Experimental Investigation on Historic Brickwork Subjected to Eccentric Axial Loads

G. de Felice
University Roma Tre, Department of Structures, Rome, Italy

ABSTRACT: Quasi-static tests have been conducted on masonry specimens manufactured using old clay bricks and lime mortar, to be representative of brickwork used in railway arch bridges, built in central Italy in the last decade of 19th Century. The specimens have been subjected to monotonic and cyclic compression, under displacement control, with concentric and eccentric loading. The experiments show a significant post-peek resistance of brick masonry and its capability to sustain loading-unloading cycles in the softening branch. The Kent–Park model was shown to represent reasonably well the stress-strain behavior of brick masonry and the comparison with experiments shows that the assumption of plane section may be adequate in predicting the behavior under eccentric loading.

1 INTRODUCTION

The load carrying capacity of masonry arch bridges may be strongly affected by the compressive strength of masonry, especially in the case of brick masonry railway bridges, where high loading is combined with weak material. The response of masonry to eccentric loading is a primary issue for arch bridges, due to the high concentration of stress that develops as a consequence of eccentricity of the resultant over the arch section.

With this in mind, the present study aims at investigating the effective strength and deformation capacities of brick masonry under centered and eccentric loading, to be used for the assessment of structural safety of masonry bridges.

The behavior of brick masonry under compressive loading has been extensively investigated over a long period of time (see for instance: Aprile et al. 2001 for historical masonry; Macchi 1985, Naraine and Sinha 1989, AlShebani and Sinha 1999 for cyclic behavior). However, except for some recent contributions (Brenchich and Gambarotta 2005; Cavaleri et al. 2005; Roberts et al. 2006) most of the experimental researches have considered only uniform compressive loading, while, in the case of arch structures a high concentration of stress arise as a result of eccentricity of the resultant over the arch section. On the other hand, a wide research have been devoted to assess the behavior of walls under eccentric loading, but in this case, the experimental results are driven mainly by the slenderness of the walls, rather than on the strength of the material.

Aiming at reproducing, in experimental tests, the compressive behavior of brickwork used for masonry vaults built between 1890 and 1894 in the viaducts of the railway line between Rome and Viterbo, some exemplars of brick have been found from two of the masonry viaducts of the railway line; cubic samples measuring 50 mm of side have been derived from the bricks and undergone cyclic tests of uniaxial compression. Aiming at building specimens of brick masonry with the same characteristics as that of the bridges under study, similar samples of brick have been found, produced at the beginning of 1900 in the clink of Monterotondo, in the same geo-
graphic area of the site. When subjected to uniaxial compression, these samples exhibit a behavior close to that of original specimens. As regards the mortar, a pre-mixed mortar made by hydraulic lime and pit sand was employed. The structural properties of mortar have been obtained from standard compression and three points bending tests.

Ten specimens of brickwork have been realized with the mortar and bricks mentioned above and subjected monotonic and cyclic compression tests with eccentricity ranging from 0 (no eccentricity) to 80 mm. The tests have undergone under displacement control in order to register both the ascending and descending branch of the load displacement curve. Monotonic and cyclic tests, consisting of repeated loading-unloading cycles, both in the initial elastic branch and in the post-peak descending branch have been performed.

The results of experiments were finally used to build up a constitutive model for brick masonry under combined axial load and bending, to be used in the assessment of masonry bridges. The model originally proposed Kent & Park for the cyclic behavior of concrete, have been used, with the coefficients obtained from the experimental results with centered loading. Then, the tests with eccentric loading have been reproduced numerically to verify if the plane section assumption may be adopted for the assessment.

2 EXPERIMENTAL INVESTIGATION ON MASONRY COMPONENTS

A few samples of the original bricks used in the railway line between Rome and Viterbo were found on site. The bricks have dimensions 260 mm high, 130 mm wide and 55 mm thick. Twenty cubic samples with 45 ± 50 mm side were extracted from six of the bricks and submitted to monotonic and cyclic compression (Fig. 1).

Aiming at reproducing in the laboratory the brickwork used in the vaults, old bricks with the same dimension as the original samples, and similar mechanical properties, were found. It was a stock of bricks of the beginning of the XX century, produced in a clink in the same region of the bridges. Eleven cubic samples with 48 mm side have been extracted from six of these bricks, and submitted to monotonic and cyclic compression tests in the direction normal to the face of the bed joints, which were accurately levelled before the test (Fig. 2). No devices have been employed to reduce the friction between the specimen and the plates of the load frame during the test. In effect, the comparison with the tests performed on parallelepiped samples, show that the friction does not affect significantly the compressive strength.

The average properties of both original and historical bricks are compared in Table 1, with the relative standard deviations.

![Figure 1: Experimental stress-strain curve of bricks under monotonic (left) and cyclic (right) compression of the specimens extracted from the original bricks.](image-url)
The crack initiation phase starts relatively close to the peak load (75%-85% of the peak load) with small vertical cracks originating from one of the edge of the specimen in contact with the load plates, often associated with the expulsion of fragments of the brick from the corners. The crack pattern develops fast and, at peak load, the cracks interest the whole height of the specimen. The softening branch starts at this stage with growing of cracks and progressive lateral opening of the specimen. The specimen continues to cracks with a progressive detachment and buckling of the external brick slices. The loading-unloading branches in the softening phase, show the capability of the brick, heavily damaged, to sustain loading-unloading cycles, without appreciable stiffness degradation.

Pre-mixed mortar consisting of natural hydraulic lime and pit sand with sieving granulometry between 0 and 0.6 mm was used for masonry specimens. The mechanical characteristics of mortar were measured by proper tests. The compressive strength was obtained by using both cubic specimens having 40 mm side, and parallelepiped specimens with base mm 40x40 and height 80 mm. The tensile strength was estimated with three point bending tests on parallelepiped specimens with base mm 40x40 and length 160 mm as well as Brazilian tests on cylindrical specimens having 100 mm diameter and 200 mm height. In the latter case the loading was applied by means of a hard wooden listels with section mm 4x10. The experimental results on mortar specimens can be summarized as follows: the compressive strength has a mean (on eleven specimens) of 2.31 N/mm² and a SD of 0.69 N/mm², the deformation at peak stress results with a mean of 7.11 \(10^{-3}\) and a SD of \(1.58 \times 10^{-3}\), the three point bending tests give an average tensile strength of 1.18 N/mm² and a SD of 0.24 N/mm².
3 EXPERIMENTAL INVESTIGATION ON MASONRY PRISMS

The experimental investigation concerned ten brick masonry prisms consisting of five layers of bricks and six mortar joints, which have undergone centred and eccentric compression tests. It has been carried out using an MTS hydraulic load frame with 500 kN load rating. The tests have undergone with 10 Hz acquisition frequency, under displacement control with velocity $v_{\text{min}}=0.01$ mm/sec in the loading branch, in order to obtain the overall shape of the stress-strain relationship. Force control with velocity $v_{\text{min}}=500$ N/sec was used in the unloading branch, to avoid the complete unloading of the specimen.

Six specimens, made by five layers of half brick with base dimensions mm 140x140 and height 300 mm have been subjected to centred compression under displacement control. The stress-strain curve of both cyclic and monotonic tests are reported in Fig. 3; the average mechanical properties, together with the relative standard deviation, are summarized in Table 2, where $\sigma_0$ is the compression strength, $\varepsilon_0$ the deformation at peak stress, $E_0$ denote the elastic modulus at 40% peak stress, $\varepsilon_u$ the ultimate strain at 20% peak stress.

Table 2 : Experimental results of masonry prisms in compression

<table>
<thead>
<tr>
<th></th>
<th>Compressive Strength $\sigma_0$ (N/mm$^2$)</th>
<th>Deformation at peak stress $\varepsilon_0$ (10$^{-3}$)</th>
<th>Elastic Modulus secant at 0.4 $\sigma_0$ (N/mm$^2$)</th>
<th>Ultimate strain at 0.2 $\sigma_0$ $\varepsilon_u$ (10$^{-3}$)</th>
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</thead>
<tbody>
<tr>
<td>Mean</td>
<td>7.54</td>
<td>5.52</td>
<td>2094</td>
<td>17.84</td>
</tr>
<tr>
<td>Deviation</td>
<td>0.81</td>
<td>1.73</td>
<td>744</td>
<td>2.27</td>
</tr>
</tbody>
</table>

Figure 3 : Experimental behaviour of six brickwork samples made by five layers of bricks and six mortar joints, with base mm 140x140 and height 300 mm under compression.

The behaviour of masonry in compression remained linear elastic up to the first crack appearance, which takes place for a vertical stress between 50% and 80% of the peak stress. However, as shown by the cyclic tests, some irreversible effects appear in the linear range, due to the mortar layer compaction, which cause an increase in the stiffness of the specimen in the loading cycles subsequent to the first unloading. Under increasing loading, new vertical cracks appear and propagate to the other layers of bricks; at peak load, the specimen is divided into slender parts separated by vertical cracks. At this stage, the load carrying capacity decreases with the progressive spalling of an external slice of the specimen (Fig. 4)
Figure 4: Crack pattern at failure of masonry specimens under centred compression tests.

The eccentric compression tests were undertaken with four specimens, with base mm 140x280 (one brick) and height 300 mm (five brick layers), made by alternate layers of one brick and two half bricks with a mortar joint in the middle, according to the arrangement surveyed in the bridge vaults. The masonry prisms have been submitted to compression tests with eccentricity equal to 40 and 80 mm. For each eccentricity, one monotonic and one cyclic test have been performed. The testing set-up, which is represented in Fig. 5, comprises two steel bars with diameter 30 mm, acting as cylindrical hinges in contact with the plates of the load frame, and two steel I bars HEB140 stiffened with vertical flanges, in contact with the bases of the specimen. The load is applied through the cylindrical hinges to the I bars, which are free to rotate around the hinges. The I bars avoid a stress concentration on the specimen while providing the plane section condition at the bases of the masonry prism.

The specimens have been instrumented with seven displacement transducers. Four transducers with sensitivity 0.1 mm and operating range ±50 mm have been devoted to measure the relative displacement at the four edges of the steel I bars at the bases of the specimen. The other three transducers have been fixed to the bricks on the side with higher compression, to measure the local strain. Two resistive transducers, with sensitivity 0.05 mm and operating range ±5 mm, were placed in horizontal direction, one of which across the head mortar joint; one transducer with sensitivity 0.07 mm and operating range ±10 mm, in vertical direction.

The results of the experiments are represented in Fig. 6, where the bending moment is plotted versus the relative rotation of the bases, divided by the height of the specimen. It appears that the tests with higher eccentricity (e=80 mm) display a more ductile behaviour (in terms of moment-curvature) with respect to those with lower eccentricity (e=40 mm). This is due to the lower axial load of the tests with higher eccentricity (which is almost half of that with lower eccentricity), that allows a progressive cracking of the specimen. The decrease in strength is
slower since, with progressive crushing at the compressed edge of brickwork, the reacting section increases, extending towards the tensile side.

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Figure 6: Experimental bending moment–curvature relation of four specimens of brickwork made with five layers of bricks with base mm 140x280 under eccentric compression. The two specimens E1,E2 have eccentricity e=40 mm, while the two specimens E3,E4 have eccentricity e=80 mm.

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Figure 7: Crack pattern of a masonry specimen under eccentric compression test: lateral side (left); compressive front edge with vertical cracks due to crushing of bricks (centre); back edge with horizontal tensile crack at brick-mortar interface (right).

The first cracks form on the side of the brick, which sustain the higher compression, along the vertical alignment of head mortar joints. With increasing loading, vertical cracks appears also in the lateral faces of the specimen, in the proximity of the compressive edge; failure arises with crushing and spalling of the compressive edge of masonry. On the opposite side, a crack develops at the brick mortar horizontal interface. The crack pattern at the end of the test is shown in Fig. 7.
Aiming at reproducing the experimental behaviour, the uniaxial behaviour of masonry in compression is modelled according to the Kent and Park (1971) curve. Originally formulated for the behaviour of confined concrete, the Kent & Park model consists of an ascending branch represented by a second-degree parabolic curve, a linear descending softening branch and a final constant branch. The model is defined by three parameters, namely the peak stress $\sigma_0$, the corresponding strain $\varepsilon_0$, the ultimate strain $\varepsilon_u$, equal to the strain reached at stress level 0.2 $\sigma_0$. Denoting by $\bar{\sigma} = \sigma / \sigma_0$, and $\bar{\varepsilon} = \varepsilon / \varepsilon_0$ the normalized stress and strain respectively, the three branches write:

$$\sigma = 2\bar{\varepsilon} - \bar{\varepsilon}^2, \text{ for } 0 \leq \bar{\varepsilon} \leq 1; \quad \sigma = 1 - 0.8 \left( \frac{\bar{\varepsilon} - 1}{\eta - 1} \right), \text{ for } 1 \leq \bar{\varepsilon} \leq \eta; \quad \sigma = 0.2, \text{ for } \bar{\varepsilon} \geq \eta \quad (1)$$

where $\eta = \varepsilon_u / \varepsilon_0$; while no resistance is assumed in traction.

On the base of the experimental results of masonry prisms in centred compression, according to Table 2, the following values are given to the Kent & Park parameters: $\sigma_0 = 7.54 \text{ N/mm}^2$, $\varepsilon_0 = 5.52 \times 10^{-3}$, $\varepsilon_u = 1.78 \times 10^{-2}$.

Now, assuming the section remains plane under normal force and bending moment, the previously defined Kent & Park stress-strain relationship is integrated over the section in order to simulate the behaviour of masonry specimens under eccentric compression. The resulting diagrams are plotted in Fig. 8 for both eccentricities $e=40 \text{ mm}$ and $e=80 \text{ mm}$, together with the experimental results.

The comparison reveals a good agreement between the model and the experiments for $e=40 \text{ mm}$ both in the ascending and the softening branches, with a slight underestimate of the maximum sustainable bending moment. A higher discrepancy appears in the case of $e=80 \text{ mm}$, where the model behaves much stiffer than the experiments. One of the reason of the mismatching may lie in the localisation of cracks that have been observed in the experiments.

The results of the experimental investigation presented in this paper give a clear view of the mechanical behaviour of historical brick masonry when subjected to concentric and eccentric compressive loading. Even though the limited number of tests does not allows drawing up a general conclusion, some preliminary results can be outlined.

Historical brick masonry shows a long softening branch in compression, where, despite the damage state, the masonry reveals the capacity of sustaining loading-unloading cycles without appreciable stiffness degradation; this after-peak deformation capacity may play a significant role in safety assessment.
The Kent & Park model was shown to be adequate in representing the stress-strain relationship of brick masonry; the comparison between experimental and numerical results shows that the assumption of plane section is suitable for predicting the behavior of brick masonry under eccentric axial load.

The study, in conclusion, gives a contribution on the knowledge of the mechanical properties of brick masonry used in railway bridges, built in central Italy before 1900, and indicates a possible way to incorporate this information for structural modeling.

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REFERENCES


