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AN EXPERIMENTAL STUDY OF BRICK MASONRY SPECIMENS SUBJECTED TO BIAXIAL BENDING

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Abstract

The paper reports the results of a series of tests on masonry specimens consisting of four clay brick units arranged in a t-shape, subjected simultaneously to bending in the vertical and horizontal directions as well as vertical in-plane compression. This is achieved using a quite sophisticated test apparatus designed to simulate the state of two way out of plane bending, with or without vertical pre-compression, which exists in masonry wall panels subjected to face loading and supported on two or more adjacent edges. In particular, the tests focus on the behaviour of the mortar joints under such loading. The paper describes the test apparatus and its capabilities. The results reported are preliminary only.

Key Words

Masonry, face loading, bending

1 Introduction

Whether being used as vertical load bearing elements, shear walls or as non-structural infill, masonry walls will almost invariably be required to resist lateral out-of-plane loads due to the action of wind, earthquakes or water or earth pressure. Of particular interest is the common case which arises when the walls are supported on two or more adjacent edges. Under these conditions the masonry is subjected to a complex state of two way (or biaxial) out-of-plane bending combined with vertical in-plane compression due to the self weight of the wall and any superimposed loads. The relative magnitudes of the bending moments in the horizontal and vertical direction depend on the wall geometry and support conditions and vary across any given wall panel, as does the vertical preload. Typical experimentally observed failure patterns for a variety of geometries and support conditions are shown in Figure 1 (Lawrence 1983).

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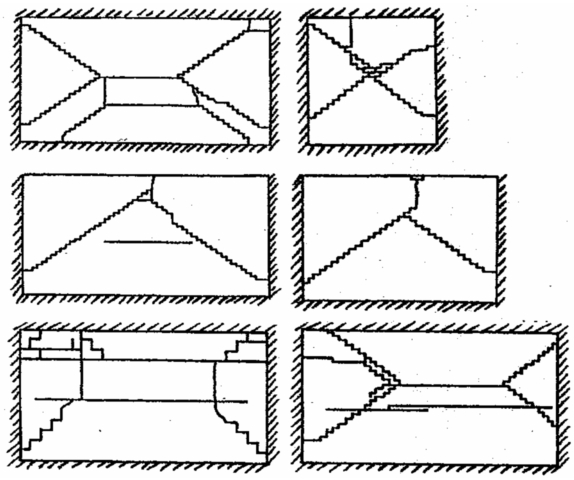

Figure 1 Examples of Wall Crack Patterns (From Lawrence (1983))

During the past several decades research has been conducted into the structural behaviour of unreinforced masonry wall panels under such loads. Comprehensive overviews of this past work have been provided by Baker (1981, et al 1985), Lawrence (1983, 1994). As a result of independent research in various parts of the world, several different approaches currently exist for the design of masonry wall panels subjected to out-of-plane loads. These various approaches often yield widely varying design recommendations and there has been significant criticism by proponents of the different methods regarding the use of alternative approaches.

One of the approaches is based on Yield Line Theory which is commonly used for reinforced concrete design. Another approach, an empirical strip method proposed by Baker (1981), has been shown to provide reasonable agreement with limited experimental results. However, it is without rational basis and cannot be used confidently outside the range of scenarios for which it was experimentally verified. More recently (Lawrence and Marshall 2000), a design method has been developed based on the virtual work approach. This is the approach currently adopted in the Australian Standard for masonry design (Standards Australia 2001). However, even this method is partly empirical and can not predict the strength of wall panels supporting vertical preload. It also ignores the strength of perpend joints and ignores strengthening due to arching effects where walls are built hard against the supports.

In fact, Lawrence and Marshall (2000) note that “no completely rational method has yet been developed”, “all methods used for design throughout the world are totally or partly empirical” and that “Further research is necessary to develop a fully rational biaxial-bending failure model that can predict behaviour under any simultaneous combination of bending moments in the two principal directions, along with a superimposed compression force on the bed joints”. Further to this, reliability based limit states design has formed the basis of the design of steel, reinforced concrete and timber structures since the early eighties. However, limit state methods for masonry design have not been developed from reliability based calibration methods (Stewart and Lawrence 2002). The levels of safety in masonry construction are not known and because of a lack of understanding of the behaviour at the fundamental level, current design approaches are necessarily conservative.

The work described in this paper forms a small part of a long-term project aimed at developing a rational approach for predicting the behaviour and peak load of unreinforced masonry wall panels when subjected to out-of-plane lateral loads. The approach developed must be based on a fundamental understanding of the behaviour including cracking and progressive failure through to wall collapse. The approach must be able to accommodate walls of varied geometry, support conditions and walls

containing window and door openings as well as walls with or without vertical preload. Finally, a basic probabilistic framework will need to be developed to allow the influence of material variability, which is significant, to be included. By developing an appropriate probabilistic framework the structural reliability of masonry walls subjected to lateral out-of-plane loads can be estimated.

Mortar joints in masonry are planes of weakness. Failure under biaxial bending can occur by fracture of bed joints (vertical bending M_v dominant) or by fracture of perpends and masonry units or toothed or stepped failures through perpend and bed joints (horizontal bending M_h dominant) or by fracture along diagonal stepped crack paths through the bed and perpend joints (combination of M_v and M_h) (Figure 1). Past research in Australia (Baker et al 1985) focused on the development of failure criteria for masonry under biaxial bending with or without vertical compression. This work led to the development by Baker and the CSIRO of an experimental testing apparatus for simulating biaxial bending in masonry. The apparatus is capable of subjecting a 4-unit masonry joint specimen to simultaneous horizontal (M_h) and vertical (M_v) bending moments as well as vertical compression (Figure 2, Figure 3). This apparatus allows attention to be focused on the behaviour of individual bed and perpend joints when subjected to the simultaneous combination of bending and torsion. Baker (1979) notes that this "single joint" specimen approximately, if it is assumed that the moment transmitted through the perpend joint is the same as in the perpends of a full wall, represents the actions on the joints in a wall panel when subjected to two way bending. However, the test apparatus was never commissioned due to shortages of research funding.

The test apparatus was recently transferred to The University of Newcastle. This paper describes an experimental approach using the apparatus, including preliminary results, for studying the behaviour of masonry joints subjected to out-of-plane biaxial bending and in-plane vertical compression.

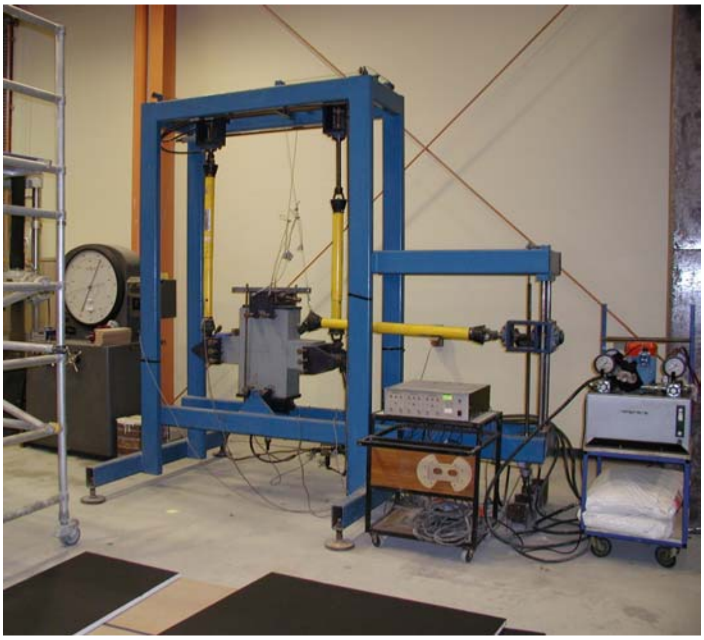

Figure 2 Biaxial Bending Test Frame

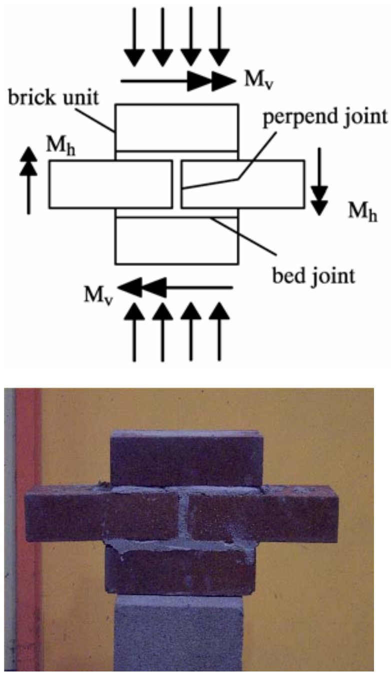

Figure 3 Biaxial Bending Test Specimen

2 Description of Test Apparatus

The test apparatus is shown in Figure 2. A typical masonry specimen is shown in Figure 3. The apparatus consists of a support frame housing a base plate and support clamp on which the specimen is placed. The horizontal moments M_h (applied about vertical axes) are applied via clamps at each side of the specimen by an actuator at the top of the frame. This actuator either pushes or pulls on levers attached to the two vertical shafts therefore applying torque in the shafts. The torque in the shafts is transferred to the specimen as a moment about the vertical axis via the side clamps. The shafts each include two universal joints to ensure that only moment is applied to the specimen and that the specimen is not restrained against translation in the out-of-plane direction. The heavy steel side clamps and torque shafts are counterweighted so that they do not apply any vertical load to the specimen.

The vertical moments M_v (applied about horizontal axes) at the top and bottom of the specimen are applied via a moving top clamp and the reaction at the base plate support clamp respectively. The moment applied to the top clamp is applied via a horizontally aligned torque shaft which has torque applied to it by a second actuator which can either push or pull on a lever attached to the shaft (Figure 2).

A third actuator is used to apply vertical pre-compression to the specimen. This actuator is positioned beneath the specimen. It reacts against the underside of the base plate and is attached to rods which pull down on a plate positioned on top of the specimen. The load is applied at the top in such a way that rotation of the specimen due to M_v is not restrained.

All three actuators are able to operate in displacement or load control and in tension or compression. This latter feature means that specimens can be subjected to moments M_h and M_v which apply tension to the same face of the specimen or opposite faces of the specimen. The level of vertical pre-compression, as well as the ratio of horizontal to vertical moments can be varied and independently controlled to represent the different combinations of actions occurring at various locations in a wall panel subjected to out-of-plane loading. The load and actuator stroke for all actuators can be continuously recorded by a data logger connected to a computer during testing and the ramp rates for actuator stroke (or load) can be pre-set and computer controlled. The moments M_h and M_v applied to the specimen are calculated simply as the appropriate actuator load multiplied by the lever length (150 mm) for the levers applying torque to the torque shafts.

Note that the specimen shown in the test frame in Figure 2 is a timber blank used for transporting the frame and is of a size equivalent to a specimen constructed from large concrete blocks. The apparatus therefore can be adjusted to test a range of specimen sizes depending on the dimensions of the masonry units used to construct the 4-unit test specimens. The apparatus can potentially also be used to apply moments at angles to the bed joint of other than zero and ninety degrees by tilting the specimen through the required angle. However, this would require redesign of the clamps as the current clamping arrangement restrains the associated twisting movements which would occur about axes aligned parallel and perpendicular to the bed joints under such loading. Under the current arrangement the moments M_h and M_v are principal moments, that is, no associated twist occurs about the vertical and horizontal axes.

3 Test Procedure

In January 2004, a preliminary series of tests was conducted using the above described apparatus.

Twenty 4-unit specimens (Figure 3) were constructed. The bricks used were solid extruded clay bricks (no frog) of dimensions 230 mm long x 76 mm high x 110 mm thick (standard clay brick size used in Australia). The mortar consisted of cement:lime:sand in proportions 1:2:9 by volume. The mortar joints were 10 mm thick

and both the bed joints and perpend joint were completely filled. Using the same materials, bond wrench and brick modulus of rupture specimens were constructed and tested in accordance with AS 3700-2001 (Standards Australia 2001) and AS/NZS 4456.15-1997 (Standards Australia/Standards New Zealand 1997) respectively. The 7 day mean flexural bond strength (10 joints tested) was 0.55 MPa, standard deviation 0.12 MPa. The mean lateral modulus of rupture for the masonry units (10 specimens tested) was 4.30 MPa, standard deviation 1.3 MPa. The 4-unit specimens were cured under indoor conditions for approximately five weeks prior to testing.

For each specimen, the vertical pre-compression (if any) was applied first and held constant during testing (load control). Two levels of pre-compression were used. Ten specimens were tested under zero pre-compression and ten under 5 kN, which equates to an average vertical stress of 0.2 MPa. The moments M_h and M_v were then applied slowly using a computer controlled ramp rate on the actuator strokes (displacement control). The ramp rates (mm/min) for the actuators applying M_h and M_v were constant during each test. Between tests the ratio of ramp rates for M_h and M_v was varied to cover 5 ratios M_h:M_v (2 specimens for each ratio) ranging from pure horizontal bending to pure vertical bending. In all cases, the moments M_h and M_v were applied such that tension due to both moments occurred on the same face of the specimen.

Each specimen was loaded until failure occurred. The actuator forces and stroke displacements applying M_h and M_v were continuously recorded. The values of M_h and M_v at failure and the mode of failure were recorded. For the purpose of recording M_h and M_v, failure was defined as first cracking of the specimen. Depending on the mode of failure, the ratio M_h:M_v and the presence of pre-compression, the specimens often supported higher loads after cracking. This post cracking behaviour was noted and has important implications for the capacity of complete walls subjected to out-of-plane loads.

4 Results

The test results are summarised in Table 1 and Figure 4. It can be seen that failure occurred in most cases either by rupture of one of the bed joints or by rupture of the masonry unit at one side of the specimen. Only in two cases was there torsional shear failure in the bed joints (Figure 7) and in both of these cases this occurred after the bed joint had already cracked but was held partly closed by the vertical pre-compression.

5 Comparison with Other Investigators

Baker (1979) reported results of tests identical in concept to those using the test apparatus described above. The tests reported used two different brick sizes and 1:1:6 mortar. A total of 310 specimens were tested. From the test results Baker proposed an empirical failure criterion in biaxial bending in the form of an elliptical interaction of F_h and F_v (Figure 8), where F_h and F_v are the ultimate extreme fibre stresses in the masonry under biaxial bending in the horizontal and vertical directions respectively. This failure criterion was later confirmed by Thürlimann and Guggisberg (1988) using a series of tests on wallettes subjected simultaneously to out-of-plane moments parallel and perpendicular to the bed joints and in-plane compressive force perpendicular to the bed joints. The failure criterion implies a reduction in flexural strength in the presence of moments in the other direction as well as an increase in both F_h and F_v in the presence of vertical pre-compression. Baker noted however, that nearly all specimens failed through the mortar joints rather than by brick rupture and that if failure is through the bricks, one would expect little increase in the horizontal bending strength as a result of increasing the pre-compression.

Table 1 Experimental results

Specimen	Pre-comp. kN	M_h (1st crack) kNm	M_v (1st crack) kNm	Failure mode
1	0	0.72	0	Brick rupture at side followed by lower bed joint failure (Fig. 5)
2	0	0.75	0	Brick rupture at side followed by lower bed joint failure
3	0	0	0.27	Failure at lower bed joint
4	0	0	0.49	Failure at upper bed joint
5	0	0.58	0.41	Failure at upper bed joint, continued to resist M_h, load removed
6	0	0.59	0.35	Brick rupture at side, continued to resist M_v, load removed
7	0	0.28	0.35	Brick rupture at side, continued to resist M_v, load removed
8	0	0.19	0.25	Failure at lower bed joint, continued to resist M_h, load removed
9	0	0.49	0.16	Brick rupture at side followed by lower bed joint failure
10	0	0.63	0.21	Brick rupture at side, continued to resist M_v, load removed
11	-	-	-	Specimen lost (bed joint failed) prior to test
12	5.0	0.80	0	Brick rupture at side
13	5.0	0	0.39	Lower bed joint cracked, continued to resist M_v due to presence of preload (Fig. 6), load removed
14	5.0	0	0.56	Upper bed joint cracked, continued to resist M_v due to presence of preload, load removed
15	5.0	0.62	0.42	Upper bed joint cracked, followed by torsional failure in bed joints (Fig. 7)
16	5.0	0.65	0.42	Brick rupture at side, continued to resist M_v, load removed
17	5.0	0.49	0.65	Upper bed joint cracked, followed by perpend cracking and then torsional failure in bed joints
18	5.0	0.52	0.63	Brick rupture at side and failure at upper bed joint
19	5.0	0.74	0.24	Brick rupture at side, continued to resist M_v, load removed
20	5.0	0.47	0.16	Brick rupture at side, continued to resist M_v, load removed

Sinha et al (1997) used a cross shaped specimen laid horizontally to establish a slightly modified failure criterion as shown in Figure 9.

The results of the current tests are shown in Figure 4. The 10 data points shown were obtained by averaging the two test results for each combination of pre-compression and ratio M_h:M_v. The values of F_h and F_v were calculated from the moments M_h and M_v using equations given by Baker (1979). Also shown are ellipses of the form used by Baker fitted to the data points representing the specimen strengths in pure vertical bending ($M_h = 0$) and pure horizontal bending ($M_v = 0$).

Clearly two specimens per data point is inadequate to draw concrete conclusions. Note that Baker's data points are each based on the average of 20 results for "Series I" and 30 results for "Series II" (Figure 8). However, the elliptical relationship between F_h and F_v does provide a fit of the current data which is not unreasonable. The smaller relative increase in F_h due to the pre-compression compared to Baker's results is probably due to the large number of failures by brick rupture for the current tests. As noted by Baker,

a larger increase in F_h due to pre-compression is expected to occur when the failure is by torsional shearing of the bed joints.
It could also be argued that the current test results for a pre-compression of 0.2 MPa are similar in nature to the failure criterion prosed by Sinha et al (1997). Further tests are needed to confirm these observations.

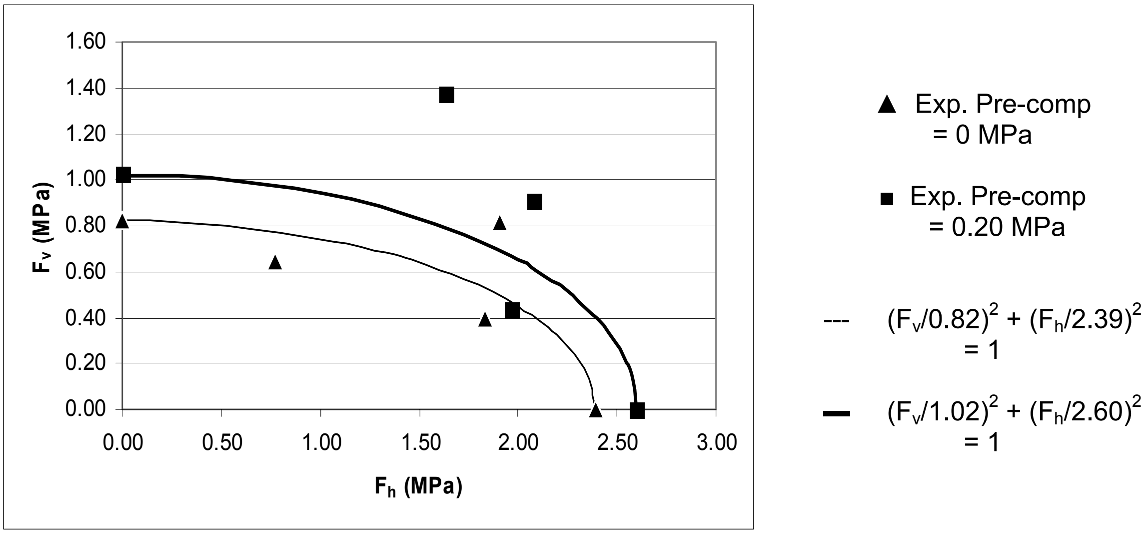

Figure 4 Experimental results

Figure 5 Failure by brick rupture

Figure 6 Bed joint cracked under preload

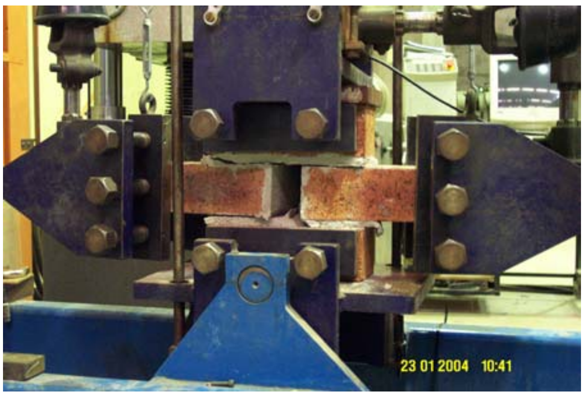

Figure 7 Torsional shear failure in bed joint

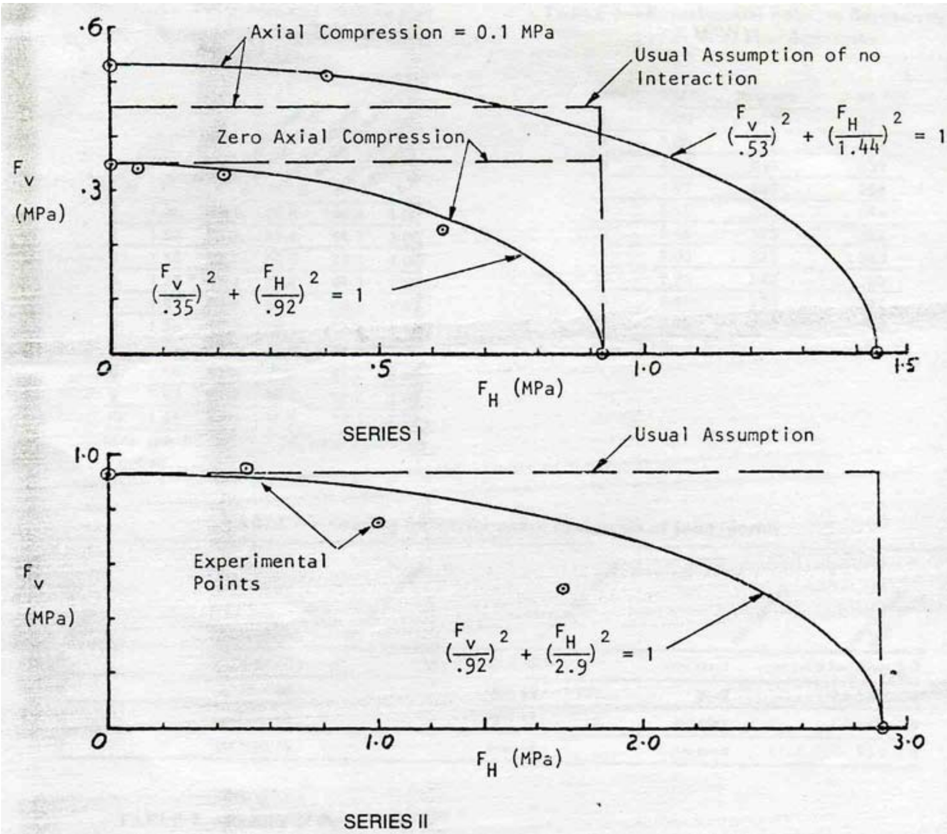

Figure 8 Failure criterion from Baker (1979)

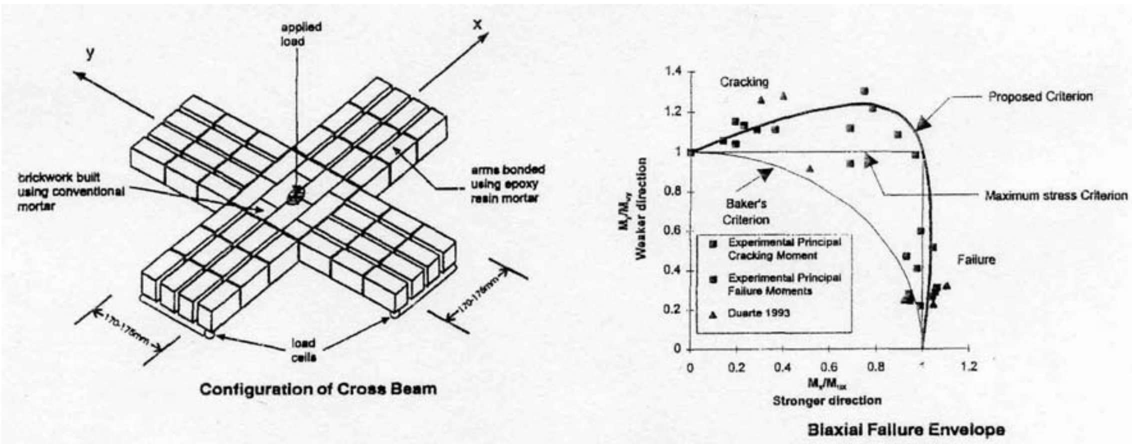

Figure 9 Failure criterion from Sinha et al (1997)

6 Future Direction

It is the intention of the authors to conduct further series of tests using the apparatus described. A greater range of variables will be investigated, including additional levels of pre-compression, the application of M_h and M_v to cause tension on opposite faces of the specimens, and specimens with empty perpend joints to isolate the torsional behaviour of the bed joints. For each combination of variables a greater number of repeat tests will be conducted. Only two specimens per combination were used for the current test series. Instrumentation will be used to record specimen displacements. Of particular interest is the post cracking behaviour of the specimens as this is thought to be of considerable importance to the post cracking response and ultimate strength of full wall panels subjected to out-of-plane loading.

Accompanying these tests will be material control tests. The control tests of importance are masonry prism compression tests to determine the Elastic Modulus of the masonry, the brick units and the mortar, bond wrench tests to measure the flexural tensile strength of the masonry, brick modulus of rupture tests to determine the flexural strength of the masonry units and triplet shear tests to establish the shear strength and frictional resistance properties of the bed joints.

In parallel with the experimental program, numerical models of the behaviour are being developed (Han and Masia 2004). The finite element method (Abaqus software) is being used. The modelling strategy is to represent the masonry units using 3D linear elastic “brick” continuum finite elements. These are connected using contact elements to represent the mortar joints as well as a potential vertical failure interface at the mid-length of each masonry unit. The contact relationship represents the normal contact across the mortar joints as elastic brittle under tensile forces and elastic with infinite capacity under compressive forces. The shear contact includes cohesion to represent the initial shear strength of the mortar joints with post peak softening once joint cracking has occurred, reducing the shear resistance to a residual value based on the frictional capacity of the cracked joint. This model has been used to successfully duplicate the behaviour observed in tests by Willis et al (2002). It has also been used to simulate qualitatively the behaviour observed in the preliminary 4-unit specimen tests reported above. A quantitative match of the behaviour will be possible once further tests are completed which include a full set of material control tests and the measurement of pre and post cracking specimen displacements.

The longer term objective is to extend the numerical approach to simulate the behaviour of full masonry walls subjected to out-of-plane loading. Numerical models based on a realistic representation of the biaxial bending behaviour of the masonry at the fundamental level, calibrated against the results of full panel tests, can be used to predict the response of masonry walls of arbitrary geometry and support conditions, outside the range of the wall panels tested. Such models form the basis of the subsequent sensitivity studies and probabilistic analyses.

When the test apparatus was originally developed at the CSIRO, it is likely that the intention was to further investigate the failure criteria proposed by Baker. The modelling strategy described above using contact to represent the mortar joints, does not require a principal stress failure criteria as described by Baker (1979, 1982a, 1982b). This means that the focus in using the test apparatus has changed since its inception. The focus now is in the validation of the numerical modelling strategy described, the quantification of material variability under biaxial bending and in the careful study of post cracking behaviour and how this relates to the behaviour of complete wall panels.

7 Conclusions

The paper describes testing apparatus designed to study the behaviour of masonry joints when subjected to out-of-plane biaxial bending, with or without in-plane vertical compression. The results of a preliminary series of tests were reported. The test results were in agreement with results reported by other investigators, but clearly a more extensive series of testing is required. Reference was made to numerical models which are being developed in parallel with the experimental program. This work was placed in the context of a larger project aimed at developing a rational approach for predicting the behaviour of unreinforced masonry walls when subjected to out-of-plane loading.

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