NUMERICAL INTERPRETATION OF THE EXPERIMENTAL RESULTS OBTAINED WITH FLAT-JACK TESTS ON A BRICK MASONRY WALL

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Abstract

Four numerical simulations of the double flat-jack test on a historic brick masonry wall, using a finite element code, are presented. The aim is to show which of the simulations best fit the experimental results, achieved measuring the strain distribution in the area between the two flat-jacks and also in the area above the upper flat-jack.

The numerical and experimental results allow to compare: i) which is the strain distribution induced by the flat-jacks during the test; ii) which are the main directions of the local compressive and tensile stresses leading to cracks; iii) which of the chosen numerical simulations gives the best fit. Finally, these results show which is the volume of the masonry wall really involved in the test.

Keywords

Flat-jack test, brick masonry, numerical simulation, stress-strain distribution.

1. INTRODUCTION

In [1] the results of two double flat-jack tests on a brick masonry wall of the Museum of Science and Technology “Leonardo da Vinci” in Milan, in the building of the “Cavallerizze” (figure 1), the riding-stables built by Napoleon’s Army, were presented.

The tests are part of the investigation programme directed to the morphological and structural characterization of the Cavallerizze masonry walls, carried out by the DIS and supported by the Ministry of Cultural Heritage.

As well known, the double flat-jack test is used to detect the stress-strain behaviour [2,3,4,5,6] of a masonry wall. The experimental research carried out by the authors aimed both to characterize the masonry and to study the strain diffusion in the masonry during the test.
The test was codified by ASTM C1196-1991 and recommended by RILEM LUM.D.2-1990; its use is also recommended by the new Italian Seismic Code since 2003, as part of the on site investigation on existing masonry buildings.

For this test, two parallel jacks, inserted in the masonry at a distance of about 40 to 50 cm, delimit a wall specimen (WS), which reveals an appreciable size for applying a uni-axial compressive stress.

![Figure 1: Milan: a) part of the museum with the ex-riding-stable “Siloteca”; b) masonry wall area subjected to double flat jack test.](image)

Linear displacement transducers (LVDT) applied to the WS face provide information on vertical and horizontal displacements. Loading cycles can be performed at increasing stress levels in order to determine the deformability modulus of the masonry in its loading and unloading phases. Usually the maximum value of stress applied during the last cycle can be increased just further than the linear phase of the stress-strain diagram. Nevertheless, it is usually not recommended to arrive to, or near to the peak stress, in order to avoid destruction of the masonry. However, at the museum Leonardo Da Vinci, the tests with double flat-jacks were carried out beyond the linear phase till failure or close to failure i.e., to the peak stress. This was possible thanks to the restoration project, which allowed the demolition of some part of the load bearing walls.

The test aimed evaluating the effect of high stress levels in presence of a small volume of wall above the upper flat-jack reacting to the applied load (lack of stress response). Several LVDTs were placed outside and in the area between the flat-jacks in order to better evaluate that effect and the stress diffusion till failure.

In the following, after a brief description of the masonry typology, the experimental tests are reported, together with a numerical simulation of the flat-jack test using a finite element code.

2. EXPERIMENTAL

2.1 Masonry description

The “Cavallerizze Napoleoniche” located near the Olivetani Monastery (figure 1) were built during the French occupation and were used as riding-stables by the Napoleonic Army. The history of the construction reports a traumatic event during the second world war, when the stables were partially destroyed. Nowadays, compared to the original plan with two
blocks of eight stables each, only six stables of one of the two blocks are remaining. The first two are used as a Museum deposit (named Siloteca) and are in quite good state of conservation. The other four are in worst conditions, partially roofed, partially collapsed and decayed. The masonry face texture is well organized with regular horizontal courses as reported in figure 2. The masonry section is made of three leaves of header bricks, one of which is alternatively constituted by half brick.

![Prospect of the masonry wall](image1)

![Section of the masonry wall (A-A)](image2)

Figure 2: Scheme of the masonry texture of Cavallerizze

### 2.2 Mortar property

The mortar joints height is around 15 mm. The joints are made of lime mortar with siliceous aggregate. The quality of the mortar determined by the Pointing Hardness tester (Schmidt Pendulum Hammer PM), according to Rilem Recommendation MS-D7, is “soft”.

### 2.3 Brick property

Three brick units were sampled from the Museum in three different areas of the building (MST-06, MST-07, MST-08) for physical and mechanical tests. The compression tests were carried out according to the EN 772-1, following laboratory modifications, on three aligned brick cubes 40x40x120 mm (figure 3), in order to obtain a reliable stress-strain compression law. Indirect tensile test were also carried out on single cubes 40x40x40 mm according to ASTM C1006-2007, with small laboratory modifications.

![Cubic brick specimens preparation](image3)

![Three aligned bricks cubes subjected to compression test](image4)

Figure 3: a) Cubic brick specimens preparation; b) three aligned bricks cubes subjected to compression test

In figure 4 the stress-strain plot is reported, showing the behaviour of the 3 different bricks transformed in three aligned brick cubes specimens.

From the results of the laboratory tests, as well as from the visual inspection, the three sampled bricks showed different properties. Only the two more diffused in the masonry wall
were chosen (MST-08 and MST-07 bricks) for the numerical simulation, removing the bricks with the highest strength values.

![Stress-strain plot on three aligned brick cubes subjected to compression test](image1.png)

**Figure 4:** Stress-strain plot on three aligned brick cubes subjected to compression test

![Displacement transducers (LVDTs) applied on the external wall](image2.png)

**Figure 5:** Displacement transducers (LVDTs) applied on the external wall

### 2.4 Experimental results of the double flat-jack test

Of the tests reported in [1] only the double flat-jack test carried out on the external wall of the “Siloteca” (MSC-J7D) was used here for the numerical simulation (figure 1). The test was carried out cutting two mortar joints at a distance of 48 cm on the external side of a lateral wall. Four vertical and one horizontal displacement transducers were applied between the two slots. In order to monitor the strain diffusion, additional LVDTs were applied on the external side of the wall around the tested area (figure 5). The test was performed beyond the linear phase close to failure. The test was interrupted at an applied stress equal to 2,16 MPa, when one flat jack was suddenly damaged. The stress-strain plot measured by LVDTs 1, 2, 3, 4 and 5 are presented in figure 6a. Only some experimental results are presented and in particular in Table 1 the Elastic modulus and the “confined expansion ratio” are reported, evaluated on the envelope contour (figure 6a).

<table>
<thead>
<tr>
<th>LVDT Stress interval Δσ [N/mm²]</th>
<th>E secant [N/mm²]</th>
<th>Confined expansion ratio [εL/εV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average 1,2,3,4 0,1 – 0,5</td>
<td>830</td>
<td>0,3</td>
</tr>
</tbody>
</table>

Along the vertical line above the upper flat-jack, LVDTs 6, 7, 8 and 9 show a variation of vertical strain that quickly decreases from LVDTs 6 to 9 (figure 6b).
Figure 6: a) Stress-Strain plot of the test MST-J7D (average strain of LVDTs 1, 2, 3, 4) and b) peak strain-height plot at each loading cycle, with reference to measurement devices

Along the horizontal line above the upper flat-jack, LVDTs 6, 10, 11 and 12 show that the compression strain decreases from the flat-jack symmetry axis (Y) to the edge. In fact, on the right edge, LVDT 11 detects an important tensile strain which decreases to a low value when it reaches LVDT 12 (figure 7). Nevertheless, the strain at LVDT 12 is twice the one at LVTD 13. These data, in particular the strain at LVDT 11, show that the volume of the masonry above the upper flat-jack, that is pushed during the test, is much larger than the column included in the vertical limits of the flat-jack.

Figure 7: Strain plot of the test MST-J7D of LVDTs 06, 10, 11, 12

3. NUMERICAL SIMULATION

3.1 Main strategies for the numerical modelling

Masonry is a composite material made of bricks (units) and mortar (joints), with distinct directional mechanical properties due to the mortar joints which act as planes of weakness.

The detailed analysis of such heterogeneous material with anisotropic characteristics demands the use of numerical models where the units, the mortar and the unit-mortar interface are represented separately.

In the literature two different methods, respectively named Micro-modelling [8,9,10,11,12,13] and Macro-modelling are used [14,15,16].

The choice of the modelling method depends not only on the purpose of the simulation, but it’s also the result of a compromise between complexity and dedicated time (to construct...
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the model and to obtain results), and the level of accuracy required in the analysis. In particular, when dealing with local phenomena, such as failure modes or joint sliding, it is necessary to refer to Micro-modelling. On the contrary, for the analysis of the global behaviour of masonry structures, where average values of stress and strain are considered, Macro-modelling is the best option. Therefore, for the analysis of global existing structures, it is usually not easy to assess the geometrical distribution and mechanical properties of brick and mortar (particularly inside the wall) and a numerical modelling assuming a single homogeneous material for the global masonry properties is easily and usually adopted, based on a linear elastic analysis.

3.2 Numerical Modelling of the flat-jack test

In order to achieve a more accurate numerical model, some numerical analysis were in the following evaluated and the results compared with the experimental results, in particular with the stress/strain behaviour of the “Siloteca” wall specimen (WS) included between the two flat jacks. For modelling, different levels of complexity were adopted in order to point out how the masonry behaviour could be represented and how these results are comparable with the experimental results.

The models were developed both with reference to the single masonry components (brick and mortar) and to the masonry as a whole (homogenous model). All the four models considered are 3D FE models (figure 8a) where the elements are organized as in a masonry texture, in a volume with similar dimension of the tested one. The first model (Mod. 1) uses the same linear-elastic constitutive law for bricks and mortar, (homogeneous linear-elastic model), characterized by an Elastic Modulus equal to the tangent at the origin of the envelope experimental WS stress-strain curve (figure 8b). The second model (Mod. 2) uses the experimental WS curve as a non-linear elastic constitutive law equal for bricks and mortar upon unloading (homogeneous non-linear elastic model). The third (Mod. 3) and the fourth models (Mod. 4) use two distinct non-linear constitutive laws for brick and mortar (non-homogeneous non-linear elastic models). The constitutive law of mortar is gathered from the experimental constitutive laws of two different bricks (MST08-3 bricks for Mod. 3 and MST07-1 for Mod. 4) and of the wall specimen (WS). In particular, in Mod. 3 and Mod. 4, the constitutive laws for mortar were gathered from the relationships of the composite materials theory, starting from the envelope experimental curve of the wall specimen (WS) and with the hypothesis that the masonry specimen is realised in the first case only with MST08-3 brick (Mod. 3) and in the second case only with MST07-1 brick (Mod. 4).

If the WS is axially compressed by flat jacks, $\Delta y$ is the general contraction of the masonry, obtained as the sum (1) of the single masonry components contraction under compression (figure 8b). The mortar strain $\varepsilon_m$ can be written for each applied stress ($\sigma = \sigma_m = \sigma_b = \sigma_w$), knowing the relative ratios of the brick and mortar thickness. In particular, the wall masonry specimen contraction due to the applied stress can be stated as:

$$\Delta y = \varepsilon_w \cdot H_w = \sum_{i} \varepsilon_h_i \cdot h_b_i + \sum_{j} \varepsilon_m_j \cdot h_m_j$$

(1)

where $\varepsilon_h_i$ and $h_b_i$ are respectively the strain and the height of the brick i; $\varepsilon_m_j$ and $h_m_j$ are respectively the average strain and the height of mortar joint j; $\varepsilon_w$ and $H_w$ are the average strain and the total height of the wall specimen. Strains are assumed to be uniform within each component.
From the wall masonry specimen shortening, with reference to the average values of the mortar joints and brick strain (2),

\[
\frac{\sum_{j=1}^{n} \varepsilon_{m,j} \cdot h_{m,j}}{\sum_{j=1}^{n} h_{m,j}} = \varepsilon_{m}, \quad \frac{\sum_{i=1}^{n} \varepsilon_{b,i} \cdot h_{b,i}}{\sum_{i=1}^{n} h_{b,i}} = \varepsilon_{b},
\]

it is possibile to obtain the average strain of the mortar joints from (3):

\[
\varepsilon_{m} = \varepsilon_{W} \cdot \frac{H_{W}}{\sum_{j=1}^{n} h_{m,j}} - \varepsilon_{b}, \quad \frac{\sum_{i=1}^{n} h_{b,i}}{\sum_{j=1}^{n} h_{m,j}}
\]

This evaluation can be repeated for different applied stress values and the stresses acting on both components are assumed to be the same. The constitutive laws corresponding to the two considered bricks (MST07-1 for Mod. 3 and MST08-3) can be evaluated.

3.2 Comparison between numerical and experimental results

The strain values derived from the four different numerical analyses are here compared with the directly on-site measured strains. In figure 9a,b) some numerical strain contour plots evaluated for the two components \(\varepsilon_{xy}\) and \(\varepsilon_{xx}\), are reported, referring to a state of stress applied by the double flat jacks and equal to 1.75 MPa. The maps show the compressed masonry area where compressive strains are significant (from \(1 \times 10^{-6}\) e \(1 \times 10^{-3}\)). The obtained maps look rather similar for all the four models, even if the non-homogenous models (both Mod.3 and 4) shows a wider strain diffusion, due to the bricks interaction. As similar, only the maps corresponding to the models 2 and 3 are represented in figure 9a-d. For all cases, the results show the local effect of the load applied by the double flat jacks test. In figure 9e the main cracks appeared on the wall during the test are schematicly represented.
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Figure 9: Strain maps referred to a state of stress applied by the double flat jacks and equal to 1.75 Mpa: a) and b) vertical strain $\varepsilon_{yy}$; c) and d) horizontal strain $\varepsilon_{xx}$; e) main cracks appeared on the wall during the test.

The comparison between the numerical and the experimental results of strain $\varepsilon_{yy}$ along the vertical line y direction ($X=0$) above the upper flat-jack of the “Siloteca” walls is presented in figure 10. The experimental vertical strain $\varepsilon_{yy}$ is rather well represented by all the four analytical models till the induced vertical stress is not higher than 0.3-0.5 MPa. Above these stress values, the fit gets worse and the deviation from the experimental curve increases, above all for the homogenous models. In figure 11 the comparison between the numerical and the experimental results of the average strain $\varepsilon_{yy}$ in the area between the two flat jack (WS) is presented.

The fit is good also for higher compressive stress levels, but only for the non-homogenous models (Mod.3 and 4). On the contrary, the curves, representing the homogenous models (Mod.1 and 2), increase the deviation with the increase of the stress level. At a compressive stress of 0.8 MPa, the linear-elastic model (Mod.1) presents a deviation from the experimental results equal to 50% that reaches the 100% for a stress of 1.6 MPa.
4. CONCLUSIONS

The experimental double flat-jack tests carried out on the brick masonry walls of the “Cavallerizze Napoletane” buildings have helped in analysing and understanding the stress and strain diffusion induced during the test.

As far as the masonry located above the upper flat-jack is concerned, some remarks could be put on evidence: i) the compressive stress diffusion has a slope equal to 45° to 50° (figure 9); ii) the compression strain along the vertical line (Y direction) rapidly decreases with the increase of the distance from the upper flat-jack (approximately equal to 0 at about 100 cm); iii) the experimental vertical strain $\varepsilon_{yy}$ measured along the symmetry axis over the upper flat jack is well represented by all the four numerical models but only when the stress applied is not exceeding 0.3-0.5 MPa (figure 10). For higher values of stress, the homogenous model is disregarded.

As far as the masonry located between the two flat-jacks is concerned, some remarks could be put on evidence: i) also for this area the experimental vertical strain $\varepsilon_{yy}$ is well represented by all the four numerical models but only for low stress values. For high values, the homogeneous models (Mod. 1 e Mod. 2) increase the deviation from the experimental results with the increase of the applied stress level. In particular at a compressive stress of 0.8 MPa, the linear-elastic model (Mod.1) presents a deviation from the experimental results equal to 50% that reaches the 100% for a stress of 1.6 MPa; ii) the fit is good for higher compressive stress levels, only for the non-homogenous models (Mod.3 and 4); iii) non-homogenous models, well represent the behaviour of the brick masonry wall (WS) subjected to compression by the double flat jack test; iv) the contour plots of the strains reported in figure 9 show that the strain state in the region around the two flat jacks is 3 dimensional, so that 2D models could not give a reliable results; v) although the mortar constitutive law is derived indirectly from the experimental results, the agreement between the experimental and numerical results confirms that the masonry wall specimen between the two flat jacks is mono-axially compressed and this in-situ test can be properly used for numerical modelling.
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