HORIZONTAL SHEAR TESTING OF MUDBRICK MASONRY MORTAR JOINTS

D.M. DOWLING[1], J. DIAZ[2], and B. SAMALI[3]

[1]PhD Candidate, [2]Graduate, [3]Professor
Centre for Built Infrastructure Research
Faculty of Engineering
University of Technology, Sydney
Broadway NSW 2007

SUMMARY

Unreinforced masonry buildings are highly susceptible to damage and destruction during seismic events. One common damage mode can be attributed to in-plane shear failure of masonry components, where failure generally occurs at the mortar-block interface. A variety of masonry joint shear strength tests have been developed over the years, but these tend to focus on conventional masonry such as fired clay bricks and concrete blocks. Shear strength testing of adobe (mudbrick) masonry joints, however, has been limited. This paper describes some preliminary testing of adobe masonry triplet units, with different configurations representing both horizontal stack and running bond patterns.

INTRODUCTION

Devastating earthquakes in Latin America, The Middle East, Africa and Asia have served as recent reminders of the vulnerability of traditional, non-engineered, low-cost housing to seismic forces. The loss of life and livelihood is often drastic, with the poorest communities most severely affected. Adobe (mudbrick) houses are at high risk due to their low-strength and brittle characteristics and generally poor construction quality. Despite these limitations, adobe houses will continue to be extensively used because vulnerable populations simply cannot afford any alternative. It seems that the most sustainable and wide-reaching method to improve the earthquake resistance capacity of adobe dwellings is to develop and promote improvement options which are simple and affordable (Dowling, 2004).

The experiment described in this paper forms part of a major research project at the University of Technology, Sydney: the investigation of appropriate technology to improve the earthquake resistance of mudbrick structures. A major focus of the research is the dynamic, shake table testing of u-shaped adobe wall units, as well as complete houses. In addition to the complex and resource-intensive dynamic testing, a number of smaller experiments are being undertaken to determine the structural properties (compression, bending, shear, tearing, etc) of individual bricks and multi-brick units. Different material properties (strength, moisture content, mix proportions, dimensions), bonding interfaces (rough/smooth, wet/dry) and curing conditions (temperature, humidity, pre-load) produce units with different structural capacities. It is anticipated that improvements in these properties will translate to improved performance of complete structures under seismic loading.

ADOBE MUDBRICK vs CONVENTIONAL MASONRY

The terms 'adobe' and 'mudbrick' are synonymous, and can be defined as air- or sun-dried bricks used for building. Adobe is a simple material which requires minimal resources for brick fabrication and wall construction. These features make it a very popular housing material in developing countries. It is a low strength, brittle material, and there is often great variability in its properties, due to variability in the soil components used and the fabrication and curing conditions. In adobe masonry, the mortar is usually made of the same mud material as the bricks. Despite the homogeneity of material used, the drying conditions of brick and mortar are vastly different, with shrinkage cracks prevalent in mortar beds. This differential contraction causes zones of weakness in the mortar-block interface. Table 1 shows some representative strength properties of adobe mudbricks and conventional masonry bricks and blocks.

Table 1. Strength of Adobe Mudbricks and Conventional Masonry

	# brick types tested	Minimum strength (MPa)	Maximum strength (MPa)	Mean strength (MPa)
Adobe mudbricks*	41	0.81	5.30	2.61
UK dimension bricks†	8	13.4	96.9	40.0
Continental bricks†	4	9.2	83.6	39.7
Blocks†	7	1.5	10.5	4.1

Sources: *McHenry (1984) †Riddington and Jukes (1994)

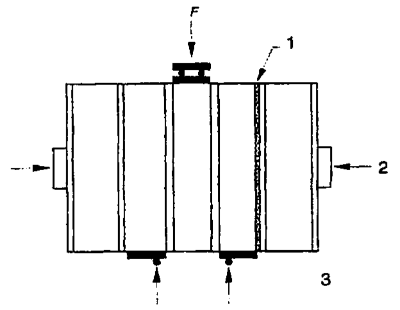
Compared to conventional masonry, the detailed testing and analysis of mudbrick masonry has been limited. This may be attributed to the relative lack of commercial interest in adobe construction, and the fact that adobe is predominantly used in developing countries, where resource limitations preclude detailed research in this field. Despite these limitations, however, a valuable opportunity exists to tap into the existing body of knowledge obtained through extensive research focussed on conventional masonry. The next challenge is to modify and adapt these established procedures and knowledge to adobe masonry, taking into account the differences in material properties and structural performance. The experiment described in this paper is one such attempt to bridge this gap.

MASONRY JOINT SHEAR TESTS AND STANDARDS

A variety of masonry joint shear strength tests have been developed over the years with a focus on conventional masonry such as fired clay bricks and concrete blocks. An evaluation of over 20 different masonry joint shear strength methods by Jukes et al (1997) showed that the Hofmann-Stöckl couplet test produced the most uniform stress distribution in the joint. The major disadvantage of this method, however, is the complexity of the test setup and apparatus required. Jukes et al (1997) noted that the triplet test method with pre-compression (later adopted as the European Standard, and described below) is a valid test method because of the ease of specimen construction, the lack of complex apparatus and the consistency of results.

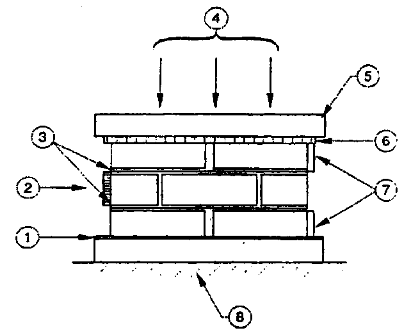
The current European Standards DIN EN 1052-3 (2002) and DIN EN 1052-4 (2000) show two methods for determining the shear strength of masonry mortar joints. The first method is a modified triplet test with vertical shear load applied to a straight stack specimen under pre-compression (Figure 1a). The second test involves a horizontal shear load applied to a running bond-configured specimen under pre-compression (Figure 1b). The second test is specified to include a damp-proof course between the mortar joints, but this is not necessary if standard mortar joint shear strength is being considered.

It is interesting to note that current Australian Standard (AS), American Society for Testing and Materials (ASTM), and International Organisation for Standardisation (ISO) standards and codes lack a simple and practical test method for determining the horizontal shear capacity of masonry components. Relevant American Society for Testing and Materials (ASTM) test methods (ASTM C1531-02 and E519-00) involve the testing of large wall panels, which is both resource intensive (materials, equipment and time) and impractical for large numbers of specimens.



Key:
1 – Strawboard / softboard / gypsum plaster
2 – Pre-compression
3 – Loading beam

Figure 1a: European Standard DIN 1052-3 (2002)



Key:
1 – Strawboard
2 – Shear load
3 – Damp proof courses
4 – Compressive load
5 – Upper platen
6 – Load spreading material
7 – Rigid abutments
8 – Lower platen

Figure 1b: European Standard DIN EN 1052-4 (2000)

NUMERICAL STUDIES

Numerical studies of shear test methods for conventional masonry show the variability of shear and normal stresses along the mortar joint (Riddington et al, 1997; Mirabella Roberti et al, 1998). The research by Riddington et al (1997) shows that shear and normal stress distributions are less variable for low pre-compressive (normal) loads (Figure 2). This would seem ideal for mudbrick units, where compressive strength is low and mudbrick buildings are generally single-storey structures with relatively low normal loading. On the other hand, however, "when no pre-compression is applied, tensile stress develops across the joint in the central region and failure is likely to be initiated in this region. Tensile bond strength will therefore have an influence on results when there is no pre-compression." (Riddington et al, 1997) (Figure 2). In the case of adobe masonry, the tensile bond strength is very low, and it would seem that avoiding the development of tensile stresses in the unit is more critical than reducing the minor variability of stress distribution across the joint. It is recommended that further numerical studies be undertaken to determine the stress distribution curves for adobe masonry. Additionally, it would be valuable to determine the minimum pre-compression load required to preclude the development of tensile stresses in the joint.

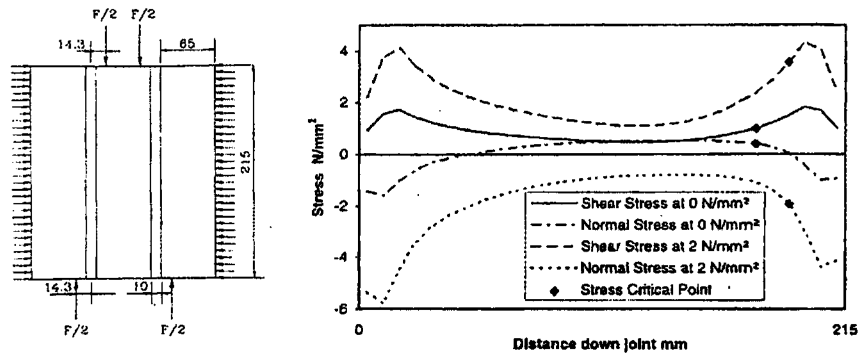


Figure 2. Triplet test: stress distributions along joint (Riddington et al, 1997)

Compression tests of mudbrick triplet units (Figure 3) undertaken at the University of Technology, Sydney, revealed minor cracks initiating at compressive loads as low as ~260 kPa in some specimens. It can be seen, therefore, that for the shear testing of mudbrick triplet units the applied pre-compressive load must be low to avoid damaging the specimen. In the case of mudbricks, it is suspected that the acceptable range of pre-compressive load is small (bound by the strength limits of the material, and the desire to minimise tensile stresses). Further research is required to determine this range, although it is possible that another test method, such as that proposed by Riddington et al (1997), is more appropriate, albeit more complex. For the purposes of the preliminary research being undertaken in this field at the University of Technology, Sydney, the triplet method is deemed to be acceptable, with anomalies in results more likely to be due to the irregularities in the material rather than problems with the testing procedure. Future testing will be comparative in nature, focussing on the relative performance of different brick and mortar specifications, as described earlier.

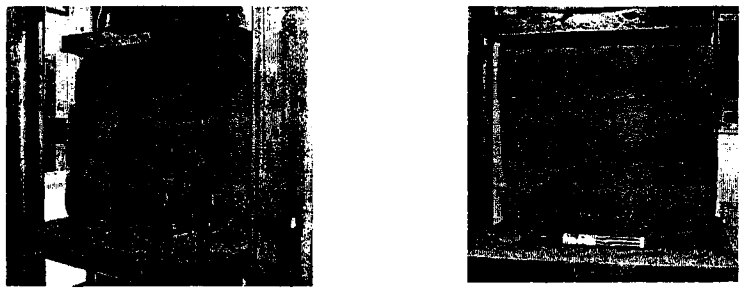


Figure 3. Compressive strength test of adobe triplet (Max. σ_c ~800kPa)

The numerical analysis undertaken by Riddington et al (1997) considers the effects of pre-compressive (normal) loading of 0, 1 and 2 MPa for conventional masonry. As stated earlier, significant pre-compressive loads are necessary to prevent the development of tensile stresses in the joint, however, it can be questioned whether such high normal loads are representative of typical loads in simple masonry structures. Calculations for the normal compressive loading for a single-storey adobe house, with a heavy clay tile roof, reveal a normal load of ~0.03 MPa at the mid-height of the wall, with the normal load at the base of the wall being ~0.05 MPa. In this application, the use of large normal compressive loads (>0.1 MPa) cannot be considered indicative of real life situations, and should thus be questioned.

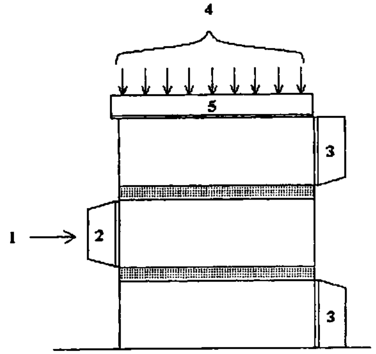
TEST AIMS

The aims of the experiment were:

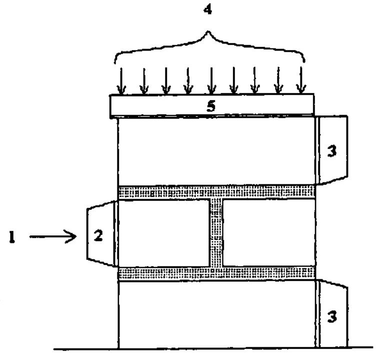
- To identify an appropriate means of evaluating the joint shear strength of mudbrick units.
- To assess the relative performance of units representing both horizontal stack (HS) and running bond (RB) patterns.
- To identify the dominant failure pattern(s) of prisms subject to joint shear testing.
- To identify and reduce the errors and inconsistencies in testing, such that future, large-scale testing may be undertaken with more reliable outcomes.

TEST METHOD

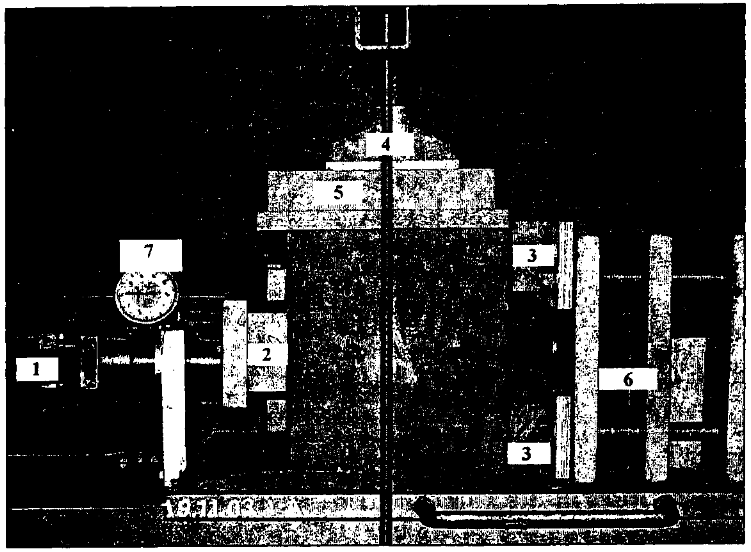
The test method adopted for this research can be considered a slight variation of the two European Standards described earlier. The test set up is shown in Figure 4. Triplet units characterising both horizontal stack and running bond patterns were tested. A modified soil mechanics shear box testing apparatus was used in the experiment. The horizontal application of load to the triplet unit is considered to more accurately represent the load distribution in actual wall units, and the slight increase in normal load is considered to be insignificant. The load was applied with a horizontal hydraulic jack (Carpanelli Type M63/4) at a constant rate of loading (1.2 mm/min) such that failure of the joint occurred between 45 seconds and 3 minutes after initial loading. (The time indicated is for analysing static horizontal loading. Failure occurring in less than 45 seconds is considered dynamically loaded.) The pushing, restraining and pre-compressive load blocks were all adjustable to allow for minor variations in specimen size. Rubber pads were placed between the blocks and the specimen to accommodate inconsistencies in the specimen surface and to ensure more uniform distribution of the loads. A dial gauge was used to record the load application, with results logged manually. Specimens were tested to failure.



(a) Horizontal Stack (HS)



(b) Running Bond (RB)



(c) Horizontal stack triplet ready for testing

Key:

1 – Shear load (from hydraulic jack)
2 – Pushing block
3 – Restraining blocks
4 – Pre-compressive (normal) load
5 – Upper platen
6 – Steel plate abutments
7 – Displacement gauge

Figure 4. Test Setup

SPECIFICATIONS

Specimen and test specifications are shown in Table 2.

Table 2. Specimen and test specifications

Mudbrick composition	3:2 soil: sand ratio (Mittagong, NSW)
Brick curing conditions	Air/sun-dried on bare earth/grass, covered with corrugated iron sheeting. Temperature range: -1°C to +33°C. Humidity range: 0 to 100%
Nominal brick dimensions*	
– top and bottom bricks	160mm x 240mm x 70mm
– middle bricks for horizontal stack	160mm x 240mm x 90mm
– half bricks for running bond	160mm x 110mm x 90mm
Mortar composition	3:2 soil:sand ratio (same as bricks)
Nominal mortar thickness (vertical and horizontal joints)	15 – 25 mm (in compliance with relevant adobe standards: IAEE, 1986; RESESCO, 1997)
Average moisture content of mortar	30 % (during construction); 2 % (during testing)
Specimen curing conditions	Standard laboratory conditions (UTS)
Specimen age (at testing)	35 to 41 days
Specimen quantity	12 x horizontal stack pattern (HS) 12 x running bond pattern (RB)
Pre-compressive (normal) loads (σ_c)**	20 kPa (6 x HS and 6x RB specimens) 30 kPa (6 x HS and 6x RB specimens)
Shear loading rate	1.2 mm/min

Notes:
*All external surfaces were saw cut to provide flat and smooth lateral surfaces. The natural roughness of the brick surfaces (top and bottom) in contact with the mortar joints was retained.
** The magnitude of normal compressive load was based on the expected loading at the mid-height of a masonry wall for a single-storey building, which is the location of the initiation of inclined shear cracking in masonry wall panels subject to in-plane forces. Values of σ_c = 20 kPa (non-load bearing wall) and σ_c = 30 kPa (load bearing wall supporting timber roof structure and tile cover) were used.

RESULTS

Table 3 provides a summary of test results. Different failure patterns were identified during the testing. The most common failure patterns are shown in Figure 5a. Combinations of different failure types were present in both running bond and horizontal stack specimens (Figure 5b). Local crushing of mortar in the vertical perpend joint was common in the running bond units.

Table 3. Test Results

Test Configuration	Max. Shear Stress, τ (kPa)	Corresponding Strain (%)	Mean Shear Stress, τ (kPa)	Standard Deviation (kPa)	Co-efficient of Variation CoV (%)
Horizontal Stack (HS) σ_c = 20 kPa	60.9	0.8			
	45.7	0.8			
	44.8	0.9			
	53.4	1.4			
	49.7	0.8			
	35.8	1.2			
			48.4	8.5	17.6
Running Bond (RB) σ_c = 20 kPa	32.8	0.9			
	35.3	1.4			
	37.3	0.6			
	37.5	1.2			
	38.0	0.4			
	48.4	2.6			
			38.2	5.3	13.9
Horizontal Stack (HS) σ_c = 30 kPa	48.1	1.2			
	42.0	0.7			
	44.2	1.2			
	49.5	0.9			
	38.1	0.8			
	36.3	0.6			
			43.0	5.3	12.3
Running Bond (RB) σ_c = 30 kPa	54.5	1.8			
	38.2	1.4			
	34.2	0.9			
	33.3	0.9			
	44.9	0.6			
	41.1	0.8			
			41.0	7.9	19.3

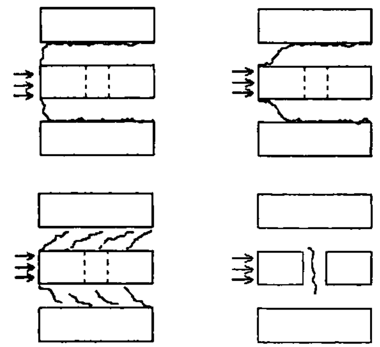


Figure 5a. Common failure patterns

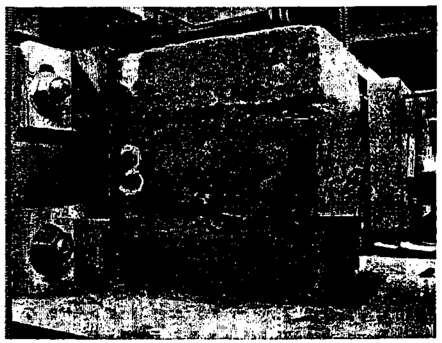


Figure 5b. Shear failure of running bond specimen.

Figure 6 shows some indicative stress-strain curves for different specimen configurations (horizontal stack, HS, and running bond, RB) with different pre-compressive loads (20 kPa and 30 kPa). The curves show the non-linear nature of adobe masonry units.

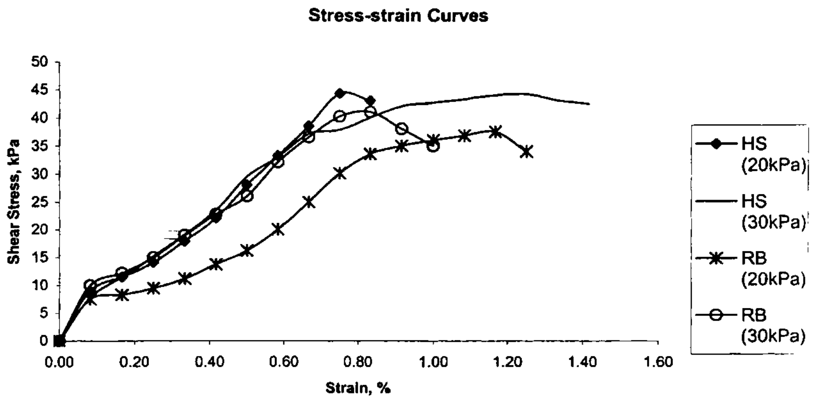


Figure 6. Typical Stress-Strain Curves

DISCUSSION

The results of this preliminary testing (four sets of six specimens per set) show an acceptable level of variation (CoV below 20%). Shear tests of over 40 sets of conventional masonry joints (four specimens per set) by Riddington and Jukes (1994) produced results with a CoV of between 4.5% and 37.9%, with most between 10% and 25%. It is expected that future testing with a larger sample number and increased experience (reducing human and testing errors) will produce even more reliable results.

As expected, the shear strength of the horizontal stack (HS) specimens was generally slightly higher than the running bond (RB) specimens. This can be attributed to two main reasons: firstly, the RB units possessed an additional plane of weakness in the vertical joint (crushing was evident in most RB specimens); and secondly, the RB specimen construction was more complex and difficult, resulting in less uniformity in triplet units.

Comprehensive testing of conventional masonry with varying pre-compressive loads shows a monotonically increasing linear relationship between the applied pre-compressive stress (σ_c) and the average shear stress at failure (τ) (DIN, 2000; Riddington and Jukes, 1994). The results of this preliminary testing are insufficient to define the corresponding relationship for adobe triplets. In fact, the results for horizontal stack (HS) units with 20 kPa pre-compression were unexpectedly higher than HS units with 30 kPa. This may be due to errors in testing, or may be a feature of such small-range, low-end testing, where the results are expected to be similar, and may even be constant (with slight positive and negative variation). Further testing with different pre-compression loads on both HS and RB adobe triplets is required to determine the relationship between pre-compressive stress (σ_c) and shear stress at failure (τ)

CONCLUSION

The triplet test has been identified as an appropriate means of evaluating the joint shear strength of mudbrick units. This preliminary testing forms a suitable platform for further research, which should focus on numerical studies (to determine the stress distributions in the mortar joints) and more comprehensive physical testing with larger sample numbers (to reduce variation of results and increase confidence). Testing may consider the effect of different material properties (strength, moisture content, mix proportions, dimensions), bonding interfaces (rough/smooth, wet/dry) curing conditions (temperature, humidity, pre-load) and testing factors (loading rate, pre-compressive load). An evaluation of these parameters is a practical step towards reducing the seismic vulnerability of adobe (mudbrick) houses.

REFERENCES

American Society for Testing and Materials (ASTM), "C1531-02: Standard Test Methods for In Situ Measurement of Masonry Mortar Joint Shear Strength Index", ASTM International, 2002, 6 p.

American Society for Testing and Materials (ASTM), "E519-00 Standard Test Method for Diagonal Tension (Shear) in Masonry Assemblages", ASTM International, 2000, 5 p.

Deutsches Institut für Normung (DIN) "DIN EN 1052-3: Methods of Test for Masonry. Part 3: Determination of Initial Shear Strength", DIN Germany, 2002, 14 p.

Deutsches Institut für Normung (DIN) "DIN EN 1052-4: Methods of Test for Masonry. Part 4: Determination of Shear Strength Including a Damp-Proof Course", DIN Germany, 2000, 10 p.

Dowling, D.M. "Adobe Housing in El Salvador: Earthquake Performance and Seismic Improvement", in Rose, W.I. et al. (eds), *GSA Special Paper 375: Natural Hazards in El Salvador*, Geological Society of America, 2004, pp.281-301.

International Association for Earthquake Engineering (IAEE) "Guidelines for Earthquake Resistant Non-Engineered Construction", IAEE, 1986, 158 p.

Jukes, P. and Riddington, J.R., "A Review of Masonry Joint Shear Test Methods", *Masonry International*, Vol. 11(2), 1997, pp.37-43.

McHenry, P.G. "Adobe and Rammed Earth Buildings: Design and Construction", John Wiley and Sons, New York, 1984, 217 p.

Mirabella Roberti, G., Binda, L. and Cardani, G., "Numerical Modeling of Shear Bond Tests on Small Brick-Masonry Assemblages", in Pande, G.N., Middleton, J. and Krajl, B. (eds), *Computer Methods in Structural Masonry – 4*, E & FN Spon, 1998, pp.144-152.

Reglamento Para la Seguridad Estructural de las Construcciones (RESESCO), "*Folleto Complementario: Lineamiento para Construcción en Adobe*", Asociación Salvadoreña de Ingenieros y Arquitectos (ASIA), El Salvador, 1997, 36 p.

Riddington, J.R., Fong, K.H. and Jukes, P. "Numerical Study of Failure Initiation in Different Joint Shear Tests", *Masonry International*, Vol. 11(2), 1997, pp.44-50.

Riddington, J.R. and Jukes, P., "A Masonry Joint Shear Strength Test Method" *Institution of Civil Engineers: Structures & Buildings*, Vol 104, August, 1994, pp.267-274.