to structural mechanics equations.

The following values were found:

- For detail (7b) (TUD_COMP-0b): $C = 170$ kNm/rad. The associated $\alpha$ for OOP is 0.029 (1/35).
- For detail (7c) (TUD_COMP-7-12): $C = 2580$ kNm/rad. The associated $\alpha$ for OOP is 0.074 (1/13.5).

It can be noted that, even if detail (7c) still presents a finite rotational stiffness, the rotational stiffness is increased by a multiplication factor of 15.

The determined value for $C$ can be verified by measurements of the rotation of the top flange of the bottom support beam.

In Figure 8 the measured lateral q-load in the elastic phase is plotted against the measured rotations (in radians) for TUD-COMP-7. A comparison with the theoretical trend line expected for a value $C = 2580$ kNm/rad is provided. The theoretical line is in good agreement with the measured trend.
The same configuration adopted for TUD-COMP-7 was used for every two-way out-of-plane test; therefore, the value \( C = 2580 \text{ kNm/rad} \) can be used for TUD-COMP-10, TUD-COMP-11 and TUD-COMP-12 also.

### 1.2.2 Vertical springs

Each vertical spring drawn in Figure 6 represents two springs with a stiffness of 50 kN/m. They are connected to the bottom and top HEB 300 beams by steel rods with a diameter of 12 mm.

### 1.2.3 Supports on the sides

For the one way out-of-plane short walls there were no horizontal supports on the vertical sides of the walls. For the two way out of plane long walls the vertical sides of the walls were horizontally supported by hinges (Figure 9). Steel tubes of 120 mm x 80 mm x 6 mm on both sides provide the horizontal support in and out-of the plane of the wall. In the out-of-plane direction (weak direction of the steel tubes) the steel tubes spans over 2 in-between supports making the span length 1/3 of the wall height. In the in-plane direction (strong direction of the steel tubes) the span of the steel tubes is the wall height. On the edges of steel tubes steel rods of 6 mm diameter are welded over the entire height. Between the 6 mm steel rod and the masonry wall wooden wedges are applied to prevent local damage to the masonry (Figure 9a, b). The wooden wedges also prevent horizontal sliding of the masonry from the steel tubes.
1.3 Description of the measurement system

The objective of the measurement recordings during the test were:
- to record the horizontal deformations of the wall out-of-the plane;
- to record the applied forces during the test;
- to produce time-displacement diagrams, time-forces diagrams and force-displacement diagrams.
- to visually examine the cracking patterns after the test;

In Figure 10 an overview of the measuring points are given (In figure 10 the force measurements on the north side are shown, in the table the force measurements on the south side are also given, they are mirrored in position of the north side). In table 2 they are further explained.

In Figure 11 and Figure 12 the positions for the horizontal measurements are given for the short walls and the long walls respectively. For the short walls there are 6 horizontal measure points, and for the long walls 9 horizontal measure points.

In this report the results are presented in graphs showing the measured net horizontal force \( F_{H,\text{net}} \) applied by the airbags on the walls against the horizontal deformations at midspan:

\[
F_{H,\text{net}} = \sum F_{N,1-4} - \sum F_{Z,1-4}
\]  

The horizontal displacement at midspan for the short walls is \( \Delta h = (\rho_2 + \rho_5)/2 \).

The horizontal displacement at midspan for the long walls is \( \Delta h = \rho_5 \).

The second way of presenting graphs is by showing the lateral pressure against the horizontal deformations at midspan. The lateral pressure is obtained by dividing the computed lateral force by the lateral area \( A \) of the wall (i.e. \( A = L \times H \)); the area of the spandrels above and below the opening in TUD-COMP-12 (which is not covered by the airbags) is excluded.

A specific configuration is adopted for sample TUD_Comp-12 (see section 3.5).
Figure 10. Overview of the measuring points for the short specimens for the in-plane tests at TU Delft.

Table 2. Overview of the measuring points and sensor types for the in-plane tests.

<table>
<thead>
<tr>
<th>No.</th>
<th>Description</th>
<th>Sensor Type</th>
<th>Stroke (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS1, FS3</td>
<td>Vertical force in springs on North side. Capacity 10 kN/load cell</td>
<td>Load cell</td>
<td>-</td>
</tr>
<tr>
<td>FS2, FS4</td>
<td>Vertical force in springs on South side. Capacity 10 kN/load cell</td>
<td>Load cell</td>
<td>-</td>
</tr>
<tr>
<td>FN1-FN4</td>
<td>Horizontal forces on reaction frame on North side. Capacity 25 kN/ load cell</td>
<td>Load cell</td>
<td>-</td>
</tr>
<tr>
<td>FS1-FS4</td>
<td>Horizontal forces on reaction frame on south side side. Capacity 25 kN/ load cell</td>
<td>Load cell</td>
<td>-</td>
</tr>
<tr>
<td>P1-p9</td>
<td>Horizontal displacement of the brick wall.</td>
<td>Linear potentiometer</td>
<td>+/-100</td>
</tr>
</tbody>
</table>

The horizontal displacements were measured against the external stiff steel frame. The linear potentiometers made no contact with the timber reaction frame. At the position of the linear potentiometers holes were made in the timber reaction frame.
Figure 11. Overview of the points measuring the horizontal deformations out-of-the plane for the short walls.

Figure 12. Overview of the measuring points measuring the horizontal deformations out-of-the plane for the long specimens.
1.4 Load application

The vertical load is applied by prestressing the four vertical springs. The principle for the application of the horizontal load is explained for the long walls in Figure 13. For the short walls the application principle is the same. The airbags on the south side and north side are pumped up to a certain initial pressure. Then the pressure on the south side is kept constant for the airbags on the south side through the whole test. Then the pressure on the north side is varied in such a way that the displacement protocol (for the long walls p5) is followed. The initial pressure is chosen at such a level that the pressure on the north side never becomes negative. The airbags put themselves off against the timber reaction frames at both sides. The forces acting on the timber reaction frame (which are the forces from the airbags on the masonry wall) are measured on both north and south sides.

![Diagram showing load application](image)

Figure 13. Principle for the horizontal load application

The airbags provide an uniform surface pressure to all sides. Therefore, the deflection of the timber reaction frame has no effect on the pressure on the wall, when this deflection is below the maximum expansion of the airbags. The timber reaction frame was designed to have a maximum deflection lower than 10 mm, far below the maximum expansion of the airbags. As explained before, the deflection of the masonry wall is not measured relative to the timber reaction frame, but relative to the stiff external steel frame. The linear potentiometers are guided through holes in the timber reaction frame, without making contact with it. The exact contact area between the airbags and the wall can hardly be prior evaluated; because of this, the pressure in the airbags is not a good measure for the load applied on the walls. Therefore, the load is measured directly on the timber reaction frame by 4 load cells that take up the reaction forces (the load applied to the wall is the same load as the load applied on the timber reaction frame).

Comparisons between the measured forces and the applied pressure showed that the effective area of the airbags (compared with when they were flat) varied between 86% for the short walls and 76% for the long walls. This is in line with values found in literature; for instance, Griffith [3] reports values between 75% and 80%. Further discussion regarding the effective contact area is presented in section 2.

1.5 Loading protocol

After the initial pressure was established the test was performed in displacement control. Every deformation was applied three times in the positive and negative direction. The deformations were increased in the first
stages with an increment of 0.5 mm and in the last stages with an increment of 10 mm. The displacement at midspan was controlled. The measured displacement at midspan was compared real-time with the target displacement and, consequently, the air pressure on the north side was increased or reduced. Because the pumping system pumped approximately every second to adjust the pressure, a small time-gap was experienced. In Figure 14 the target midspan displacement and the measured midspan displacements are plotted together over time for TUD-COMP-0b (the difference in figure 14 is difficult visible because they practically overlap). The difference between target displacements and measured, plotted in Figure 15 shows that the measured midspan displacement approximates the target displacement very well; however, the flaws in the load-displacements diagrams (the fact that the graphs do not give a perfect “smooth” connection between the data points) can be explained by the fact that the difference in figure 15 is not completely zero.

Figure 14. Target displacement and measured displacement at midspan over time for TUD-COMP-0b

Figure 15. Difference between target displacement and measured displacement at midspan over time for TUD-COMP-0b
2 Primary results

The initial elastic stiffness of the wall, measured as the secant stiffness between the extreme displacements of the first cycle, and the out-of-plane resistance of the wall are considered primary results of the performed tests. Both the values are evaluated in terms of applied lateral forces (\(K_{0h}, F_{h}^+\) and \(F_{h}^-\) for the stiffness and the positive and negative resistances, respectively) and pressures (\(k_{0h}, p^+\) and \(p^-\) for the stiffness and the positive and negative resistances, respectively).

The primary results recorded after each test are reported in Table 3.

The lateral force (\(F_h\)) is evaluated according to equation (1).

The lateral pressure is obtained by dividing the computed lateral force by the lateral area \(A\) of the wall (i.e. \(A = L \times H\)); the area of the spandrels in TUD-COMP-12 above and below the opening (which is not covered by the airbags) is excluded. The net horizontal displacement (\(\Delta h\)) is evaluated as the average value between the displacements recorded by transducers \(p2\) and \(p5\) for the short walls, and directly as the value recorded by transducers \(p5\) for the long walls (as described in section 1.3).

Both the lateral forces and the displacements are assumed to be positive when applied from the south to the north side of the wall, as described in section 1.3.

The lateral force vs the measured mid-height displacement of the wall is plotted in Figure 16 for each test performed. Both the original cyclic curves (a) and the corresponding backbone (b) curves are plotted. The backbone curves are obtained by connecting the shear loads at the extreme displacements of each cycle.

Similarly, Figure 17 shows the lateral pressure vs the measured mid-height displacement of the walls.

Figure 18 and Figure 19 show a comparison between the backbone curves of all the tested walls in terms of applied lateral forces and pressures, respectively. Given the different dimensions of the walls, considering the lateral pressures provide a more direct comparison between short and long walls.

Figure 20 and Figure 21 provide a comparison between the backbone curves of the one-way and two-way tests, respectively, in terms of lateral pressures.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Type of test</th>
<th>(\sigma_v)</th>
<th>(K_{0h})</th>
<th>(F_{h}^+)</th>
<th>(F_{h}^-)</th>
<th>(k_{0h})</th>
<th>(p^+)</th>
<th>(p^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUD_COMP-0b(^1)</td>
<td>One way</td>
<td>0.2</td>
<td>1.65(^1)</td>
<td>6.61(^1)</td>
<td>-7.09(^1)</td>
<td>0.42(^1)</td>
<td>1.67(^1)</td>
<td>-1.79(^1)</td>
</tr>
<tr>
<td>TUD_COMP-7</td>
<td>One way</td>
<td>0.2</td>
<td>4.50</td>
<td>10.15</td>
<td>-10.16</td>
<td>1.13</td>
<td>2.56</td>
<td>-2.56</td>
</tr>
<tr>
<td>TUD_COMP-10</td>
<td>Two way</td>
<td>0.05</td>
<td>12.88</td>
<td>45.91</td>
<td>-39.88</td>
<td>1.17</td>
<td>4.16</td>
<td>-3.61</td>
</tr>
<tr>
<td>TUD_COMP-11</td>
<td>Two way</td>
<td>0.05</td>
<td>12.00</td>
<td>31.16</td>
<td>-27.00</td>
<td>1.09</td>
<td>2.82</td>
<td>-2.45</td>
</tr>
<tr>
<td>TUD_COMP-12</td>
<td>Two way with opening</td>
<td>0.05</td>
<td>6.5(^2)</td>
<td>22.40</td>
<td>-25.00</td>
<td>1.07(^2)</td>
<td>3.67</td>
<td>-4.10</td>
</tr>
</tbody>
</table>

Where: \(K_{0h}\) = initial stiffness in terms of lateral force (measured as the secant stiffness between the extreme displacements of each cycle); \(V^+\), \(V^-\) = lateral force for positive and negative displacements, respectively; \(k_{0h}\) = initial stiffness in terms of lateral pressure; \(p^+, p^-\) = lateral pressure for positive and negative displacements, respectively.

\(^1\) both stiffness and resistance of sample TUD_COMP-0b are affected by the configuration of the frame set-up adopted for this specimen.

\(^2\) the presented stiffness is evaluated in the measurement point p4, which detected the maximum out-of-plane displacement of the wall.
TU Delft – Out-of-plane tests

(a) TUD_COMP-0b
(b) TUD_COMP-0b

(a) TUD_COMP-7
(b) TUD_COMP-7

(a) TUD_COMP-10
(b) TUD_COMP-10

Lateral force (kN)
Mid-height displacement (mm)
Net horizontal displacement (mm)
Figure 16. Lateral force vs Measured mid-height displacement of the wall. Both total (a) and backbone (b) curves are plotted.
Figure 17. Lateral pressure vs Measured mid-height displacement of the wall. Both total (a) and backbone (b) curves are plotted.

Figure 18. Comparison between the backbone curves of the Lateral force vs Measured mid-height displacement of the walls (TUD_COMP-0b, TUD_COMP-7, TUD_COMP-10, TUD_COMP-11, TUD_COMP-12).
Figure 19. Comparison between the backbone curves of the Lateral pressure vs Measured mid-height displacement of the walls (TUD_COMP-0b, TUD_COMP-7, TUD_COMP-10, TUD_COMP-11, TUD_COMP-12).

Figure 20. Comparison between the backbone curves of the Lateral force vs Measured mid-height displacement of the walls, for one way tests only (TUD_COMP-0b, TUD_COMP-7).
Figure 16 to Figure 21 show small asymmetry between the positive and negative sides of the force-displacement curves; this is more noticeable for the two-way tests during the last cycles, where, on the negative side softening is more enhanced than on the positive side.

For positive displacements the active side pushes, whereas the passive side works as a contrast; the opposite for negative displacements. In the latter case, the pressure in the contrasting airbags is almost zero; therefore, the force-displacement curves for negative displacements can be considered representative of the out-of-plane behaviour of a wall loaded on a single side, and the difference observed in the post-peak phase for positive displacements can be related to the confining pressure provided by the airbags on the passive side. Nevertheless, the adopted loading system (which varies the pressure on the airbags on one side only) proved to be able to prevent any possible uncontrolled collapse of a wall during the tests, and allowed to provide a stable load application (as discussed in section 1.5).

The pressure on the passive side can be further analysed. The effective area is defined as the ratio between the external pressure measured from the contrast frame and the airbag internal pressure. The effective area increases for positive displacements and decreases for negative ones (Figure 22). The contact surface increases when a larger pressure on both sides is recorded. This feature is common to every test, but more evident for two-way bending tests, and it generates small fluctuations in the reading of the pressure on the passive side of increasing amplitude for large displacements.
3  Crack patterns and remarks for every single tests

The following sections offer an accurate description of the out-of-plane behaviour of each single performed test; additional readings regarding the recorded displacement of every measuring point and the applied pressure on each single side of the wall are provided.

Pictures documenting the state of the samples at the end of the test are also presented. In general, photographs could not be taken during the test due to the presence of the air-bags and timber reaction frames. During the executions of one-way bending tests photographs could be shot from one lateral side (e.g. Figure 26), whereas for the two-way bending tests even that view was precluded by the presence of the lateral support columns. However, the profiles provided by the displacements of the measurement points suggest that, after cracking, the crack pattern did not change significantly throughout the test.

3.1  TUD_COMP-0b

Specimen TUD_COMP-0b was tested according to a one-way bending procedure.

The specimen was glued at the top and bottom row of bricks to a plywood layer that was fixed to the top and bottom beam, as shown in Figure 23.

During the test, the bonding of this connection remained intact. However, the stiffness of the wall in the test set-up was lower than that expected for a double clamped wall because of the rotation of the web of both the top and bottom beam, caused by the support reactions of the walls (both lateral force and clamping moment) that had to be transferred through the web to the flange that was connected to the crossbeams.

Based on rotation measurements, the rotation stiffness at the top and bottom support is estimated equal to 170 kNm/rad.

Before the test, a constant vertical load of 30 kN was applied at the top of the wall. This load represents a vertical pressure of 0.2 MPa.

During cycles 1 and 2 (up to ± 1.5 mm), no cracks were observed and the specimen behaved linear. In the following cycles (3-7, up to ± 20 mm), cracks were observed to form near the top and bottom clamped supports, as can be seen in Figure 24a and b.

In cycle 8, up to ± 30 mm, cracks also developed near the mid-height as can be observed in Figure 25a, and the deflection of the wall became visible, as shown in Figure 25b.

During the last cycle (± 80 mm), the cracks near the supports and at mid span became clearly visible when these opened up, as can be seen in Figure 26a,b,c. Besides, also the deflection of the wall appeared evident (Figure 26d). In the force-displacement graph (Figure 16 in section 2), a negative loading was recorded. Indeed, the crack in the middle of the beam was a few bricks higher than at mid-height (from which the displacement was controlled); the displacement at the crack was therefore higher, close to the critical displacement, where snap-through could occur. This is however prevented by the airbag, which had to increase the pressure to maintain the stability of the wall and keep it at the target displacement. This has no physical meaning for the wall, which actually failed when the load was at zero.

Inspection of the sample after the test revealed that the cracks were horizontal along the whole mortar bed joints (Figure 27a). Furthermore, it became clear the mortar in cracked joints also crushed (Figure 27b).

Figure 28 represents the displacement of the couple of control points P1-P4, P2-P5, P3-P6: the ratio between the maximum displacement of the central points (P2-P5) and the other points remains approximately constant throughout the whole test after that cracking occurs. This suggests that the crack pattern remained the same during the test and is properly described by the pictures taken at the end stage.

Figure 29 shows the forces recorded on the timber reaction frames (which are on both the active and passive side). Besides the limited change of airbag pressure at varying the imposed displacement discussed in section 2, the fluctuation of the reaction force on the passive side for displacements larger than 30 mm indicates that the control of the post-peak stage becomes more difficult. That means that for displacements larger than 30 mm the calculated net forces might deviate from 5% at 30mm to 30% at 80 mm compared to when a perfect control would have been applied.

Since the test experienced the rotation of the supports, which affects both initial stiffness and resistance (as discussed in section 3.2), this has to be taken into account in numerical simulations.
Figure 23. Clamped connection at the top and bottom of the specimen

Figure 24. First cracks near the bottom (a) and top (b) supports, after cycle 3.

Figure 25. State of the specimen during cycle 8 (± 30 mm): cracks near mid-height.
Figure 26. Cracks (a,b,c) and deflection (d) of the specimen during cycle 8 (±80 mm).

Figure 27. Horizontal crack and crushed mortar in the bed joints at mid-height (a) and at the bottom (b) of the wall at the end of the test.
Figure 28. Displacement of the control points P1, P2, P3, P4, P5, P6 for sample TUD_COMP-0b.

Figure 29. Measured internal pressure of the airbags on the active and passive side of TUD_COMP-0b.

3.2 TUD-COMP-7
Specimen TUD_COMP-7 was tested according to a one-way bending procedure. With respect to specimen TUD_COMP-0b the supporting frame was stiffened in order to avoid any significant rotation at the base of the wall, and to provide an efficient clamping to the wall top and bottom ends. Figure 30 shows the stiffened beams at the bottom (a) and the top (b) of the wall.
The top and bottom row of bricks were glued to a plywood layer that was fixed to the top and bottom beam. During the test, the bonding of this connection remained intact. The initial stiffness of the specimen was 2.7 larger than the stiffness measured for TUD_COMP-0, proving the efficiency of the adopted stiffening system. Before the test, a constant vertical load of 30 kN was applied at the top of the wall. This load represents a vertical pressure of 0.2 MPa. The specimen denoted an elastic behaviour for the first four cycles, up to a displacement of 2 mm and a force of 8 kN. First cracks appeared at the top and bottom mortar layer (Figure 31a, b), and at a second stage at mid-span (Figure 31c), in cycles 5-7 (for displacements comprised between 2 and 5 mm). The peak resistance was reached during cycle 7, and remained almost constant for the further two cycles (cycles 8 and 9). For displacements larger than 20 mm (cycles 10-15), a gradual reduction of resistance occurred. During cycle 15, for a displacement of ±80 mm (80% of the thickness of the wall), the actual resistance of the wall was approximately null.
At the final stage, the cracks at the supports and at mid-span were clearly visible and fully open (Figure 32a,b), and also the deflected shape of the wall could be distinctly observed (Figure 32c).

![Image](a)

![Image](b)

**Figure 30.** Stiffened bottom (a) and top (b) beams for specimen TUD_COMP-7.

![Image](a)

![Image](b)

**Figure 31.** TUD_COMP-7: initial cracks near the top (a) and bottom (b) supports during cycle 6, and at mid-height (c), during cycle 7.
Figure 32. TUD_COMP-7: cracks (a,b) and deflected shape (c) of the specimen at end stage.
Figure 33 represents the displacement of the couple of control points P1-P4, P2-P5, P3-P6: the ratio between the maximum displacement of the central points (P2-P5) and the other points remains approximately constant throughout the whole test after that cracking occurs. This suggests that the crack pattern remained the same during the test and is properly described by the pictures taken at the end stage.

Figure 34 shows the measured internal pressure of the airbags on both the active and passive side. Besides the limited change of pressure at varying the imposed displacement discussed in section 2, some fluctuation of the pressure on the passive side occur for displacements larger than 70 mm. Those fluctuations occurred during the unloading phase; therefore, the negative lateral forces measured during the unloading phase for positive displacements can be explained by these sudden drops of pressure.

Figure 33. Displacement of the control points P1, P2, P3, P4, P5, P6 for sample TUD_COMP-7.

Figure 34. Measured internal pressure of the airbags on the active and passive side of TUD_COMP-7.

The difference of outcomes between the tests performed on samples TUD_COMP-0b and TUD_COMP-7 are mainly determined by the different boundary conditions (deformable supports for the former and almost rigid supports for the latter, as described in section 1.1). If the yield line analogy is adopted to evaluate the out-of-plane strength of the specimens, as suggested by Eurocode 6 [1], it is required to compute the energy dissipated to crack the masonry; if the sections at top and bottom of the wall are partially free to rotate (Figure 35a) the crack opening, and therefore the dissipated energy, is lower than the one that occur when rigid supports are considered (Figure 35b). Consequently, the peak strength of a wall with rotating supports (such as TUD_COMP-0b) is lower than that of a wall with rigid supports (such as TUD_COMP-7).

The presence of multiple cracks at mid-height of the wall should not affect the global resistance of the wall. Once again, according to the yield line analogy the energy dissipated for one crack or multiple cracks is the
same as long as the total rotation does not change; hence, the rigid-body idealization appears to be a simplified but reliable approximation of the tested samples. It should also be noticed that the out-of-plane vertical four-points bending test performed on masonry wallets (described in [2]) showed that either a single or multiple cracks can occur (Figure 36); for that reason it appears that the presence of multiple cracks is not determined by the specific employed loading application technique.

Further comments on the resistance of the two specimens is provided in Section 0.

Figure 35. Scheme of the crack opening in a wall during a one-way bending test for flexible (a) and rigid (b) supports.

![Figure 35](image)

Figure 36. Crack patterns of calcium silicate masonry specimens subject to out-of-plane vertical bending test: TUD_MAT-12c, and TUD_MAT-12f [2].

![Figure 36](image)

### 3.3 TUD_COMP-10

The test specimen was subjected to a two-way out-of-plane bending test. Unlike previous tests, the masonry of specimen TUD_COMP-10 is composed by clay bricks and BM2 mortar. The boundary conditions are those described in section 1.2. The top and bottom row of bricks were glued to a plywood layer that was fixed to the top and bottom beam; the supporting frame was stiffened in order to provide an efficient clamping to the wall ends. The specimen was also pinned on the sides. The supports were provided by four steel rollers, welded on four steel tubes (Figure 37a). The tubes were bolted to the top and bottom beam; a runner in the top part
guarantees the tube to remain straight but allows the top beam to move free in the vertical direction (Figure 37b). To avoid any localised damage and guarantee a more homogeneous contact, timber wedges were placed between the rollers and the bricks (Figure 37c).

Figure 37. Hinge supports system of the specimen: general overview (a); details of the runner (b) and of the wedges (c).

Before the test, a constant vertical load of 10 kN was applied at the top of the wall. Together with the glued top beam and the traverse stiffening beams, this gives a vertical pressure of 0.05 MPa on the wall. The initial stiffness of the specimen was similar to that measured for specimen TUD_COMP-7.

The specimen denoted an almost elastic behaviour for the first six cycles, up to a displacement of 3 mm and a force of 13 kN: every cycle exhibited an elastic behaviour with a step by step reduced stiffness.

The peak resistance was reached at a lateral displacement of 10 mm (cycle 8) and it was equal to 42.9 kN for positive drifts; whereas it was obtained at -10 mm (cycle 8) and it was equal to -38.9 kN.

The resistance decreased gradually after cycle 11 for the following cycles up to the largest displacement (80 mm); a residual resistance of 40.4 kN for positive drifts (94% of the correspondence peak resistance), and 28.6 kN for negative drifts (74% of the correspondence peak resistance).

Given the presence of the airbags and of the contrast timber panels, the evolution of the crack pattern could not be observed during the test. At the final stage, the following cracks can be described:

- Two horizontal cracks along the bed joints close to the supports (cracks 1 in Figure 38a);
- Four diagonal cracks, mainly along the mortar joints, approximately starting from the corners and oriented towards the centre of the wall (cracks 2 in Figure 38a); one half diagonal two cracks are detected (crack 2a in Figure 38a; detail in Figure 39a);
- A horizontal crack along the bed joint at mid-height, connecting the diagonal cracks (crack 3 in Figure 38a).
- A sub-vertical crack (crack 4 in Figure 38a; detail in Figure 39b,c).

Even if the cracks developed mainly along the mortar head and bed joints, also some bricks cracked (Figure 39b,c); besides, many bricks crushed close to the cracks (Figure 39d). Finally, sliding along the mortar joints is proved by the residual sliding between adjacent bricks in the same bricklayer that can be observed in Figure 39d.
Figure 40 and Figure 41 show the ratio between the measurement points aligned on the vertical or the horizontal direction, respectively. Both ratios remain approximately constant throughout the whole test after that cracking occurs; besides, the displacements of points p2, p5, p8 (which all locate almost on the horizontal crack 3 of Figure 38a) are almost the same for the whole test duration. This suggests that the crack pattern remained the same during the test and is properly described by the pictures taken at the end stage.

Figure 42 shows the measured internal pressure of the airbags on both the active and passive side. Despite a couple of sudden changes in the measured pressure on the passive side during cycle 9 and 11, the detected fluctuations are in line with those discussed in section 2; therefore, the test appears not to be significantly affected by the pressure variation of the airbags on the passive side.
Figure 38. TUD_COMP-10: crack pattern at end stage; front (a) and back side (b) of the wall.

![Image of crack pattern at end stage](image)

Figure 39. TUD_COMP-10: details of the crack pattern at end stage. Details: double diagonal crack (a); sub-vertical crack (b,c); crushing of the bricks and sliding along the mortar joints (d).

![Image of crack pattern details](image)

Figure 40. Displacement of the control points P4, P5, P6 for sample TUD_COMP-10.

![Graph showing displacement of control points](image)
3.4 **TUD_COMP-11**

The test specimen was subjected to a two-way out-of-plane bending test. The boundary conditions are the same as described in section 3.3 for specimen TUD_COMP-10. The same system used to pinned the lateral side of the wall is adopted (Figure 43).

Before the test, a constant vertical load of 10 kN was applied at the top of the wall. Together with the glued top beam and the traverse stiffening beams, this gives a vertical pressure of 0,05 MPa on the wall. The initial stiffness of the specimen in terms of $p$-load is almost equal to that measured for TUD_COMP-7 and TUD_COMP-10.
The specimen denoted an elastic behaviour for the first four cycles, up to a displacement of 2 mm and a force of 13 kN. The peak resistance was reached at a lateral displacement of 30 mm (cycle 10) and it was equal to 30.7 kN for positive drifts; whereas it was obtained at -20 mm (cycle 9) and it was equal to -26.9 kN. The resistance remained almost constant for the following cycles up to the largest displacement (80 mm) for positive drifts, whereas the resistance decreased lightly (-15%) for negative drifts.

Once again, given the presence of the airbags and of the contrast timber panels, the evolution of the crack pattern could not be observed during the test, but only at the end of the test. The detected cracks are shown in Figure 44 and Figure 45.

At the final stage, the following cracks can be described:
- Two horizontal cracks along the bed joints close to the supports (cracks 1 in Figure 45a);
- Four diagonal cracks, mainly along the mortar joints, approximately starting from the corners and oriented towards the centre of the wall (cracks 2 in Figure 45a);
- A horizontal crack along the bed joint at mid-height, connecting the diagonal cracks (crack 3 in Figure 45a).

The crack pattern is almost symmetrical; however, a larger residual displacement could be observed on the right side of the specimen, which was also more damaged (Figure 44a). Finally, even if the cracks developed mainly along the mortar head and bed joints, also some bricks cracked (Figure 44b).

Figure 46 and Figure 47 show the ratio between the measurement points aligned on the vertical or the horizontal direction, respectively. Both ratios remain approximately constant throughout the whole test after that cracking occurs; besides, the displacements of points p2, p5, p8 (which all locate almost on the horizontal crack 3 of Figure 45a) are almost the same for the whole test duration. This suggests that the crack pattern remained the same during the test and is properly described by the pictures taken at the end stage.

Figure 48 shows the measured internal pressure of the airbags on both the active and passive side. Despite a couple of sudden changes in the measured pressure on the passive side during cycle 9 and 11, the detected fluctuations are in line with those discussed in section 2; therefore, the test appears not to be significantly affected by the pressure variation of the airbags on the passive side.

Figure 43. Hinge supports system of the specimen: general overview (a); details of the runner (b) and of the wedges (c).
Figure 44. TUD_COMP-11: crack pattern at end stage; details (a, b).
Figure 45. TUD_COMP-11: crack pattern at end stage; front (a) and back side (b) of the wall (the main cracks are highlighted in red on the front side).

Figure 46. Displacement of the control points P4, P5, P6 for sample TUD_COMP-11.
Figure 47. Displacement of the control points P2, P5, P8 for sample TUD_COMP-11.

Figure 48. Measured internal pressure of the airbags on the active and passive side of TUD_COMP-11.

3.5 TUD_COMP-12

The test specimen was subjected to a two-way out-of-plane bending test. The masonry of specimen TUD_COMP-12 is composed by calcium silicate bricks and mortar and a prefabricated concrete lintel above an opening. There were only airbags positioned at the left and right pier, no airbags at the masonry above and below the opening. In Figure 49 the positions of the airbags on one side are drawn; on the other side they are at a mirrored position. Two measuring points (p4 and p6) are considered to evaluate the out-of-plane displacement of the wall. Point p4 was used as control for the target displacement.
The boundary conditions are the same described in section 3.3 for specimen TUD_COMP-10. The same system used to pinned the lateral side of the wall is adopted (Figure 43). Before the test, a constant vertical load of 10 kN was applied at the top of the wall. Together with the glued top beam and the traverse stiffening beams, this gives a vertical pressure of 0.05 MPa on the wall. It was observed that the top row of the masonry was not vertical in line with the bottom row. There was a horizontal difference of approximately 1.5 cm in the out-of-plane direction between the bottom and the top row, being the bottom row placed in the center of the plywood on the bottom steel beam.

The initial stiffness of the specimen is equal to 6.5 kN/mm in point 4 and 15.5 kN/mm in point 6, in terms of total lateral force vs. displacement at these points, as shown in Figure 50a (or, alternatively, to 1.07 kPa/mm for point 4 and 2.55 KPa/mm in point 6, in terms of lateral p-load vs. displacement at these points - Figure 50b). The initial stiffness of the specimen in terms of p-load is almost equal to that measured for TUD_COMP-7, TUD_COMP-10, and TUD_COMP-11, proving the uniformity of the provided boundary conditions.

The specimen denoted an elastic behaviour for the first three cycles, up to a displacement of 1.5 mm and a force of 8.6 kN (see Figure 51). The peak resistance was reached at a lateral displacement of 30 mm (cycle 10) and it was equal to 22.4 kN for positive drifts; it was obtained at -30 mm (cycle 10) equal to -25.0 kN for negative drifts.
After the peak the resistance lowered for every cycle, but not so strong as for the one-way out-of-plane specimen. At the largest displacement (100 mm for cycle 16) for positive drifts the resistance was 15.3 kN, whereas the resistance for negative drifts at -100 mm for cycle 16 the resistance was -15.0 kN, as shown in Figure 53.

Figure 51. TUD_COMP-12: lateral force vs. displacement at mid-height for points p4 and p6 during cycles 1-3, up to +/- 1.5 mm (elastic phase).

Figure 52. TUD_COMP-12: lateral load vs. displacement at mid-height for points p4 and p6 during cycles 1-10, up to peak load (+/-30 mm).
Compared to the fully masoned specimen the following observations could be made:
- The initial stiffness for the measuring point closest to the centre of the wall is lower than for a fully masoned specimen. This can be explained by the opening, where the left long pier is mostly 3-sided supported. Indeed, the initial stiffness of the specimen in terms of p-load is almost equal to that measured for the other two-way bending tests.
- The concrete lintel remained intact during the test (cracks can be observed at the supports of the lintel). The upper side of the opening therefore remained straight; on the other hand, the bottom side of the opening was heavily horizontally deformed.

Figure 54 shows the difference in horizontal displacement of the long pier and the small pier during the test. This difference is also shown in the load-displacement plots of Figure 55.
Similar to the other tests, given the presence of the airbags and of the contrast timber panels, the evolution of the crack pattern could not be observed during the test. The crack patterns observed at the end of the test is reported in Figure 56.

Figure 57-Figure 60 show details of the crack pattern observed at end stage.

Figure 61 shows the measured internal pressure of the airbags on both the active and passive side. The only detected fluctuations are in line with those discussed in section 2; therefore, the test appears not to be significantly affected by the pressure variation of the airbags on the passive side.
Figure 57. TUD_COMP-12: Crack patterns at end stage.

Figure 58. TUD_COMP-12: Crack patterns on the long pier at the top (left) and at the bottom (right).
Figure 59. TUD_COMP-12: Crack patterns on the long pier at the support of the lintel.

Figure 60. TUD_COMP-12: Crack patterns on the small pier at the top (left) and at the bottom (right).
Figure 61. Measured internal pressure of the airbags on the active and passive side of TUD_COMP-12.
4 Conclusions

In the Stevin II laboratory of the Delft University of Technology, four calcium silicate brick walls and one clay brick wall have been tested under cyclic out-of-plane loading.

The test program consisted of:
- Two short walls (1.47 m x 2.75 m) composed of calcium silicate brick masonry, tested one-way out-of-plane, with flexible out-of-plane supports at the top and bottom.
- Two long walls (4.0 m x 2.75 m), one composed of calcium silicate brick and one of clay brick masonry, tested two-way out-of-plane, with flexible supports at the top and bottom and hinges at the vertical sides.
- One long wall (4.0 m x 2.75 m) with an opening, composed of calcium silicate brick masonry, tested two-way out-of-plane, with flexible supports at the top and bottom and hinges at the vertical sides.

An overview of the test results is given in Table 4.

Table 4. Overview of the results from the performed out-of-plane tests.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Type of test</th>
<th>(\sigma_v)</th>
<th>(K_m)</th>
<th>(F_H^+)</th>
<th>(F_H^-)</th>
<th>(k_m)</th>
<th>(p^+)</th>
<th>(p^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TUD_COMP-0b(^1)</td>
<td>One way</td>
<td>0.2</td>
<td>1.65(^1)</td>
<td>6.61(^1)</td>
<td>-7.09(^1)</td>
<td>0.42(^1)</td>
<td>1.67(^1)</td>
<td>-1.79(^1)</td>
</tr>
<tr>
<td>TUD_COMP-7</td>
<td>One way</td>
<td>0.2</td>
<td>4.50</td>
<td>10.15</td>
<td>-10.16</td>
<td>1.13</td>
<td>2.56</td>
<td>-2.56</td>
</tr>
<tr>
<td>TUD_COMP-10</td>
<td>Two way</td>
<td>0.05</td>
<td>12.88</td>
<td>45.91</td>
<td>-39.88</td>
<td>1.17</td>
<td>4.16</td>
<td>-3.61</td>
</tr>
<tr>
<td>TUD_COMP-11</td>
<td>Two way</td>
<td>0.05</td>
<td>12.00</td>
<td>31.16</td>
<td>-27.00</td>
<td>1.09</td>
<td>2.82</td>
<td>-2.45</td>
</tr>
<tr>
<td>TUD_COMP-12</td>
<td>Two way</td>
<td>0.05</td>
<td>6.5(^2)</td>
<td>22.40</td>
<td>-25.00</td>
<td>1.07(^2)</td>
<td>3.67</td>
<td>-4.10</td>
</tr>
</tbody>
</table>

Where: \(K_m\) = initial stiffness in terms of lateral force (measured as the secant stiffness between the extreme displacements of each cycle); \(\sigma_v\), \(\sigma_v\) = lateral force for positive and negative displacements, respectively; \(k_m\) = initial stiffness in terms of lateral pressure; \(p^+, p^-\) = lateral pressure for positive and negative displacements, respectively.

\(^1\) both stiffness and resistance of sample TUD_COMP-0b are affected by the configuration of the frame set-up adopted for this specimen.

\(^2\) the presented stiffness is evaluated in the measurement point p4, which detected the maximum out-of-plane displacement of the wall.

The main remarks are hereinafter discussed.

For the one-way out-of-plane tests:
- The maximum loads calculated according to EC 6 (Appendix A), based on the material properties derived in the companion material tests [2], underestimate the measured loads.
- The maximum loads calculated according to the yield line analogy (Appendix B) are in line with the measured loads.
- The ultimate horizontal deflection was +/- 80 mm at midspan. At this point the load that could be sustained by the walls was reduced to zero. This is in line with the second order theory for large displacements.
- The magnitude of the out-of-plane rotational stiffness at the supports influences the maximum load capacity of the wall, which can be explained by the yield line analogy. A larger rotational stiffness provides a larger capacity.
- The observed stiffness's of the walls are consistent with the material properties derived in the companion material tests [2] and with the derived rotational stiffness of the supports.
- Horizontal cracks are observed at the first mortar layer at the top and bottom of the wall, at midspan the observed cracks were spread over multiple layers.

For the two-way out-of-plane tests without openings:
- The maximum loads calculated according to EC6 (Appendix A), based on the material properties derived in the companion material tests [2], underestimate the measured loads.
- The maximum loads calculated according to the yield line analogy (Appendix B) still underestimate the experimental wall resistance.
For the CS brick wall the maximum load in terms of lateral pressure has almost the same value as for the one way out-of-plane, but for the two way-out-of-plane almost no reductions of the maximum load is observed at the maximum center displacement at midspan of 80 mm.

For the clay brick wall the maximum load is higher than for the CS wall, which is expected based on the properties derived in the companion material tests [2]. After the peak load there is a slight reduction at the maximum center displacement at midspan of 80 mm, but still higher than for the CS wall.

Horizontal cracks were observed at the bottom and top mortar layer; in the CS wall a well-defined envelope pattern was observed, whereas the clay wall showed multiple crack lines.

The observed stiffness's of the walls are consistent with the properties derived in the companion material tests [2] and with the derived rotational stiffness of the supports.

For the two-way out-of-plane tests without openings:

- The diagonal cracks at the top initiated from the supports on the masonry of the concrete lintel.
- The wall acted similarly to two piers supported on three sides.
- A well-defined envelope pattern was observed.

General points:

- The effective area of the airbags able to transfer the applied pressure compared to the total wall surface varies between 76% and 86% (in line with the values found in literature [3]), depending on the number of airbags and the imposed midspan displacements. For this reason, the applied load has to be measured with load cells on a reaction frame.
- The applied system allowed to observe the entire load-deformation path for the OOP until zero residual loading, and for displacements almost equal to the whole thickness of the wall.
References


APPENDIX A - Comparison with values proposed by the Eurocodes

Eurocode 8 gives no verification rules for masonry walls loaded out-of-plane. Therefore the results are evaluated against the verification rules of Eurocode 6.

A.1 One way out –of-plane

For one-way out-of-plane the moment resistance of a masonry wall is given according to equations (6.16) and (6.17) of [1]: In the equations the indices indicating design values are removed, because the walls will be verified with the mean values of the masonry properties as input values.

Equation (6.16) of [1]:

\[ M_R = f_x Z \] (2)

with:
- \( f_x \) is the flexural strength appropriate to the plane of bending;
- \( Z \) is the elastic section modulus of unit height or length of the wall.

When a vertical load is present, then \( f_x \) in equation (6.16) becomes \( f_{x, \text{app}} \) in equation 6.17 in [1]:

\[ f_{x, \text{app}} = f_x + \sigma \] (3)

with:
- \( f_{x, \text{app}} \) is the apparent flexural strength with the plane of failure parallel to the bed joints;
- \( f_x \) is the flexural strength with the plane of failure parallel to the bed joints;
- \( \sigma \) is the compressive stress on the wall.

Then for a one way out-of-plane loaded wall, the maximum lateral load per unit area (\( W_E \)) becomes:

\[ W_E = \frac{f_{x, \text{app}} Z}{\alpha_1 H^2} \] (4)

with:
- \( W_E \) is the maximum lateral load per unit area;
- \( \alpha_1 \) is the coefficient to calculate the maximum elastic moment over the height of the wall, depending on the boundary conditions at the top and the bottom where the highest value \( \alpha \) of the clamping moment at the support or the moment at midspan has to be taken.

The maximum horizontal load on the wall is then calculated as:

\[ F_H = W_E \times A_w \] (5)

with:
- \( F_H \) is the maximum horizontal load on the wall;
- \( A_w \) is the area of the wall subjected to the lateral load per unit area.

A.2 Two way out –of-plane

The maximum moment of a masonry wall loaded in two-way bending is calculated according to equation (5.17) of [1] when the plane of failure is parallel to the bed joints in the \( f_{x, \text{app}} \) direction:

\[ M_{E,1} = \alpha_1 W_E l^2 \] (6)

with:
- \( W_E \) is the maximum lateral load per unit area;
- \( \alpha_1 \) is the bending moment coefficient in the \( f_{x1} \) direction taking into account the degree of fixity at the edges of the walls, the height to length ratio of the walls; they can be obtained from a suitable theory;
- \( l \) is the length of the wall.

The maximum moment of a masonry wall loaded in two-way bending is calculated according to equation (5.18) of [1] when the plane of failure is perpendicular to the bed joints in the \( f_{x2} \) direction:

\[
M_{E,2} = \alpha_2 W_E l^2
\]  

With:
- \( \alpha_2 \) is the bending moment coefficient in \( f_{x2} \) direction taking into account the degree of fixity at the edges of the walls, the height to length ratio of the walls; they can be obtained from a suitable theory.

In the note under equation (5.18) in [1] is stated that the coefficients \( \alpha_1 \) and \( \alpha_2 \) may be obtained from Annex E for single leaf walls with a thickness less or equal to 250 mm, where \( \alpha_1 = \mu \alpha_2 \).

Where \( \mu \) is the orthogonal ratio of the flexural strengths of the masonry:

\[
\mu = \frac{f_{x1}}{f_{x2}}
\]

Annex E of [1] gives for different boundary conditions the value of \( \alpha_2 \) based on the ratio \( H/l \) and \( \mu \).

Because the support conditions used in the tests for TUD-COMP-10 and TUD-COMP-11 (clamped at the top and bottom and hinged at the sides) are not given in the tables of annex E the maximum horizontal force for walls support conditions E (hinged on all sides) and I (clamped on all sides) will be calculated. These are then minimum and maximum values for the tested boundary conditions.

Then the maximum lateral load per unit area \( W_E \) becomes:

\[
W_{E,1} = \frac{f_{x1} Z}{\alpha_1 * l^2}
\]

\[
W_{E,2} = \frac{f_{x2} Z}{\alpha_2 * l^2}
\]

Because the orthogonal strengths are integrated in the bending moment coefficients \( W_{E,1} \) and \( W_{E,2} \) will give the same result.

The maximum horizontal load on the wall is then calculated as:

\[
F_H = W_E * A_w
\]

with:
- \( F_H \) is the maximum horizontal load on the wall;
- \( A_w \) is the area of the wall subjected to the lateral load per unit area.

### A.3 One-way out-of-plane: TUD-COMP-0b and TUD-COMP-7

The resistances of the specimen TUD_COMP-0b and TUD_COMP-7 are evaluated according to equations (2)-(5).

The following properties are considered:
- \( f_{x1} = 0.21 \) N/mm\(^2\) the mean value of the calcium silicate flexural strength when the plane of failure is parallel to the bed joints, based on the material tests at TUD according to [2];
- \( \sigma = 0.2 \) N/mm\(^2\) the applied vertical stress on the walls.

The maximum horizontal loads are calculated according to two different boundary conditions: \( \alpha_1 = 0.096 \) (for the unstiffened clamping at top and bottom) and \( \alpha_1 = 0.074 \) (for the stiffened clamping at top and bottom):
- for \( \alpha_1 = 0.096 \) (TUD-COMP-0b): \( F_H = 3.6 \) kN;
- for \( \alpha_1 = 0.074 \) (TUD-COMP-7): \( F_H = 4.8 \) kN;
A.4 Two way -out-of-plane: TUD-COMP-10 and TUD-COMP-11

The resistances of the specimen TUD_COMP-10 and TUD_COMP-11 are evaluated according to equations (6)-(10).

The considered properties and the estimated resistances are reported in Table 5. \( f_{x1} \) and \( f_{x2} \) are the mean value of the flexural strength when the plane of failure is parallel to the bed joints and perpendicular to the bed joints respectively, based on the material tests at TUD according to [2].

Table 5. Calculated lateral resistance of the specimens tested in two-way bending tests

<table>
<thead>
<tr>
<th>Type of masonry</th>
<th>TUD_COMP-10</th>
<th>TUD_COMP-11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type of masonry</td>
<td>Clay</td>
<td>Calcium silicate</td>
</tr>
<tr>
<td>( f_{x1} ) (N/mm(^2))</td>
<td>0.4</td>
<td>0.21</td>
</tr>
<tr>
<td>( f_{x2} ) (N/mm(^2))</td>
<td>1.12</td>
<td>0.76</td>
</tr>
<tr>
<td>( \mu )</td>
<td>0.35</td>
<td>0.28</td>
</tr>
<tr>
<td>( H/l )</td>
<td>1.45</td>
<td>1.45</td>
</tr>
<tr>
<td>Annex E table E (hinged all sides) ( \alpha_2 )</td>
<td>0.081</td>
<td>0.085</td>
</tr>
<tr>
<td>Annex E table E (hinged all sides) ( \alpha_1 )</td>
<td>0.029</td>
<td>0.023</td>
</tr>
<tr>
<td>( F_H ) (annex table E, hinged all sides) (kN)</td>
<td>14.8</td>
<td>9.6</td>
</tr>
<tr>
<td>Annex E table I (clamped all sides) ( \alpha_2 )</td>
<td>0.040</td>
<td>0.041</td>
</tr>
<tr>
<td>Annex E table I (clamped all sides) ( \alpha_1 )</td>
<td>0.014</td>
<td>0.011</td>
</tr>
<tr>
<td>( F_H ) (annex table I, clamped all sides) (kN)</td>
<td>30.0</td>
<td>19.8</td>
</tr>
</tbody>
</table>

A.5 Comparison between the code predictions and the measured resistances

A comparison between the resistances computed for one-way and two-way bending tests in sections 0 and 0, respectively, and those recorded during the experimental tests is presented in Table 6. The resistances calculated according to the equations provided in [1] strongly underestimate the values measured experimentally. However, it should be noted that the equations in Eurocode 6 are based on the elastic moments of the wall, and not on the limit condition.

Table 6. Lateral resistance of the tested specimens: comparison between the experimental and the predicted results.

<table>
<thead>
<tr>
<th>Type</th>
<th>TUD_COMP-0b</th>
<th>TUD_COMP-7</th>
<th>TUD_COMP-10</th>
<th>TUD_COMP-11</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F_{H+} ) (kN)</td>
<td>6.6</td>
<td>10.2</td>
<td>45.9</td>
<td>31.2</td>
</tr>
<tr>
<td>( F_{H-} ) (kN)</td>
<td>-7.1</td>
<td>-10.2</td>
<td>-39.9</td>
<td>-27.0</td>
</tr>
<tr>
<td>Predicted</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>( F_H ) (kN)</td>
<td>3.6</td>
<td>4.8</td>
<td>14.8(^1)/30.0(^2)</td>
<td>9.6(^1)/19.8(^2)</td>
</tr>
</tbody>
</table>

Where: \( F_{H+} \), \( F_{H-} \) = lateral force for positive and negative displacements, respectively; \( F_H \) = average lateral force.

1 force estimated for wall hinged at the top, bottom, and at the sides.
2 force estimated for wall clamped at the top, bottom, and at the sides.
APPENDIX B - Predictions based on the yield line analogy

The application of the principles of virtual work to identify failure mechanism, known as yield line analogy, is often proposed in the literature (e.g. [4]). Different formulations are proposed for the one-way and the two-way bending tests.

B.1 One-way out-of-plane test

For the one-way bending test, a simple failure mechanism involving three horizontal cracks (at top, in the middle, and at bottom of the wall) is assumed. The internal work is produced by the vertical bending moment acting along horizontal bed joints: \( \delta U_{\text{int}} = \Sigma (M_u \delta) \).

The vertical bending moment \( M_v \) is calculated as the cracking moment, considering the apparent flexural resistance \( f_{\text{app}} \) defined in Equation (3). The rotational stiffness of the supports is included in the calculation of the dissipated energy; therefore, a rotation at supports equal to 41% of the one assumed for rigid supports is considered for TUD_COMP-0b and equal to 88% for TUD_COMP-7 (the values are obtained considering a resisting bending moment \( M_r = 2.24 \text{kNm} \), rotational stiffness \( C_{\phi} = 170 \text{kNm/rad} \) and \( C_{\gamma} = 2580 \text{kNm/rad} \), and a total rotation at peak \( \theta_{\text{tot},0} = 0.22 \text{rad} \) and \( \theta_{\text{tot},7} = 0.11 \text{rad} \).

The external work is produced by the applied lateral pressure (p): \( \delta U_{\text{ext}} = p \int (\delta h dA) \), being \( \delta h \) the horizontal displacement of each point. By equating internal and external work, it is possible to evaluate the lateral pressure (and consequently the lateral force) that determines the considered failure mechanism.

The following predicted lateral resistances are obtained:

\[
F_{H,\text{COMP0b}} = \frac{\delta U_{\text{int}}}{\delta h dA} BH = 8.26 \kPa \tag{11}
\]

\[
F_{H,\text{COMP7}} = \frac{\delta U_{\text{int}}}{\delta h dA} BH = 11.0 \kPa \tag{12}
\]

B.2 Two-way out-of-plane test

For the two-way bending fully masoned test (TUD_COMP-10 and TUD_COMP-11) the assumptions proposed in [4] are considered. Specifically, according to those assumptions the moment capacities along the diagonal and vertical crack lines are all reached simultaneously, whereas the horizontal cracks are assumed to develop in an early stage in the load-displacement response, and thus the moment resistance of these crack lines is neglected.

The expressions of the horizontal \( (M_h) \) and diagonal \( (M_d) \) bending moment capacity of masonry walls are the followings:

\[
M_h = \min \left( \frac{1}{\Sigma (h_b + t_j)} \left( f_{b_t} - v \sigma \right) \cdot h_b \frac{t_j^2}{6} ; \frac{1}{h_b + t_j} \left( t_u \kappa_b \cdot 0.5 (l_b + t_j)t_j^2 \right) \right) \tag{13}
\]

\[
M_d = \frac{\sin \phi}{h_b + t_j} \left( \sin \phi \right)^3 t_u \kappa_b \cdot 0.5 (l_b + t_j)t_j^2 + \left( \cos \phi \right)^3 (f_{x1} + \sigma) 0.5 (l_b + t_j)t_j^2 \right) \tag{14}
\]

where \( l_b \), \( b_t \), and \( h_b \) are the length, thickness and height of the brick unit; \( t_j \) is the mortar joint thickness; \( \phi \) is the slope of a diagonal crack line which can be determined from unit geometry; \( f_{x1} \) is the flexural tensile strength of the masonry; \( f_{b_t} \) is the flexural tensile strength of the brick; \( t_u \) is the ultimate shear bond stress of a bed joint \( (t_u = 1.6 f_{b_t} + 0.9 \sigma) \); \( v \) is the Poisson’s ratio of the masonry, assumed as 0.2; \( \kappa_b = 0.2134 \); and \( \sigma \) is the vertical compressive stress in the wall.

The following predicted lateral resistances are obtained:
\[ F_{H,COMP10} = \frac{\delta U_{10b}}{\delta \alpha dA} BH = 26.1 \text{kPa} \]  \hspace{1cm} (15)

\[ F_{H,COMP11} = \frac{\delta U_{11v}}{\delta \alpha dA} BH = 22.3 \text{kPa} \]  \hspace{1cm} (16)

For TUD_COMP-12 cracks are assumed to develop on the side of the large pier only, and from the corners of the wall to the corners of the opening on the side of the short pier. A sketch of the considered crack pattern for the two-way bending samples is provided in Figure 62.

Figure 62. Assumed crack pattern for the two-way bending tests: fully masoned walls (a) and wall with an opening (b).

The following predicted lateral resistance is obtained for TUD-COMP-12:

\[ F_{H,COMP12} = \frac{\delta U_{12b}}{\delta \alpha dA} BH = 20.3 \text{kPa} \]  \hspace{1cm} (17)

**B.3 Comparison between the analytical predictions and the measured resistances**

A comparison between the resistances computed for one-way and two-way bending tests in sections 0 and 0, respectively, and those recorded during the experimental tests is presented in Table 7. The yield line analogy provides a good estimation of the resistance of the one-way samples. It is also able to predict the different strengths caused by the flexible supports. However, for the two-way tests the considered approach still underestimates the resistance measured experimentally. More specific assumptions for the specific boundary conditions of the tests may lead to better results for the yield line analogy approach.

<table>
<thead>
<tr>
<th>( F_{H} )</th>
<th>TUD_COMP-0b</th>
<th>TUD_COMP-7</th>
<th>TUD_COMP-10</th>
<th>TUD_COMP-11</th>
<th>TUD_COMP-12</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Experimental</strong></td>
<td>+6.6 kN</td>
<td>+10.2 kN</td>
<td>+45.9 kN</td>
<td>+31.2 kN</td>
<td>+22.4 kN</td>
</tr>
<tr>
<td></td>
<td>-7.1 kN</td>
<td>-10.2 kN</td>
<td>-39.9 kN</td>
<td>-27.0 kN</td>
<td>-25.0 kN</td>
</tr>
<tr>
<td><strong>Eurocode 6</strong></td>
<td>3.6 kN</td>
<td>4.8 kN</td>
<td>14.8 kN/30.0 kN</td>
<td>9.6 kN/19.8 kN</td>
<td>-</td>
</tr>
<tr>
<td><strong>Yield line analogy</strong></td>
<td>8.3 kN</td>
<td>11 kN</td>
<td>26.1 kN</td>
<td>22.3 kN</td>
<td>20.3 kN</td>
</tr>
</tbody>
</table>

\(^1\) force estimated for wall hinged at the top, bottom, and at the sides.

\(^2\) force estimated for wall clamped at the top, bottom, and at the sides.