ESECMaSE Enhanced Safety and Efficient Construction of Masonry Structures in Europe

Horizontal Research Activities Involving SMEs
Collective Research
Work Package N° 7

D 7.1b Test results on the behaviour of masonry under static cyclic in plane lateral loads

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<td>PP Restricted to other programme participants (including the Commission Services)</td>
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<td>RE Restricted to a group specified by the consortium (including the Commission Services)</td>
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Deliverable D7.1 b: Test results on the behaviour of masonry under static cyclic in plane lateral loads

Project: Enhanced Safety and Efficient Construction of Masonry Structures in Europe

Client: European Commission
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48 Annex

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1. Introduction

Deliverable 7.1 of ESECMaSe deals with the static cyclic tests on masonry walls. Since the static cyclic wall tests of the ESECMaSE project were carried out at three different laboratories, the deliverable is divided into three parts:

⇒ D 7.1 a – University of Kassel (UNIK)
⇒ D 7.1 b – Technical University of Munich (TUM)
⇒ D 7.1 c – University of Pavia (UPavia)

This report describes the static cyclic wall tests with a test set-up developed in WP 6 on different kinds of masonry (clay, calcium silicate) with different specimen dimensions, carried out at Technical University of Munich.

2. Specimen and material properties

Totally eight tests on walls were performed within this part of this work package 7.1, deliverable 7.1b. The thickness of the walls was 175 mm for all specimens and also the height of 2.5m was constant for all tests. The details of the material properties of the different kind of units and mortar can be found in deliverable 5.5.

Table 1: Overview of the tested wall specimen under static cyclic loading

<table>
<thead>
<tr>
<th>Name</th>
<th>l[m]</th>
<th>σ_v [MPa]</th>
<th>Unit size [mm³]</th>
<th>Reinforcement</th>
<th>Bed joints (thin layer)</th>
<th>Head joints</th>
<th>Minimum overlapping length</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS01</td>
<td>1.25</td>
<td>1.0</td>
<td>248x175x248 conventional units</td>
<td>No</td>
<td>Quick mix KSK grob</td>
<td>unfilled</td>
<td>l_uvw/2 = 12.5cm</td>
</tr>
<tr>
<td>CS02</td>
<td>1.25</td>
<td>1.0</td>
<td>248x175x248 optimised units</td>
<td>No</td>
<td>Quick mix KSK grob</td>
<td>unfilled</td>
<td>l_uvw/2 = 12.5cm</td>
</tr>
<tr>
<td>CS03</td>
<td>2.5</td>
<td>1.0</td>
<td>998x175x625</td>
<td>No</td>
<td>Quick mix KSK grob</td>
<td>filled</td>
<td>l_uvw/2 = 50cm</td>
</tr>
<tr>
<td>CS04</td>
<td>1.25</td>
<td>1.0</td>
<td>998x175x625</td>
<td>Internal</td>
<td>WEP</td>
<td>filled</td>
<td>l_uvw/2 = 50cm</td>
</tr>
<tr>
<td>CS05</td>
<td>2.5</td>
<td>1.0</td>
<td>998x175x625</td>
<td>Internal</td>
<td>WEP</td>
<td>filled</td>
<td>l_uvw/2 = 50cm</td>
</tr>
<tr>
<td>CS06 (*)</td>
<td>2.5</td>
<td>1.0</td>
<td>998x175x625</td>
<td>Internal</td>
<td>WEP</td>
<td>filled</td>
<td>25cm (*)</td>
</tr>
<tr>
<td>CS07</td>
<td>2.5</td>
<td>2.0</td>
<td>998x175x625</td>
<td>Internal</td>
<td>WEP</td>
<td>filled</td>
<td>l_uvw/2 = 50cm</td>
</tr>
<tr>
<td>Clay01</td>
<td>1.5</td>
<td>0.44</td>
<td>375x175x248</td>
<td>No</td>
<td>DM</td>
<td>unfilled</td>
<td>l_uvw/2 = 18cm</td>
</tr>
</tbody>
</table>

(*) here the minimum overlapping length was reduced from l_uvw/2 to 25cm
2.1. Materials used

2.1.1. Walls made of Clay units
Specimen Clay01 was built with a vertically perforated clay brick, type: Bellenberg HLZ – Plan – 12 – 0.9 9DF, optimized 2. The width of the brick was 175mm, the height 249mm and the length 363mm. The head joints were left unfilled according to the groove and tongue of the units. As mortar for the bed joints, a thin layer mortar type “Bellenberger Planziegel Dünnbettmörtel (DIBT Zul.-Nr. Z.17.1-261)” was used.
2.1.2. Walls made of Calcium silicate units

Three different types of calcium silicate units were used. Specimen CS01 and CS02 were built with units type KSP 20-1.8-6DF (248x175x248 mm) (conventional and optimized), and a thin layer mortar (class M10, according to DIN EN998-2) for the bed joints. The head joints were left unfilled.

For the other specimen, CS03 to CS07, large-sized units, type KS XL-PE (width: 175mm, height: 623mm, length: 998 mm) were used. The units of CS 03 and the remaining calcium silicate Walls differ from each other by the existence of an internal reinforcement (three reinforcing bars, diameter 12 mm, per unit) inside the units and the usage of two different kinds of mortar (CS03: thin layer mortar class M10, DIN EN998-2 ; CS04-CS07: optimized thin layer mortar “KS-Werkplanmörtel”, in the following referred to as “WEP”, with a higher adhesive tensile strength). The head joints of all Specimens were filled with the same mortar which was used for the bed joints.

---

**Figure 3:** KSP 20-1.8-6DF (175), conventional

**Figure 4:** KSP 20-1.8-6DF (175), optimized

**Figure 5:** KS XL-P (175) with internal reinforcement
3. Experimental results

3.1. Test method

The tests were performed on full scale masonry walls with nearly a constant axial compression force $N$ and a cyclic application of a displacement at the top of the wall. As the vertical axial force was applied by two independently force-controlled vertical actuators, also an in-plane bending moment could be applied. To avoid rotations of the top of the wall caused by the horizontal loadings, a counteracting moment was applied at the top of the wall. The aim was, to get the in-plane bending moment at mid height of the wall to zero.

![Figure 6: Idealized load and stress state at a single wall according to the defined boundary conditions](image)

![Figure 7: Test set-up used for the static-cyclic tests at the TU Munich](image)
3.2. Maximum horizontal force and deformation capacity

The results of the tests concerning the maximum horizontal load $H_{\text{max}}$ and the maximum displacements $d_{\text{max}}$ are given below.

**Table 2: Normal forces and maximum horizontal loads**

<table>
<thead>
<tr>
<th>Name</th>
<th>N</th>
<th>$H_{\text{max}}$</th>
<th>$d_{\text{max}}$</th>
<th>H/N</th>
<th>Geometry l/h (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS01</td>
<td>219 kN</td>
<td>84 / -85 kN</td>
<td>13 / -13 mm</td>
<td>0.38</td>
<td>0.5</td>
</tr>
<tr>
<td>CS02</td>
<td>219 kN</td>
<td>86 / -82 kN</td>
<td>7 / -6 mm</td>
<td>0.38</td>
<td>0.5</td>
</tr>
<tr>
<td>CS03</td>
<td>438 kN</td>
<td>243 / -228 kN</td>
<td>10 / -10 mm</td>
<td>0.53</td>
<td>1</td>
</tr>
<tr>
<td>CS04</td>
<td>219 kN</td>
<td>92 / -90 kN</td>
<td>8 / -8 mm</td>
<td>0.42</td>
<td>0.5</td>
</tr>
<tr>
<td>CS05</td>
<td>438 kN</td>
<td>316 / -341 kN</td>
<td>6 / -6 mm</td>
<td>0.75</td>
<td>1</td>
</tr>
<tr>
<td>CS06</td>
<td>438 kN</td>
<td>292 / -316 kN</td>
<td>6 / -6 mm</td>
<td>0.69</td>
<td>1</td>
</tr>
<tr>
<td>CS07</td>
<td>875 kN</td>
<td>462 / -445 kN</td>
<td>7 / -7 mm</td>
<td>0.52</td>
<td>1</td>
</tr>
<tr>
<td>Clay01</td>
<td>97 kN</td>
<td>50 / -50 kN</td>
<td>20 / -20 mm</td>
<td>0.52</td>
<td>0.5</td>
</tr>
</tbody>
</table>

(*) assuming rocking limitation and double fixation

The deformation capacity of the walls is determined from the load-displacement curves obtained from the tests according to deliverable 7.1a.

The relevant parameters were the point of the first crack ($H_{\text{cr}}$ and $u$), the maximum load $H_{\text{F}}$ and the maximum deformations $d_{u1}$ and $d_{u2}$ on both sides were taken from the data. The calculation of the ductilities is carried out assuming

$$\mu = \frac{d_{\mu}}{d_{e}}$$

where $d_{\mu} = \frac{d_{u2}H_{u1}}{H_{cr}}$

**Table 3: Overview about the results of the static cyclic tests**

<table>
<thead>
<tr>
<th>Name</th>
<th>$d_{u1}$ [mm]</th>
<th>$d_{u2}$ [mm]</th>
<th>$d_{u1}$ [mm]</th>
<th>$d_{u2}$ [mm]</th>
<th>$H_{u1}$ [kN]</th>
<th>$H_{u2}$ [kN]</th>
<th>$H_{u1}$ [kN]</th>
<th>$H_{u2}$ [kN]</th>
<th>$d_{u1}$ [mm]</th>
<th>$d_{u2}$ [mm]</th>
<th>$\mu_1$ [-]</th>
<th>$\mu_2$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS01</td>
<td>13.1</td>
<td>-13.2</td>
<td>1.2</td>
<td>1.2</td>
<td>49</td>
<td>50</td>
<td>72</td>
<td>72</td>
<td>71</td>
<td>1.4</td>
<td>-1.7</td>
<td>7.4</td>
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<tr>
<td>CS02</td>
<td>5.7</td>
<td>-5.9</td>
<td>1.1</td>
<td>-1.0</td>
<td>63</td>
<td>-47</td>
<td>79</td>
<td>-72</td>
<td>63</td>
<td>1.4</td>
<td>-1.5</td>
<td>4.1</td>
</tr>
<tr>
<td>CS03</td>
<td>8.9</td>
<td>-7.2</td>
<td>1.3</td>
<td>-1.0</td>
<td>179</td>
<td>-136</td>
<td>216</td>
<td>-187</td>
<td>179</td>
<td>1.6</td>
<td>-1.4</td>
<td>5.7</td>
</tr>
<tr>
<td>CS04</td>
<td>7.0</td>
<td>-6.6</td>
<td>1.1</td>
<td>-0.9</td>
<td>63</td>
<td>-52</td>
<td>81</td>
<td>-81</td>
<td>63</td>
<td>1.4</td>
<td>-1.4</td>
<td>4.9</td>
</tr>
<tr>
<td>CS05</td>
<td>5.3</td>
<td>-5.2</td>
<td>1.0</td>
<td>-0.8</td>
<td>239</td>
<td>-267</td>
<td>278</td>
<td>-311</td>
<td>239</td>
<td>1.2</td>
<td>-0.9</td>
<td>4.5</td>
</tr>
<tr>
<td>CS06</td>
<td>5.4</td>
<td>-5.0</td>
<td>0.8</td>
<td>-0.8</td>
<td>217</td>
<td>-233</td>
<td>272</td>
<td>-294</td>
<td>217</td>
<td>1.0</td>
<td>-1.0</td>
<td>5.3</td>
</tr>
<tr>
<td>CS07</td>
<td>6.6</td>
<td>-6.5</td>
<td>1.4</td>
<td>-1.3</td>
<td>333</td>
<td>-337</td>
<td>421</td>
<td>-397</td>
<td>333</td>
<td>1.8</td>
<td>-1.6</td>
<td>3.7</td>
</tr>
<tr>
<td>Clay01</td>
<td>16.8</td>
<td>-17.9</td>
<td>1.0</td>
<td>-1.2</td>
<td>38</td>
<td>-37</td>
<td>48</td>
<td>-48</td>
<td>38</td>
<td>1.3</td>
<td>-1.6</td>
<td>13.1</td>
</tr>
</tbody>
</table>

Regarding the calculated ductilities of clay01 it has to be mentioned, that the level of axial compression was relatively low.
3.3. Comparison of different vertical compression level

The walls CS05 and CS07 were built with the same material and the same geometry. During the tests the vertical compression level was doubled within the test on wall CS07 compared to CS05.

The behaviour of the specimen CS05 and its crack pattern is dominated by cracks in the joints (head and bed joints) where the behaviour of the specimen CS07 and its crack pattern is dominated by diagonal cracks running through the units. The dissipated energy is significantly higher in the tests of CS05 compared to the hysteresis of CS07.

The maximum horizontal load bearing capacity is not proportionally increased with the rising axial force.

Figure 8: Crack pattern of the specimen CS05 and CS07

Figure 9: Hysteresis of the tests on the specimen CS05 and CS07
3.4. Comparison of optimisation process

The walls CS01 and CS02 were built with conventional resp. optimised cs-units. All other parameters were not varied during the tests. Regarding the crack pattern and load displacement curve it is obvious, that the reduced compression strength of the optimized units leads to unfavourable behaviour. The displacement capacity of CS02 is reduced significantly caused by the cracks in the units. The load bearing capacity is not influenced significantly.

![Crack pattern of the specimen CS01 and CS02](image)

**Figure 10:** Crack pattern of the specimen CS01 and CS02

![Hysteresis of the tests on the specimen CS01 and CS02](image)

**Figure 11:** Hysteresis of the tests on the specimen CS01 and CS02
3.5. Comparison of the effect of internal reinforcement

The difference between the test on the specimen CS03 and CS05 is the internal reinforcement in the CS-units in CS05 and the usage of a mortar with higher adhesion. The load bearing capacity is increased significantly by the internal reinforcement. The reinforcement cannot avoid cracks but after the opening of the cracks additional dowel effects can be activated. The energy dissipation described by the fullness of the hysteresis is increased noticeable by the internal reinforcement. Specimen CS05 shows also a considerable higher stiffness at the beginning of the experiment. This is probably a consequence of the usage of the mortar with higher adhesion.

Figure 12: Crack pattern of the specimen CS03 and CS05

Figure 13: Hysteresis of the tests on the specimen CS03 and CS05
3.6. Comparison of the effect of overlapping length

The difference between the specimen CS05 and CS06 is the overlapping length of the units. For specimen CS06 it was reduced from 50cm (=half of length of the units) to 25cm. The load bearing capacity is decreased through the reduction of the overlapping length, particularly at a higher level of horizontal displacement. The crack pattern of specimen CS06 is dominated by diagonal cracks inside the units, contrary to the crack pattern of specimen CS05, which shows mainly cracks of the bed and head joints. The dissipated energy is significantly lower in the test of CS06 compared to the hysteresis of CS05.

Figure 14: Crack pattern of the specimen CS05 and CS06

Figure 15: Hysteresis of the tests on the specimen CS05 and CS06
3.7. Comparison of the effect of the length of the Wall

Specimen CS04, CS05 and CS06 were tested under the same compression stress but CS04 was half of the length of specimen CS05 resp. CS06. The load bearing capacity of CS04 was ca. 90 kN whereas the maximum load of CS05 and CS06 was about 315 kN. This is an enhancement of approx. 350% for the maximum load. The behaviour of CS04 is dominated by rocking of the whole wall (crack number 1 occurred in the first and last mortar layer of the wall) therefore the hysteresis shows only a little fullness. Specimen CS05 and CS06 however, showed a completely different behaviour. The first cracks suggest a failure of the bed and head joints followed by cracking of the units. The comparison of these specimens therefore is not reasonably, because of the dominant effect of the geometric restriction of specimen CS04.

**Figure 16:** Crack pattern of the specimen CS04, CS05 and CS06

**Figure 17:** Hysteresis of the tests on the specimen CS04, CS05 and CS06
4. Summary

At the Technical University of Munich eight tests on different full scale masonry walls under static-cyclic loading were performed, to investigate the behaviour under seismic loading. Seven wall specimens were built of calcium silicate units with different dimensions and material properties, one specimen was constructed with clay bricks. Chapter 2 gives a detailed overview of the materials and the geometric dimensions of the specimen.

In chapter 3 the test setup is described and the results, especially the maximum horizontal load bearing capacity, the horizontal deformation capacity and the ductility of the different walls, are displayed. In addition to it, the results of walls with different properties are compared to each other. Among others, the comparison of the influence of the vertical compression level shows, that an increasing normal force leads to an increasing maximum horizontal bearing capacity, but the enhancement is not proportionally.

The comparison of tests with specimens, constructed with calcium silicate elements with an internal reinforcement, to the unreinforced ones, shows the significantly increased load bearing capacity of the reinforced elements and an enormous enhancement of the fullness of the hysteresis.

The reduction of the overlapping length of the calcium silicate elements, compared to an overlapping length of half an unit, leads only to a small reduction of the maximum horizontal force, but at the same time, the specimens showed completely different crack pattern.

The comparison of specimen CS04 with CS05 resp. CS06 should display the influence of the length of the tested walls. Unfortunately, the behaviour of the specimen was totally different. Therefore, a reasonable conclusion about this influence was not possible. To get authoritative results, some additional tests with miscellaneous geometries have to be carried out.

5. References


[6] Schermer, D.: Theoretical Investigation on Stress States of Masonry Structures Subjected to Static and Dynamic Shear Loads (Lateral Loads); Analysis of Apartment House; Technical report of the collective Research project ESECMaSE, 2005
6. ANNEX

**Figure 18:** Dimension of the test specimen CS01

**Figure 19:** Position of the hydraulic actuators at test specimen CS01
Figure 20: Position of the LVDTs at test specimen CS01

Figure 21: Crack pattern of the test specimen CS01
Figure 22: Crack pattern of the test specimen CS01

Figure 23: Load-displacement curve (hysteresis) of the test on specimen CS01
Figure 24: Progress of the vertical forces V1 and V2 during the test on specimen CS01

Figure 25: Progress of the horizontal force H during the test on specimen CS01
Figure 26: Progress of the horizontal displacement during the test on specimen CS01

Figure 27: Progress of the vertical displacements during the test on specimen CS01
Figure 28: Progress of the in-plane bending moments at the top and at the bottom of the wall during the test on specimen CS01

Figure 29: Progress of the in-plane rotation at the top of the wall during the test on specimen CS01
Figure 30: Dimension of the test specimen CS02

Figure 31: Position of the hydraulic actuators at test specimen CS02
Figure 32: Position of the LVDTs at test specimen CS02

Figure 33: Crack pattern of the test specimen CS02
Figure 34: Crack pattern of the test specimen CS02

Figure 35: Load-displacement curve (hysteresis) of the test on specimen CS02
Figure 36: Progress of the vertical forces V1 and V2 during the test on specimen CS02

Figure 37: Progress of the horizontal force H during the test on specimen CS02
Figure 38: Progress of the horizontal displacement during the test on specimen CS02

Figure 39: Progress of the vertical displacements during the test on specimen CS02
Figure 40: Progress of the in-plane bending moments at the top and at the bottom of the wall during the test on specimen CS02

Figure 41: Progress of the in-plane rotation at the top of the wall during the test on specimen CS02
Figure 42: Dimension of the test specimen CS03

Figure 43: Position of the hydraulic actuators at test specimen CS03
Figure 44: Position of the LVDTs at test specimen CS03

Figure 45: Crack pattern of the test specimen CS03
Figure 46: Crack pattern of the test specimen CS03

Figure 47: Load-displacement curve (hysteresis) of the test on specimen CS03
**Figure 48:** Progress of the vertical forces V1 and V2 during the test on specimen CS03

**Figure 49:** Progress of the horizontal force H during the test on specimen CS03
**Figure 50:** Progress of the horizontal displacement during the test on specimen CS03

**Figure 51:** Progress of the vertical displacements during the test on specimen CS03
**Figure 52:** Progress of the in-plane bending moments at the top and at the bottom of the wall during the test on specimen CS03

**Figure 53:** Progress of the in-plane rotation at the top of the wall during the test on specimen CS03
**Figure 54:** Dimension of the test specimen CS04 with the internal reinforcement

**Figure 55:** Position of the hydraulic actuators at test specimen CS04
**Figure 56:** Position of the LVDTs at test specimen CS04

**Figure 57:** Crack pattern of the test specimen CS04
Final cracks:

**Figure 58**: Crack pattern of the test specimen CS04

**Figure 59**: Load-displacement curve (hysteresis) of the test on specimen CS04
Figure 60: Progress of the vertical forces V1 and V2 during the test on specimen CS04

Figure 61: Progress of the horizontal force H during the test on specimen CS04
Figure 62: Progress of the horizontal displacement during the test on specimen CS04

Figure 63: Progress of the vertical displacements during the test on specimen CS04
Figure 64: Progress of the in-plane bending moments at the top and at the bottom of the wall during the test on specimen CS04

Figure 65: Progress of the in-plane rotation at the top of the wall during the test on specimen CS04
Figure 66: Dimension of the test specimen CS05

Figure 67: Position of the hydraulic actuators at test specimen CS05
Figure 68: Position of the LVDTs at test specimen CS05

Figure 69: Crack pattern of the test specimen CS05
Figure 70: Crack pattern of the test specimen CS05

Figure 71: Load-displacement curve (hysteresis) of the test on specimen CS05
Figure 72: Progress of the vertical forces V1 and V2 during the test on specimen CS05

Figure 73: Progress of the horizontal force H during the test on specimen CS05
Figure 74: Progress of the horizontal displacement during the test on specimen CS05

Figure 75: Progress of the vertical displacements during the test on specimen CS05
Figure 76: Progress of the in-plane bending moments at the top and at the bottom of the wall during the test on specimen CS05

Figure 77: Progress of the in-plane rotation at the top of the wall during the test on specimen CS05
Figure 78: Dimension of the test specimen CS06 with the internal reinforcement

Figure 79: Position of the hydraulic actuators at test specimen CS06
Figure 80: Position of the LVDTs at test specimen CS06

Figure 81: Crack pattern of the test specimen CS06
Figure 82: Crack pattern of the test specimen CS06

Figure 83: Load-displacement curve (hysteresis) of the test on specimen CS06
Figure 84: Progress of the vertical forces V1 and V2 during the test on specimen CS06

Figure 85: Progress of the horizontal force H during the test on specimen CS06
Figure 86: Progress of the horizontal displacement during the test on specimen CS06

Figure 87: Progress of the vertical displacements during the test on specimen CS06
Figure 88: Progress of the in-plane bending moments at the top and at the bottom of the wall during the test on specimen CS06

Figure 89: Progress of the in-plane rotation at the top of the wall during the test on specimen CS06
Figure 90: Dimension of the test specimen CS07 with the internal reinforcement

Figure 91: Position of the hydraulic actuators at test specimen CS07
Figure 92: Position of the LVDTs at test specimen CS07

Figure 93: Crack pattern of the test specimen CS07
Figure 94: Crack pattern of the test specimen CS07

Figure 95: Load-displacement curve (hysteresis) of the test on specimen CS07
Figure 96: Progress of the vertical forces V1 and V2 during the test on specimen CS07

Figure 97: Progress of the horizontal force H during the test on specimen CS07
Figure 98: Progress of the horizontal displacement during the test on specimen CS07

Figure 99: Progress of the vertical displacements during the test on specimen CS07
Figure 100: Progress of the in-plane bending moments at the top and at the bottom of the wall during the test on specimen CS07

Figure 101: Progress of the in-plane rotation at the top of the wall during the test on specimen CS07
**Figure 102:** Dimension of the test specimen Clay01

**Figure 103:** Position of the hydraulic actuators at test specimen Clay01
Figure 104: Position of the LVDTs at test specimen Clay01

Figure 105: Crack pattern of the test specimen Clay01
Figure 106: Crack pattern of the test specimen Clay01

Figure 107: Load-displacement curve (hysteresis) of the test on specimen Clay01
Figure 108: Progress of the vertical forces V1 and V2 during the test on specimen Clay01

Figure 109: Progress of the horizontal force H during the test on specimen Clay01
Figure 110: Progress of the horizontal displacement during the test on specimen Clay01

Figure 111: Progress of the vertical displacements during the test on specimen Clay01
Figure 112: Progress of the in-plane bending moments at the top and at the bottom of the wall during the test on specimen Clay01

Figure 113: Progress of the in-plane rotation at the top of the wall during the test on specimen Clay01