IN-PLANE SHEAR AND OUT-OF-PLANE BENDING CAPACITY INTERACTION IN BRICK MASONRY WALLS

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SUMMARY
Under seismic loading a wall is subjected to simultaneous in-plane and out-of-plane actions. Numerous research to-date have considered the separate effects of these two actions. In this paper, the results of a series of tests with different levels of simultaneous in-plane shear and out-of-plane bending loadings on brick walls are presented. The tests results indicate noticeable interaction between the in-plane shear and out-of-plane bending strengths of brick walls. The interaction curve appears to follow a circular trend. A simple analytical approach is also presented for evaluating the in-plane shear and out-of-plane bending interaction curve for unreinforced brick walls.

Keywords: masonry, brick wall, in-plane shear, out-of-plane bending, capacity interaction

1. INTRODUCTION

During an earthquake, a brick wall, similar to any structural system, undergoes a global acceleration field in which it is subjected to both in-plane and out-of-plane loads; the former results from the storey shear force under horizontal loading and the latter is either due to the out-of-plane inertia force caused by the considerable mass of the brick wall or the out-of-plane action of the floor on the wall. Considerable experimental, numerical and analytical studies are carried out on the behaviour of masonry buildings, particularly under earthquake loading; most carried out on the behaviour of brick walls [1-8]. Many investigations on masonry were aimed at deriving simplified analytical models for the response and capacities of this material. Although analytical methods have their own limitations, they are popular due to simplicity. Majority of analytical methods have been presented for the in-plane shear response of masonry walls. Calderini et al [9] reported on a series of existing analytical methods for calculating the in-plane strength of unreinforced masonry walls. In another research, Bojsilivic et al [10] also reviewed the existing analytical methods for evaluating the in-plane strength of masonry walls and presented an approach for calculating the performance limit of masonry buildings. Roca [11] used simple equilibrium equations to calculate ultimate strength of solid brick walls and walls with openings under concentrated or distributed gravity and lateral loads. Giordano et al [12] also presented a simple formula for predicting the in-plane strength of masonry portals based on limit analysis approach. Benedetti and Steli [13] derived the lateral load-displacement curve for unreinforced and FRP reinforced masonry walls through analytical methods. They assumed an elastic-perfectly plastic behaviour for the masonry material.

Considerable experimental work is also reported for the strength and response of brick walls under out-of-plane loads including; Kanit and Atimatay [14], Griffith et al [15], Derakhshan et al [16] and Meisl et al [17]. In a recent experimental study Maheri et al [8] highlighted the orthotropic nature of the out-of-plane response of brick walls. In addition to the above experimental works, numerous numerical investigations have also been carried out in recent years to further study the individual responses of brick walls to in-plane and out-of-plane loading. A review of these studies is beyond the scope of this article. Good reviews can be found in [18-21].

Due to the multidirectional characteristic of the ground motion during an earthquake, the brick walls are simultaneously subjected to in-plane and out-of-plane loads. However, as reviewed above, the majority of studies on the behaviour of brick walls consider either the in-plane shear or the out-of-plane bending response. Very limited studies carried out on the response under simultaneous in-plane and out-of-plane loadings concentrate on infill panels. Shapiro et al [22] studied the interaction of the in-plane and out-of-plane responses in brick infills in concrete frames. They carried out a series of tests to investigate the effects of in-plane cracks on the out-of-plane strength of brick infills. Their test results showed that the in-plane cracks may reduce the out-of-plane strength of infills up to 100%. Another similar experimental study was carried out by Falangan et al [23] on brick infills in steel frames. Recently, Hashemi and Mosalam [24] have also studied the behaviour of concrete frames with infills under the combined effects of in-plane and out-of-plane loads. For this purpose, they conducted an in-plane shake table test on a concrete infilled frame. They subsequently used the test results to calibrate a numerical model which was further developed to include out-of-plane loading. In the present study, an experimental investigation directly addressing the in-plane shear, out-of-plane bending capacity interaction in brick masonry is carried out. Based on the experimental data, an approximate analytical solution to the interaction problem is also presented.

2. TESTS ON WALL PANELS

In the experimental program, in total, twenty seven, single-layer square brick wall panels were constructed. All the panels were of the same size, material, workmanship and post-construction treatment so that the variation in their strengths would be reduced to a minimum. The wall panels for these tests were 60cm by 60cm and 10cm thick. In constructing the panels, compressed brick units were used. These were the best type of engineered bricks available with low variation in quality and strength. Also, the mortar was made of ordinary Portland cement and fine sand (passing sieve # 20) with a weight ratio of 1:3. The wall panels were cured under polythene sheet for 28 days against loss of moisture and for uniformity of treatment. Such treatment was shown previously by Maheri et al [7, 8] to result in considerable brick-mortar bond strength. It also ensured identical failure mechanisms for the panels. A number of samples were also made for the material and prism tests. These included; compressive and tensile tests on mortar, compressive and flexural tests on brick units, shear, compression and bending capacity tests of brickwork and determination of modulus of elasticity of mortar, brick units and brickwork. Selected properties are listed in Table 1.

Table 1. Material properties of the test specimens

Property	*Standard brick (lime-sand)*	*Standard mortar (cement-sand)*
Comp. strength (MPa)	11	34
Tensile strength (MPa)	1.1	4.4
Young's modulus (MPa)	7500	12000
Shear bond Strength (MPa)	-	.0915
Water absorption rate (%)	17.5	-

Based on the observations made on the behaviour of walls during earthquakes and supported by experimental research reported in the literature, the most controlling in-plane shear failure mode in unreinforced brick walls is diagonal shear cracking. This failure mode is characterized with a diagonal crack perpendicular to the maximum tensile stress in the wall panel. There are a number of test set-ups in use for in-plane shear test on brick walls. Descriptions of different test set ups are given by Vilet [25]. In the present study, the ASTM-519 [26] was utilised, regarding the size and preparation of the specimens, the test set-up and the procedure, to obtain the in-plane diagonal cracking strength of unreinforced brick walls. In this test, the brick wall panel is subjected to a static diagonal compressive force until failure. For the present study, a minor modification was, however, needed for the test set-up so that simultaneous application of the in-plane and out-of-plane loads to the wall panels could be carried out. To be able to subject the wall panels to the out-of-plane load, a reaction frame was constructed in such a way that it did not confine the brick panel and also did not reduce the effective dimensions of the panel. For these purposes, a square steel frame having internal dimensions slightly smaller than the brick panel was positioned vertically on one face of the panel. To avoid local stress concentration at the interface between the rough surface of brickwork and the smooth surface of the steel frame, a thin layer of fast setting gypsum was applied at the interface.

The general test setup is shown in Fig. 1. The in-plane diagonal compressive load and out-of-plane point load were applied to the panels using 300 kN capacity hydraulic jacks. The in-plane load was applied vertically on the vertical diagonal and the out-of-plane load was applied at the centre of the panel. Due to the relatively low out-of-plane strength of the brick panels, the out-of-plane load was exerted to the panel through a load ring at smaller load steps of 250 N. In each load step, panel displacements were measured with displacement transducers and recorded with a digital data logger. The positions of loading and the measuring sensors are shown in Fig. 1. Three Contacting LVDTs were used to measure the displacements of the panels during loading; two transducers (S1 and S2), positioned on the horizontal diagonal, were to measure in-plane displacements on this diagonal and one transducer (S3), positioned at the centre of the panel directly opposite the central loading jack (P-O), was to measure the maximum out-of-plane displacement of the panel at that location.

Three different tests were conducted on the wall panels. The ultimate pure in-plane shear capacities of the wall panels were determined first. For this purpose and to verify the repeatability of the tests, three panels were subjected to in-plane load (P-I) only and the results were compared. The mode of failure of all three panels was, expectedly, an explosive diagonal crack (Fig. 2) and the difference in the ultimate strengths recorded for the three panels were very small (within 3%); indicating the uniformity of panel construction and performance. The average ultimate in-plane diagonal strength of the panels was measured as 48 kN.

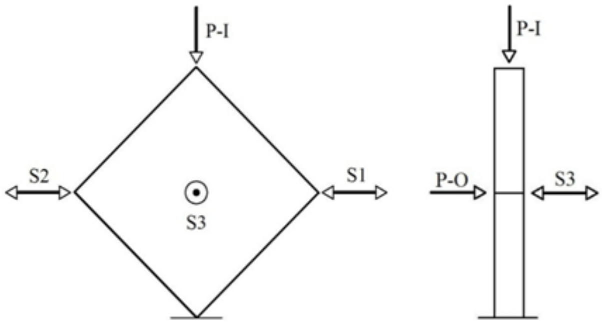

Figure 1. Position of loading jacks (P) and LVDT sensors (S) in the test set-up

Figure 2. Typical failure of the wall panels under in-plane shear load

In the second set of tests, the behaviour and capacity of the wall panels to out-of-plane bending alone was investigated. For this purpose, three out-of-plane loading conditions were considered; (i) two-way bending, (ii) bending parallel to the bed joints and (iii) bending perpendicular to the bed joints. The object of the two latter tests was to obtain the orthotropic tensile strengths of brickwork in perpendicular directions. In total, nine wall panels were tested in this phase; three for each bending condition to verify repeatability of the tests. Similar to the in-plane tests, the results of the repeated tests regarding both the mode of failure and the ultimate flexural capacity were very similar. In Fig. 3 typical mode of failure of the brick panels under two-way bending is shown.

The failure of the panels under two-way bending occurred in the form of two cross inclined lines at an ultimate point load equal to 11.75 kN. The failure of the panels in bending parallel to the bed joints was, expectedly, a single line crack along a bed joint, while the failure of panels in bending perpendicular to bed joints was a single line crack through bricks and head joints. The ultimate line loads applied to the two latter sets of specimens were 3.37 kN and 18 kN, respectively. Average load-displacement curves for the test panels are presented in Fig. 4.

Figure 3. Out-of-plane failure of the wall panel under two-way bending

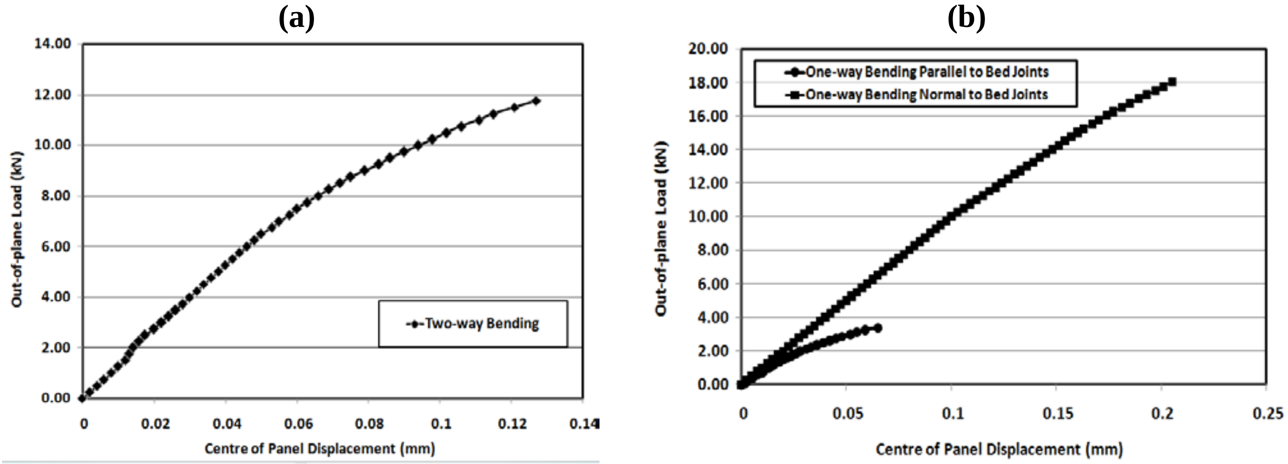

Figure 4. Average out-of-plane load-displacement curves; (a) two way bending, (b) one way bending

The third and the main phase of the experimental program consisted of a series of tests on panels with different combinations of in-plane and out-of-plane loads. In each set of tests, the wall panel was first subjected to a certain value of out-of-plane load; then, while the out-of-plane load was kept constant, the in-plane diagonal compressive load was exerted stepwise to the panel and at each step displacements were recorded. The in-plane loading continued until failure. Each load combination was carried out on three panels for repeatability and their results averaged. The differences between the results obtained for the three panels in each load combination were small; indicating the consistency of the test panels. In total, five load combinations were thus tested. These load combinations corresponded to out-of-plane loads being, respectively, 33%, 50%, 67%, 83% and 90% of the ultimate flexural strength of the panels. The load-displacement curves for the test panels are presented in Fig. 5. The results shown in this figure are average results for each load combination. It is evident that as the out-of-plane load increases, the in-plane shear capacity of the panel reduces. The shear stiffness of the brick panels is also reduced with increasing out-of-plane load.

The failure mechanism of the wall panels under combined in-plane and out-of-plane loads appears to be a combination of the in-plane diagonal shear and the out-of-plane bending failures discussed previously. The crack pattern of the panels subjected to low levels of out-of-plane loads follows a diagonal shape. With increasing out-of-plane load, bending cracks accompany the diagonal shear cracks at failure. As it was stated, the test results show reduction in the in-plane shear strength of brick wall panels in the presence of the out-of-plane load. This reduction appears more profound when the out-of-plane load nears the out-of-plane capacity of the panel. Similarly, the out-of-plane bending capacity is reduced in the presence of the in-plane shear loads. To gain a better insight into the in-plane shear and out-of-plane bending capacity interaction, the test results are plotted, in normalised form, in Fig. 6. The in-plane, out-of-plane capacity interaction appears to almost follow a circular line.

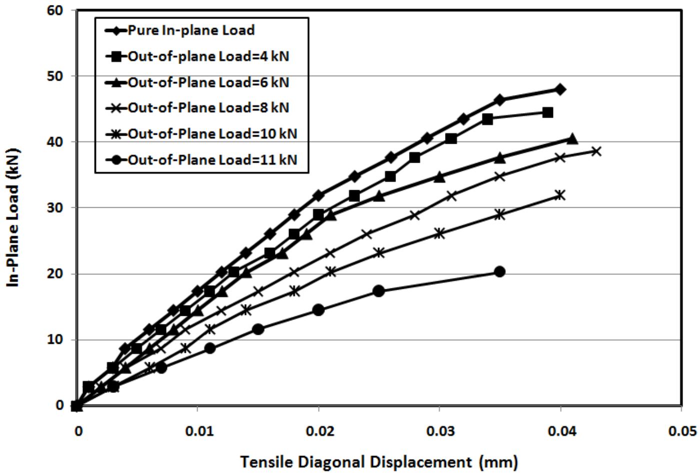

Figure 5. Average in-plane load-displacement curves for different in-plane, out-of-plane load combinations

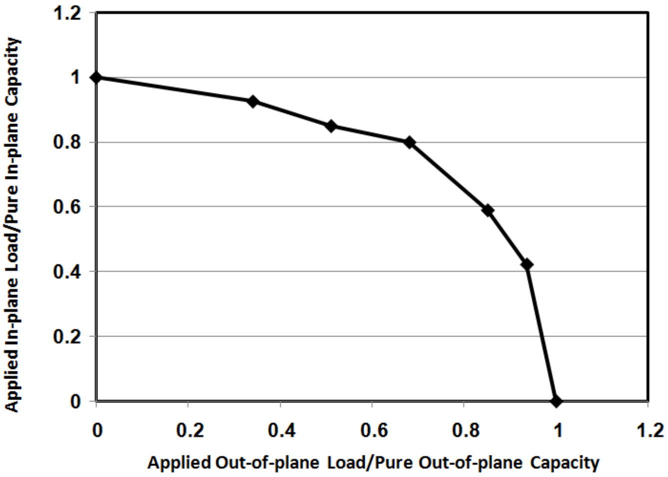

Figure 6. In-plane, out-of-plane capacity interaction curve for the wall panel

3. ANALYTICAL STUDIES

In this part, a simple analytical method is developed for deriving the in-plane, out-of-plane interaction curve for brick masonry. The test results are utilised to verify and calibrate this method. The mechanical properties of the brickwork found in the previous section are used for calculating the state of stress and the failure criteria. Since the out-of-plane failure of a simply supported brick panel and the diagonal in-plane failure of a brick panel are both tension failures resulting from tensile stresses in principal directions, this analytical approach is based on comparing the state of principal stress at the centre of the wall panel and the tensile strength of the brickwork along the principal stress direction. The proposed analytical approach is discussed in the following sections.

3.1. Stresses Due to Out-of-Plane Point Load

According to the elastic theory of plates, the state of principal stresses in a simply supported rectangular plate (panel) under an out-of-plane point load is tension-tension and the maximum tensile stress is located at the centre of the panel and on the tension side. The cracking of the panel under out-of-plane loads therefore starts from the centre and propagates towards the supports. This type of failure was also observed in the panels tested. The same type of failure has also been reported by the authors in previous works [7, 8] and by other researchers [27]. Ultimate strength of a wall under out-of-plane loading depends on such parameters as boundary conditions and the intensity of gravity load on the wall. The results of the current experimental study indicate that for the type of boundary conditions and loading used, the ultimate out-of-plane capacity is close to the cracking load for the panel.

Relations for evaluating stresses in brick walls under an out-of-plane point load can be derived by the aid of analytical approaches given in classical theories of plates, such as the Navier's method [28]. As masonry walls are both stiffness and strength orthotropic, particularly under the out-of-plane loading, the analytical formulas for calculating the state of stress in the wall must be based on orthotropic plates. Therefore, the stresses, σ_x , σ_y and τ_{xy} in simply supported rectangular plates under out-of-plane centre point load may be estimated as follows [28]:

$$\sigma_x = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{t}{2}\left[E_x\left(\frac{m\pi}{a}\right)^2 + E_{xy}\left(\frac{n\pi}{b}\right)^2\right]a_{mn}\sin\left(\frac{m\pi x}{a}\right)\sin\left(\frac{n\pi y}{b}\right) \quad (1)$$

$$\sigma_y = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\frac{t}{2}\left[E_y\left(\frac{n\pi}{b}\right)^2 + E_{xy}\left(\frac{m\pi}{a}\right)^2\right]a_{mn}\sin\left(\frac{m\pi x}{a}\right)\sin\left(\frac{n\pi y}{b}\right) \quad (2)$$

$$\tau_{xy} = \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} t\left[G\left(\frac{m\pi}{a}\right)\quad\left(\frac{n\pi}{b}\right)\right]a_{mn}\cos\left(\frac{m\pi x}{a}\right)\cos\left(\frac{n\pi y}{b}\right) \quad (3)$$

where,

$$a_{mn} = \frac{\left(\frac{4P}{ab}\right)\sin\left(\frac{m\pi}{2}\right)\sin\left(\frac{n\pi}{2}\right)}{\left(\frac{m^4\pi^4}{a^4}\right)D_x + 2H\left(\frac{n^2m^2\pi^4}{a^2b^2}\right) + \left(\frac{n^4\pi^4}{b^4}\right)D_y} \quad (4)$$

In the above equations parameters *a*, *b* and *t* are length, width and thickness of the rectangular plate, respectively. Also:

$$E_x = \frac{E_x'}{1-\vartheta_x\vartheta_y}, \qquad E_y = \frac{E_y'}{1-\vartheta_x\vartheta_y}, \qquad E_{xy} = \frac{E_x'\vartheta_y}{1-\vartheta_x\vartheta_y} = \frac{E_y'\vartheta_x}{1-\vartheta_x\vartheta_y} \quad (5)$$

$$D_x = \frac{t^3E_x}{12}, \quad D_y = \frac{t^3E_y}{12}, \quad D_{xy} = \frac{t^3E_{xy}}{12}, \quad G_{xy} = \frac{t^3G}{12} \text{ and } H = D_{xy} + 2G_{xy}$$

Also, *G* is the shear modulus and ϑ_x, ϑ_y, E_x' and E_y' are the effective Poisson's ratio and effective modulus of elasticity, in x and y directions, respectively. It is noted that the mechanical properties of brickwork as a homogenized orthotropic material are used to calculate the stress state due to the out-of-plane load.

3.2. Stresses Due to In-Plane Diagonal Compressive Load

According to the theory of elasticity, the maximum tensile stress in a square panel subjected to a compressive diagonal force is located at its centre and perpendicular to the line of compressive load. The stress state developed by Frocht [29] is presented in Fig. 7. This figure shows that the principal direction for the test panels is in a direction at 45°angel to the bed joints. It should be noted that, for the test panels, the state of principal stresses at the centre of the panel is a tension-compression type. The test results indicate that the diagonal crack occurs when the tensile stress at the centre of the panel reaches its ultimate value. The crack propagates rapidly and failure is explosive.

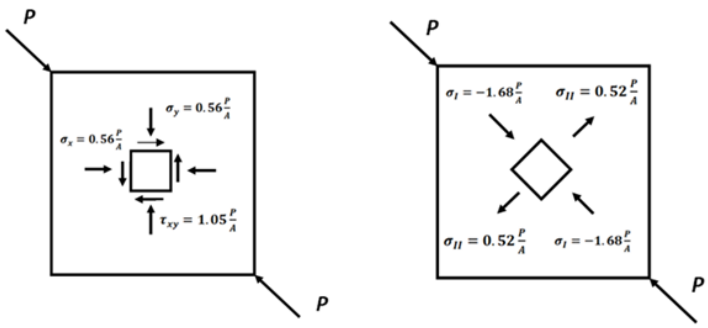

Figure 7. Stress state in a square plate subjected to compressive diagonal force

3.3. Stresses Due to Combined In-plane and Out-of-plane Loads

As it was discussed in the preceding sections, both the in-plane diagonal failure and the out-of-plane failure of brick walls initiate at the centre of the wall. In other words, for a wall panel subjected to the combined actions of the in-plane and out-of-plane loads the state of stress at the centre of the panel is critical. The stress state at the centre of the panel can be obtained by simply combining the stresses due to in-plane shear and out-of-plane bending as described in the previous sections. To these, the stresses due to gravity load action can be added as follows;

$$(\sigma_x)_t = (\sigma_x)_b + (\sigma_x)_s \tag{6}$$
$$(\sigma_y)_t = (\sigma_y)_b + (\sigma_y)_s + (\sigma_y)_g \tag{7}$$
$$(\sigma_{xy})_t = (\sigma_{xy})_b + (\sigma_{xy})_s \tag{8}$$

In the above relations, the index t stands for the total value of stress and indices b, s and g stand for stresses due to out-of-plane bending, in-plane shear and in-plane gravity loads, respectively.

3.4. Strength of Brickwork Subjected to Combined In-plane and Out-of-plane Loads

The cracking strength of the wall can be obtained by comparing the state of the principal stress at the centre of the panel due to all loadings (in-plane shear, out-of-plane bending and gravity loads) with an appropriate failure criterion taking into consideration the orthotropic nature of the problem. As both the out-of-plane and the in-plane failures of the wall under the mentioned loads are tension failures, the strength of the wall under the combined effects of in-plane and out-of-plane loads can be evaluated by comparing the resultant principal tensile stress with the tensile strength of brickwork. A look at the principal stresses at the centre of the wall panel under combined loading shows that the state of principal stress at that point might be either tension-tension or tension-compression. As a result, a failure criterion for an orthotropic material, having both, tension-tension and tension-compression, zones is needed.

A number of researchers have proposed failure criterion for masonry. The failure criteria generally consider the orthotropic nature of the masonry material. Because of the complexity of the behaviour of masonry, the proposed failure criteria are usually built using some surfaces to simulate the actual behaviour of the material. One of the most popular failure surfaces for masonry is proposed by Lourenco et al [19]. This failure surface is a combination of a Rankin type failure criterion for tension failure and a Hill type failure criterion for compression failure of masonry.

The general shape of the failure criteria for masonry is as illustrated in Fig. 8. This failure surface has three zones; tension-tension, tension-compression and compression-compression. Different zones of the failure surface may be obtained using bidirectional tests or homogenization techniques. The tension-compression zones are generally formed by lines connecting the tension-tension and tension-compression surfaces. In the present study, Rankin's failure criterion (maximum tensile strength) is adopted to form the tension-tension zone (Fig. 9) and the tension-compression surfaces are formed by connecting the tensile strength to the compressive strength.

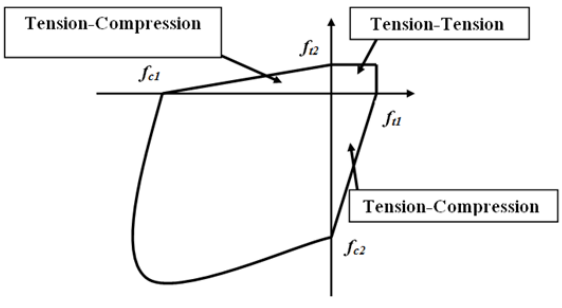

Figure 8. General shape of the applied failure criterion

In order that the Rankin's failure criterion could be established, tensile strength of brickwork in different directions needs to be determined. To this end tests were conducted on representative brickwork specimens and the tensile strengths were measured in three directions at 0, 45 and 90 degrees angels to the bed joints. The results of these tests are plotted in Fig. 10. An estimate of the tensile strength in directions other than those tested may be estimated by interpolation such as using the second order curve fitted to the results as seen in Fig. 10. Also, based on the results of the previously reported tests and the recommended relations in the literature, the direct tensile strength of brickwork may be assumed to be 60% of the rapture modulus of the brickwork.

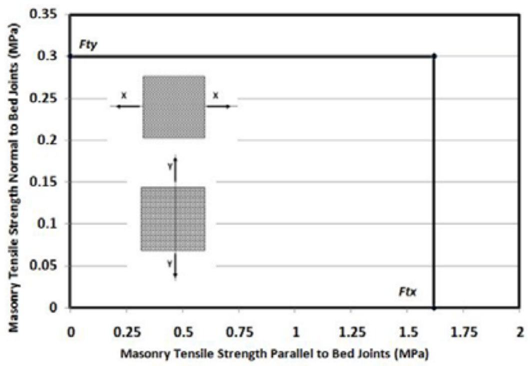

Figure 9. Rankin's failure criteria for brickwork (principal direction along the bed joints)

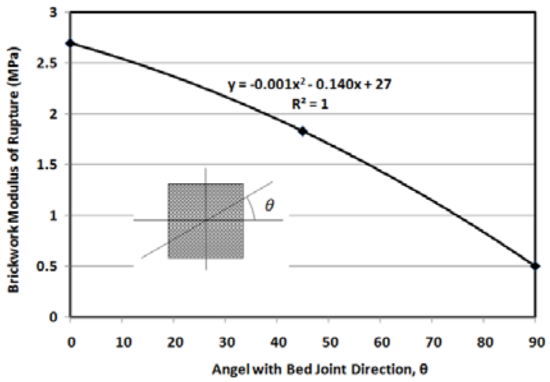

Figure 10. Brickwork modulus of rupture in different directions

The calculated principal stresses due to combined loads, show that, for the wall panels tested in this research and in the absence of the gravity loads, the state of principal stress for low levels of out-of-plane loading fall in the tension-compression zone of the failure criterion with principal direction close to 45 degrees to the direction of the bed joints. In other words, the failure criterion for tension-compression zone is needed only for the principal direction at 45 degrees to the bed joints. Strength values for the tension-compression zone are derived from the diagonal compressive test of the brickwork panels based on the stress state at the centre of the panel. Therefore, the diagonal compressive test results may be used as points of failure to form the tension-compression zones, as shown in Fig. 11. In Fig. 11, the failure surfaces in the tension-tension zone are obtained using the flexural test results carried out on the specimens at a 45 degrees direction to the bed joints. Fig. 11 presents the proposed failure criterion for considering the in-plane shear, out-of-plane bending capacity interaction in unreinforced brick masonry walls. The state of stress at the centre of a wall undergoing different in-plane and out-of-plane loadings may be calculated using Eqns. 6 to 8 and compared with the failure criterion presented in Fig. 11 to evaluate the state of the wall under the applied loads.

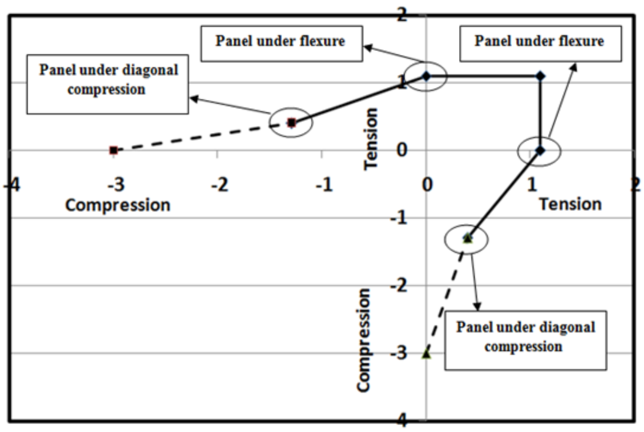

Figure 11. Proposed failure criteria for the combined in-plane, out-of-plane loading (principal direction at 45 degrees to the bed joints)

3.5. Comparison of the Analytical and Experimental Interaction Curves

The above procedure was applied to the test specimens undergoing different constant out-of-plane loads and their in-plane shear strengths were evaluated. The results of these analytical evaluations, in the form of a normalized interaction curve are compared with the normalized interaction curve obtained experimentally in Fig. 12. This figure shows that the analytical procedure described can predict reasonably well the in-plane shear, out-of-plane bending capacity interaction in brick masonry walls. The analytical prediction appears to be more accurate at the regions where either the in-plane load or the out-of-plane load is dominant; that is at the end regions of the interaction curve. In the central parts of the interaction curve, however, discrepancies between the experimental results and the analytical predictions appear to be more marked; nevertheless, they are below 10%. Furthermore, the analytical prediction in the central sections of the interaction curve can be seen to be on the conservative side.

It was stated in section 2.3 that the experimental interaction curve appears to follow a circular line. In Fig. 12 a quarter circle with a radius equal to unity is drawn for comparison with the experimental and analytical interaction curves. Both interaction curves can be seen in the figure to closely follow the circular curve. The experimental curve matches very well with the circular curve at the end regions, where either the in-plane shear force or the out-of-plane bending load in dominant. However, in the central part of the interaction curve the match is less profound. On the other hand, differences between the analytical predictions for the central part and the circle line appear to be, for most parts, less than those for the experimental curve. As it was mentioned earlier, in the experimental program, due care was given to minimize the effects of boundary conditions. However, these effects, together with the possible effects of scale factor due to the size of the specimens tested, may account for the small departure of the experimental interaction curve from the circle line in the central sections. It follows that, the in-plane shear; out-of-plane bending capacity interaction diagram may indeed be of a circular form. Further work on the interaction, in the form of numerical studies of full-scale brick walls, are currently being conducted by the authors to further verify this notion.

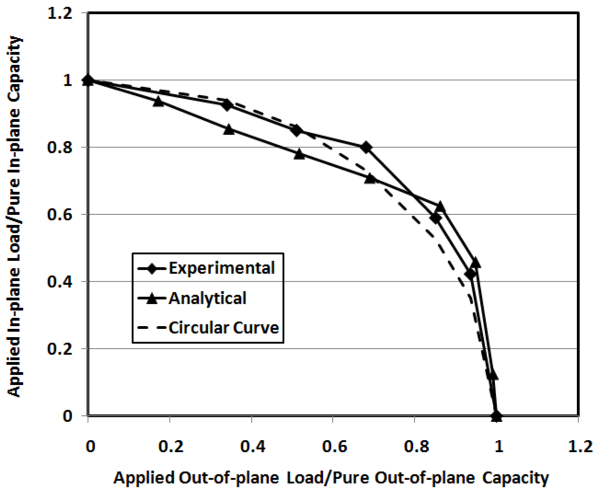

Figure 12. Comparison of the in-plane, out-of-plane capacity interaction curves for brick masonry

4. CONCLUSIONS

The results of the investigations presented in this paper are summarised as follows;

1. Noticeable interaction exists between the in-plane shear and out-of-plane bending capacities of brick walls. The interaction is particularly strong when one of the load types nears the wall's corresponding ultimate capacity. It is therefore recommended that this capacity interaction is taken into consideration when designing, undertaking vulnerability studies or retrofitting masonry buildings.
2. A simple analytical method is developed to evaluate the capacity interaction curve of unreinforced brick walls under combined in-plane and out-of-plane loads. The procedure was shown to fairly accurately and conservatively match the experimental results.
3. The in-plane shear, out-of-plane bending capacity interaction curve appears to follow a circular form; a notion in need of further investigations.

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