ABSTRACT

The determination of the shear strength parameters by means of in-situ shove test is a key issue in the material characterization of unreinforced brick masonry buildings. The wall stress distribution following the removal of the bricks and the mortar joint dilatancy affect the determination of the friction angle and the initial shear strength respectively. A new approach for the definition of the compression in the test unit and the evaluation of the effect of the joint dilatancy on the initial shear strength has been developed. The compression in the test unit is evaluated based on simple formulas which relate the compression stress on the test unit to both the geometry of the specimen and the existing compression on the wall. The joint dilatancy produces an increment of both shear and normal stress at the initial phase of the shove test when the specimen is at low level of compression and at small relative horizontal displacements. In particular, it was observed that the increment of normal stress is due to restrain the tendency of the joint to expand vertically while the brick is pushed. The new approach was validated by means of an experimental benchmark campaign developed at University of Pavia and Delft University of Technology in which specimens made by replicated brick masonry were subjected to triplet tests.

Keywords: shove test; shear strength; cohesion; dilatancy; unreinforced masonry.

1. INTRODUCTION

1.1 Context

This paper is the result of a work performed by Arup, in collaboration with University of Pavia, EUCENTRE and TU Delft, on the mechanical characterization of brick masonry for seismic risk assessment and the structural upgrading of buildings in The Netherlands. Induced seismic hazard is due to hydrocarbons extraction, whereas structural upgrading of buildings is the intervention in which Arup is involved to mitigate this risk. A testing campaign was organized between 2015 and 2017 for the mechanical characterization of the masonry which is the main structural material of the building stock in Groningen province (roughly 70% of the total amount of buildings, Zapico et al. 2018).

1.2 The importance of In-Situ testing

The evaluation of the structural behavior of an entire existing building is a non-trivial task. The problem can be very complex, especially for brick masonry buildings. The bricks and the mortar are two independent materials, each possessing inherently different properties. When an existing masonry building is analyzed to assess its structural behavior, it is not sufficient to test only the properties of one

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single component (e.g. compressive strength of the bricks). Therefore, it is recommended to evaluate the behavior of all components acting together. In order to characterize these components, it is possible to perform laboratory as well as in-situ tests. The first are destructive and time consuming, implying the extraction of several material samples per building. Since this would excessively damage the buildings, it is practically impossible to perform large amount of laboratory tests. Therefore, non-destructive and slightly-destructive testing methods become relevant. This kind of tests can be easily performed in-situ, but imply added uncertainties in the interpretation of results. The idea of the presented testing campaign was to find reliable correlations between laboratory and in-situ tests results. As a result future extensive material characterization campaigns would benefit of having many but low invasive in-situ tests correctly calibrated with benchmark laboratory test results. A proposal for an improved interpretation procedure of a specific slightly-destructive in-situ test is presented in this paper. The method is called shove test and it is adopted to assess the sliding shear strength parameters of brick masonry. These parameters are fundamental for the seismic assessment of a masonry building, especially when the floor diaphragms and anchorages are sufficient to ensure a box behaviour of the building, when the walls in-plane failure is not precluded by premature local out-of-plane mechanisms.

2. SHOVE TEST INTERPRETATION: STATE OF THE ART

The purpose of the test is to estimate the shear strength of brick masonry in case of through-joints failure (i.e. strong brick and weak mortar), evaluating in-situ the shear strength index of the two horizontal bed joints bounding a single brick unit. This type of failure is commonly represented by Coulomb-type criteria (eq. 1). This formulation is based on two parameters: the cohesion, \( f_{v0} \) (shear strength at zero normal compression), and the friction coefficient, \( \mu \). The current standard regarding the shove test procedure and results interpretation is the ASTM C1531-16 in which three testing methods are presented. “Method A”, in which two flat jacks, one above and one below the tested brick, control the vertical stress and the horizontal load is applied by means of a small cylindrical jack (Figure 1), appears to be the most complete.

The first step consists in applying a vertical compressive load by means of two flat jacks a couple of courses above and below the test unit. Then, the brick is pushed horizontally by a jack, after the removal of two adjacent bricks in the same course (Figure 1). The procedure is repeated at increasing load steps imposed by the flat jacks. Using a linear regression, it is possible to obtain the sliding shear strength, \( \tau \), as a function of the normal compressive stress \( \sigma_b \) in the brick unit test according to the Coulomb’s law:

\[
\tau = f_{v0} + \mu \cdot \sigma_b
\]

Where \( f_{v0} \) is the bed joint shear stress at zero normal compressive stress, i.e. cohesion \( (\sigma_b = 0) \) and \( \mu \) is friction coefficient of the masonry. The friction coefficient is taken as the slope of the line relative to the linear regression of all the points \((\sigma_{bl}, \tau_l)\), except the first \((\sigma_{bl1}, \tau_c)\).

![Figure 1. Shove test setup and definition of the stresses. (Rossi et al. 2015)](image-url)
2.1 ASTM C1531-16 interpretation procedure

In ASTM C1531-16 (ASTM 2016) the compressive stress is calculated by using the modification factor $j$ that multiplies the stress applied by the flat jacks to the masonry $\sigma_j$:

$$\sigma_b = j \cdot \sigma_j$$  \hspace{1cm} (2)

Where $\sigma_b$ is the normal stress on test unit and $j$ is the modification factor which depends on the wall configuration. This interpretation procedure has intrinsic critical aspects. For instance, the existing vertical compression in the wall is not taken into account. ASTM C1531-16 (ASTM 2016) considers $\sigma_b=0$ if $\sigma_j=0$, while lab tests performed at DICAr laboratory (University of Pavia) as well as nonlinear numerical models have shown that this is not the case. Not considering the compression of the brick at $\sigma_j=0$ leads to unrealistic results. Furthermore, the procedure does not take into account the effect of bed joint dilatancy at the onset of sliding.

3. AN IMPROVED SHOVE TEST INTERPRETATION PROCEDURE

In this paper, an improved interpretation procedure to calculate more accurately the effective normal stress on the test brick based on experimental and numerical results from previous researches is proposed (Rossi et al. 2015 and Graziotti et al. 2018). According to this approach, the main factors affecting the normal compressive stress in the test unit are:

a) The modification of stress flow due to removal of the bricks adjacent to the test unit (flat jack contribution);

b) The far-field effect due to the overburden loads acting on the wall;

c) The restrained expansion of the bed joints due to dilatancy at the onset of sliding.

3.1 Flat jack pressure contribution

Two approaches are presented herein to determine the contribution of the flat jack pressure to the normal compressive stress on the test brick by means of a correction factor ($\sigma_{bj} = k_{bj} \sigma_j$). The first one uses a correction factor calculated as the ratio of the elastic moduli of the masonry measured before and after removal of the adjacent bricks, according to the double flat jack method described in ASTM C1197-14a. It was originally proposed by Rossi et al. (2015) and refined by Graziotti et al. (2018). The second approach considers a correction factor based solely on the dimensions of test brick and of flat jacks (Graziotti et al. 2018). In Figure 2, the geometric effect on the compressive stress diffusion from the flat jack to the test unit is qualitatively showed (Rossi et al. 2015).

![Figure 2. Flat jack pressure contribution to the normal stress on the test brick: qualitative stress flow in the shove-test configuration. (Rossi et al. 2015)](image-url)
3.1.1 Refined approach: elastic moduli ratio

The jack-to-brick correction factor \( k_{bj} \) is the ratio between the elastic modulus of the masonry between the flat jacks \( E \) and a fictitious elastic modulus \( E^* \). The values of \( E \) is obtained executing the double flat jack test on the intact wall (Figure 3) whereas the fictitious elastic modulus is obtained executing the double flat jack test on the wall in shove test configuration (adjacent bricks to test-unit removed).

![Double flatjack test](Image)

**Figure 3. Elastic modulus and fictitious elastic modulus. (Rossi et al. 2015)**

3.1.2 Simplified approach: Flat jack-to-Brick Length ratio

Experimental results showed that an initial estimate of the jack-to-brick correction factor \( k_{bj} \) could be obtained considering only geometric properties of the test setup, using the following relation (for single-leaf walls) proposed by Graziotti et al. (2018):

\[
k_{bj} = A_{je} / A_b
\]

Where \( A_{je} \) is the effective contact area between the flat jacks and the masonry wythe containing the test brick. The effective contact area is calculated simply looking at deformed shape of the flat jack after the pumping of the oil; \( A_b \) is the area of the horizontal cross-section of the test brick. When this procedure is adopted, evaluating the fictitious elastic modulus, \( E^* \), is not necessary, and only one double flat jack test on the intact masonry wall has to be performed in order to determine the elastic modulus, \( E \).

3.2 Far-field effect contribution

The far-field effect is due to the existing vertical compression in the wall which is sum of overburden and wall self-weight. It is possible to calculate the overstress due to the far-field effect \( \sigma_{bf} \) from the residual shear strength \( \tau_{res} \) according to relation (4), because they both represent the same phenomenon as shown in Figure 4. The residual shear strength \( \tau_{res} \) is the y-intercept of the linear regression line of all the test points except the first (Figure 4), and should be in theory null.

\[
\sigma_{bf} = \frac{\tau_{res}}{\mu}
\]

(4)
3.3 Dilatancy contribution

In general terms, dilatancy is a mechanical phenomenon that implies the tendency to expansion under plastic shear strain. In case of brick masonry, the dilatancy happens in the mortar bed joints. The sliding surface of a mortar bed joint may be seen as a composition of asperities with different size (Figure 5). Primary asperities are the largest ones and are responsible of bed-joint dilation ($\psi$) while secondary asperities, which act at a smaller scale, govern the friction at the inclined contacts of primary asperities ($\phi_v$). Depending on the boundary conditions, if the vertical dilation of the mortar joint is constrained it results in a local variation of the normal stress with the consequent variation of the initial shear strength. Considering that the most critical aspect of the shove test is the evaluation of the compressive stress in the mortar bed joint, the dilatancy is a phenomenon that cannot be disregarded.

Experimental tests (Andreotti et al. 2018) show that the dilation behaviour varies with the magnitude of sliding shear displacement and normal compression. Larger dilatancy angles can be observed upon first-cracking and during the initial stage of sliding, especially if the normal compressive stress is low. The sliding brick of a shove test is confined at top and bottom by the surrounding masonry, compressed by the flat jacks, and by the overburden loads: in this configuration, the dilation of the two mortar joints is partially restrained. The onset of sliding results then in additional normal stress on the tested brick, $\sigma_{bdil}$, to overcome the clamping effect of the surrounding material. Since both dilatancy angle and dilation reduce as sliding displacement and normal compression increase, only the first data point, ($\sigma_{b,i}, \tau$), can be significantly influenced by this effect. It is then possible to estimate the contribution of dilatancy to the normal compressive stress as follows (Graziotti et al. 2018):

$$\sigma_{bdil,i} = \begin{cases} k_{dil} \cdot (\sigma_{bj,i} + \sigma_{bff}) & \text{for } i = 1 \\ 0 & \text{for } i = 2, \ldots, N \end{cases}$$

(5)

Where $i$ is the identification number of the test points and $k_{dil}$ is theoretically a function of the dilatancy angle $\psi$. Numerical results on single-wythe calcium-silicate masonry walls obtained by Andreotti et al.
(2018) and experimental evidence on double-wythe clay-brick walls by Rossi et al. (2015) suggest that \( k_{dil} \) can be set between 0.1 (lower values of \( \psi \)) and 0.5 (higher values of \( \psi \)).

### 3.4 Determination of the cohesion

The total normal stress on the test brick for the initial test point \((i=1)\) can be calculated as follows:

\[
\sigma_{b,i} = \sigma_{bj,i} + \sigma_{bff} + \sigma_{bdil}
\]

(6)

If a straight line with slope equal to \( \mu \) is drawn on the \((\sigma_b, \tau)\) plane through the initial test point \((\sigma_{b,i}, \tau_c)\), its \( y \)-intercept represents the real cohesion, \( f_{v0} \), as shown in Figure 6:

\[
f_{v0} = \tau_c - \mu \cdot \sigma_{b,i}
\]

(7)

![Figure 6. Determination of the cohesion with the new approach. (Graziotti et al. 2018)](image)

### 4. BENCHMARK TESTING CAMPAIGN

In September 2016, a benchmark campaign for material testing took place at Delft University of Technology. Both destructive and non/slightly destructive tests were performed under controlled laboratory conditions on replicated calcium silicate brick masonry wall (measured brick dimensions 214x102x72 mm). The companion samples were constructed, aside from the large-scale wall adopted for the shove test activities with the aim to be subjected to destructive tests. Non-destructive tests were performed on the wall at various locations whereas slightly destructive tests were performed on the wall at three locations. The shear properties obtained by the triplet tests were used as a benchmark to interpret the results obtained from the Shove Test. In Table 1 a summary of all the tests performed during the campaign is presented and in Figure 7 the test setup are shown.

<table>
<thead>
<tr>
<th>Test Category</th>
<th>Test type</th>
<th>No. specimen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Destructive tests</td>
<td>Triplet tests</td>
<td>10 triplets</td>
</tr>
<tr>
<td>Non-destructive in-situ tests</td>
<td>Rebound hammer test</td>
<td>1 wall</td>
</tr>
<tr>
<td></td>
<td>Penetrometric test on mortar</td>
<td>1 wall</td>
</tr>
<tr>
<td></td>
<td>Ultrasonic test</td>
<td>1 wall</td>
</tr>
<tr>
<td>Slightly destructive in-situ tests</td>
<td>Single flat jack test</td>
<td>3 tests on 1 wall</td>
</tr>
<tr>
<td></td>
<td>Double flat jack test</td>
<td>3 tests on 1 wall</td>
</tr>
<tr>
<td></td>
<td>Shove test</td>
<td>3 tests on 1 wall</td>
</tr>
<tr>
<td></td>
<td>Bond-wrench test</td>
<td>1 wall</td>
</tr>
</tbody>
</table>
4.1 Shear Triplet Tests Results

The triplet tests were performed according to EN 1052-3:2002 standard. Fourteen specimens of modified triplet were prepared. The modified triplet is made of bricks bonded in different patterns as shown in Figure 8. The results of all the shear tests performed on modified triplets gave the benchmark values of cohesion and friction for calcium silicate brick masonry.

In particular, a cohesion value $f_{c0}$ of 0.18 MPa and a friction coefficient $\mu$ of 0.5 were found.
4.2 Shove Test on a replicated masonry wall

All the shove tests were performed on a single calcium silicate wall at three locations. The dimensions of the wall were approximately 2 m long and 3.3 m high. The wall was built within a steel frame and it was pre-compressed via pre-stressed rods placed between the top steel beam and the steel column to simulate the gravity loads in a real building situation. Load cells measured the applied pre-compression force.

The three different test locations were the following:

- Test location n.1: eight bricks courses from the bottom of the wall with a pre-compression overburden equal to 0.25 MPa;
- Test location n.2: seven bricks courses from the top of the wall with a pre-compression overburden equal to 0.6 MPa;
- Test location n.3: exactly at the middle of the wall with the lowest overburden level equal to 0.15 MPa.
After the three tests it was decided to perform one more test in the third location to simulate a shorter brick dimension, i.e. reduced bed joint shear area already in de-cohesion phase. This additional test allowed to verify the reliability of the simplified approach for the calculation of the flat jacks pressure contribution.

![Figure 10. Benchmark campaign: shove test.](image)

### 4.3 Interpretation of the shove test with ASTM 1531 procedure

The Shove Test results using the ASTM C1531 procedure are summarized in Table 2. The results of these tests are a further confirmation of the problem of the ASTM C1531 procedure in estimating the cohesion. The average value of the cohesion was calculated only with the first three results and resulted to be 0.36 MPa. This value was considered the most appropriate to take since the brick in the fourth test has already undergone large plastic displacements in the third test, having already reached a de-cohesion phase. Thus, the value 0.13 MPa is mostly due to “far-field” effect and thus is not a real cohesion.

![Figure 11. Test location 3*: Shove test setup.](image)

<table>
<thead>
<tr>
<th></th>
<th>$j$</th>
<th>$f_{cc}$ [MPa]</th>
<th>$\mu$ [-]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST 1</td>
<td>1.7</td>
<td>0.40</td>
<td>0.46</td>
</tr>
<tr>
<td>TEST 2</td>
<td>1.7</td>
<td>0.35</td>
<td>0.56</td>
</tr>
<tr>
<td>TEST 3</td>
<td>1.7</td>
<td>0.34</td>
<td>0.45</td>
</tr>
<tr>
<td>TEST 3*</td>
<td>1.7</td>
<td>0.13</td>
<td>0.47</td>
</tr>
<tr>
<td>average</td>
<td></td>
<td>0.36</td>
<td>0.49</td>
</tr>
</tbody>
</table>

Table 2. Summary of all the results. (Bonura 2017)
4.4 Interpretation of the shove test with the new procedure

The tests results were then re-processed and interpreted with the new interpretation procedure presented in this paper and proposed by Rossi et al. (2015) and Graziotti et al. (2018).

4.4.1 Interpretation not considering the dilatancy contribution

The proposed procedure was first applied taking into account only the flat jack contribution and the far-field effect. Regarding the flat jack contribution, in order to assess the jack-to-brick coefficient $k_{bj}$, both the simplified and refined procedure were applied. For the refined procedure, double flat jack test in both intact masonry and shove test configuration was performed for all the four shove test, in order to derive the elastic moduli ratio. The results are summarized in Table 3.

<table>
<thead>
<tr>
<th></th>
<th>$k_{bj}$ (simplified approach)</th>
<th>$k_{bj}$ (refined approach)</th>
<th>$\mu$ [-] (simplified approach)</th>
<th>$\mu$ [-] (refined approach)</th>
<th>$f_{c0}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST 1</td>
<td>1.43</td>
<td>1.26</td>
<td>0.55</td>
<td>0.63</td>
<td>0.27</td>
</tr>
<tr>
<td>TEST 2</td>
<td>1.61</td>
<td>1.65</td>
<td>0.59</td>
<td>0.57</td>
<td>0.23</td>
</tr>
<tr>
<td>TEST 3</td>
<td>1.59</td>
<td>1.34</td>
<td>0.48</td>
<td>0.57</td>
<td>0.23</td>
</tr>
<tr>
<td>TEST 3*</td>
<td>1.92</td>
<td>1.34</td>
<td>0.42</td>
<td>0.60</td>
<td>0.018</td>
</tr>
</tbody>
</table>

The average value of the cohesion, calculated only with the first three results (i.e. test 1, 2 and 3), is 0.24 MPa. With the new proposed procedure, the value of cohesion taking into account the far-field effect is 33% lower than the one found with the ASTM procedure. This confirms how the results are affected by the far-field effect (not accounted in ASTM procedure). This can be clearly noticed looking at the value of cohesion for the test 3* which is now 0.018 MPa (close to 0) which has expected, since the cohesion for this test should be null.

4.4.2 Interpretation considering the dilatancy contribution

The simplified methodology was re-applied to re-interpret the results of the shove tests considering also the bed joint dilatancy contribution. In Table 4 the data needed for the calculation performed for all the three shove tests are presented. The shove test 3* is not considered since is a test at zero cohesion.

Table 4. Input data for the calculation of the corrected cohesion. (Bonura 2017)

<table>
<thead>
<tr>
<th></th>
<th>$\mu$ [-]</th>
<th>$\tau_c$ [MPa]</th>
<th>$\sigma_{bj,l} + \sigma_{bff}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST 1</td>
<td>0.55</td>
<td>0.47</td>
<td>0.17</td>
</tr>
<tr>
<td>TEST 2</td>
<td>0.59</td>
<td>0.44</td>
<td>0.19</td>
</tr>
<tr>
<td>TEST 3</td>
<td>0.48</td>
<td>0.41</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The results of the calculations are presented in Table 5. The calculations were performed according to eq.5 proposed by Graziotti et al. (2018) where the coefficient $k_{dil}$ for the calculation of the overstress due to dilatancy ($\sigma_{dil}$) ranges between 0.1 and 0.5.
Table 5. Calculation of the “corrected” cohesion. (Bonura 2017)

<table>
<thead>
<tr>
<th></th>
<th>$\sigma_{bdil}$ [MPa]</th>
<th>$\sigma_{b1}$ [MPa]</th>
<th>$f_{v0}$ [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>TEST 1</td>
<td>0.017 - 0.085</td>
<td>0.19 - 0.26</td>
<td>0.26 - 0.22</td>
</tr>
<tr>
<td>TEST 2</td>
<td>0.019 - 0.095</td>
<td>0.21 - 0.29</td>
<td>0.21 - 0.17</td>
</tr>
<tr>
<td>TEST 3</td>
<td>0.019 - 0.094</td>
<td>0.21 - 0.28</td>
<td>0.22 - 0.18</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>0.23 - 0.19</td>
</tr>
</tbody>
</table>

The results confirm the importance to consider the contribution of dilatancy on the calculation of the cohesion. In particular, the cohesion found with this approach ranges between 0.19 and 0.23 MPa which compares well with the 0.18 MPa found with the triplet tests.

5. CONCLUSIONS

The presented works focused on the interpretation of the results of a benchmark experimental campaign performed at Technical University of Delft in 2016 on replicated calcium silicate brick masonry representative of the building stock of Groningen in the north of The Netherlands. The aim was to validate a new interpretation procedure of an in-situ test called shove test, adopted to assess the sliding shear strength parameters of brick masonry. The new procedure is validated comparing the results of four shove tests executed in laboratory on a single leaf wall with the results of the triplets tests conducted on specimens extracted from the same wall.

The shear parameters found with the triplet tests were used as reference for interpreting the results of the shove test. The study showed that the interpretation procedure according to the ASTM 1531 leads to unreliable results in terms of cohesion. The difference on the value of cohesion between the triplet and the shove test was mainly due to the far field effect of overburden stresses and to the dilatancy phenomenon of the mortar bed joint at the onset of sliding. These aspects are not taken into account in the ASTM 1531 standards.

An alternative interpretation was adopted to calculate more accurately the effective normal stress on the test brick as the sum of three contributions. The first contribution comes from the applied flat jack pressure, considering the disturbance on the stress flow due to removal of the bricks adjacent to the test unit. The second component is caused by the far-field effect of the overburden loads. The last contribution is due to the restrained expansion of the bed joints due to dilatancy at the onset of sliding.

The conclusion of this study shows the effectiveness of the new interpretation procedure. However, these conclusions are the result of limited number of tests executed on a single leaf wall built with a specific type of bricks in controlled conditions. Looking at the problem from a wider perspective, further investigations are needed in order to take into account other aspects such as different masonry patterns, wall typologies, overburden level, construction quality and materials.

6. ACKNOWLEDGEMENTS

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7. REFERENCES


