THREE-POINT BENDING TEST TO DETERMINE MASONRY SHEAR BOND STRENGTH

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SUMMARY

Z-shaped shear specimen and test method to determine masonry shear bond strength by torsion are presented.

INTRODUCTION

Shear bond strength of masonry, f_{vk}, has been shown to be a function of number of factors. These include block properties such as strength, surface roughness, sand particle size distribution, moisture content of mortar, normal precompression stress, and the workmanship which is often crucial (Hendry and Khalaf 2001; Sinha 1967). Another important factor is the intrusion of mortar into the blocks, especially if highly porous concrete blocks are used (Hamid and Drysdale 1980; Riddington and Jukes 1994).

Hamid and Drysdale (1980) tested masonry prisms with angled joints to study shear behaviour. The whole specimen can be tested at an angle relative to the loads or a smaller specimen can be cut from a specimen constructed with horizontal bed joints so as to produce the effect of angled bed joints. Typical specimens are shown in Figure 1. The authors showed that the behaviour of walls under shear loading is a compound of failure events, and as a result the behaviour of mortar joints is obscured.

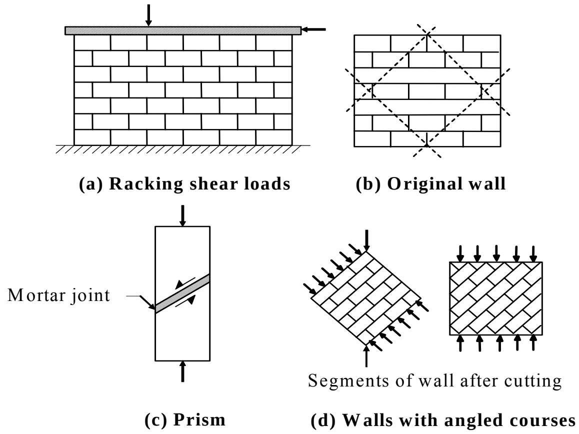

Figure 1. Test Set-up Adopted to Study Masonry Shear behaviour
(Hamid and Drysdale 1980)

Previous works (Hendry 1998; Stöckl and Hofmann 1988) showed that for precompression stress levels below approximately 2.0 N/mm^2, the relationship between the characteristic shear bond strength, f_{vk}, characteristic initial shear strength under zero compression stress, f_{vko}, and precompression stress, σ_d, could be adequately expressed by a Coulomb type equation (1):

$$f_{vk} = f_{vko} + \mu\ \sigma_d \qquad (1)$$

BS EN 1996-1-1 (2005) "Eurocode 6: Design of Masonry Structures", suggested determining the values of f_{vko} and the coefficient of internal friction, μ, for bed joints from triplet test with precompression (Figure 2) in accordance with BS EN 1052: Part 3 (2002). However, if test data is not available, the value of f_{vko} can be obtained from specified values provided in a table. From f_{vko} the value f_{vk} is derived using equation (1) above. Eurocode 6 suggested that μ used is 0.4 for all kinds of masonry unit and types of mortar used and the value of f_{vk} in equation (1) should not be greater than 0.065 f_b or f_{vlt}. Where f_b is the normalised compressive strength of the masonry units for the direction of loading and f_{vlt} is a limit to the value of f_{vk}.

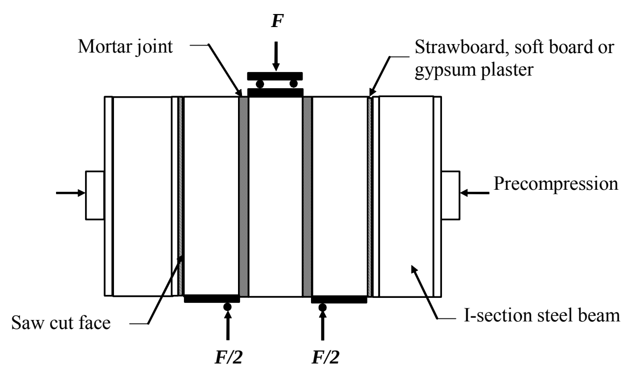

Figure 2. Triplet Test Set-up Adopted by BS EN 1052: Part 3 (2002)

The testing of triplet specimens requires careful set-up of heavy specimens and shearing of two unit/mortar interfaces. Since triplet specimens are loaded at four points, it is not clear how many unit/mortar interfaces will fail simultaneously. It was assumed in the triplet test that two interfaces would fail at the same time. This is not the case since usually only one interface fails first, followed by complete disintegration of the specimen. This is due to the inherent variations in workmanship and materials. Additionally, the setting up and loading of a triplet specimen certainly induces eccentricity in the specimen resulting in an uneven type of failure. Therefore, it is more conservative to derive the value of f_{vko} by dividing the failure load by the area of two interfaces. Clearly if the values for f_{vko} and μ used in design were more closely related to the actual shear bond strength of masonry more economical designs are produced.

The test method presented in this paper is based upon some of the principles given above and on work carried out by the same author on brickwork specimens and published in 1995 (Khalaf 1995).

EXPERIMENTAL PROCEDURE

Materials Used in Construction

The materials used in the construction of the specimens included one type of concrete block and four types of mortar, 1:2:8, 1:1:6, 1:½:5 and 1:¼:3 (cement (C): lime (L): sand (S) proportions by volume). The blocks were 214 x 120 x l00 mm with a compressive strength of 7 N/mm^2. The source blocks were cut with a rotating diamond saw to the size of a common clay bricks (214 x 102 x 65 mm). Two cut units were bonded together by either a circular or a rectangular mortar joint. The four types of mortar used were as recommended by the British Masonry Standard BS 5628: Part 1 (2005) for the construction of masonry walls. The reason for choosing these mortar types is to study the effect of changing mortar proportions and strength on the shear bond strength. In all cases the workability was keep constant at a medium level within one mix and also for all other mixes of mortar used. For each batch of mortar type used in the construction of the specimens six 100 mm cubes were cast to determine the compressive and splitting strengths of mortar. Mortars properties and joint types used in the construction of the shear specimens are summarised in Table 1.

An additional number of units were cut from the blocks in such a manner as to allow the cut faces to be bonded together. These specimens were bonded with 1:¼:3 mortar to produce the circular and rectangular joints.

Table 1. Mortar Types, Properties and Shapes Used in Constructing the Z-shaped Specimens

Mortar type (C:L:S)	Mortar compressive strength (N/mm^2)	Mortar splitting strength (N/mm^2)	Joint shape
1:2:8	3.8	0.28	Rectangular Circular
1:1:6	4.5	0.37	Rectangular Circular
1:½:5	8.0	0.76	Rectangular Circular
1:¼:3	15.4	1.97	Rectangular Circular Rectangular (cut face) Circular (cut face)

C:L:S = Cement: Lime: Sand mortar mixed by volume.

Construction of Z-shaped Shear Specimens

The test specimens were composed of two block units laid flat and connected by a mortar joint in a Z-shaped configuration (Figure 3). The circular mortar joints were constructed using a plastic ring 10 mm thick, thus allowing a circular mortar bed joint of 90 mm inner diameter and 10 mm thick to be formed. The plastic ring acts as a form whilst laying one block on top of the other (Figure 3). A piece of timber was used to support the top block and to align the specimen during construction. A weight of 5 kg was placed on top of the specimens after construction to reduce cracking, achieve consistency, and to simulate load from the top courses in actual construction. The timber trimmer and the 5 kg weight were left in place for 5 days to allow the mortar to gain strength before removal. During these 5 days the specimens were covered with polythene sheeting for curing. On removal, the author noticed that there were no shrinkage cracks on the specimens. The specimens were then left for additional 21 days to cure under ambient laboratory conditions at a temperature of 17^{o}C and a relative humidity of 38% before testing in 28 days from construction.

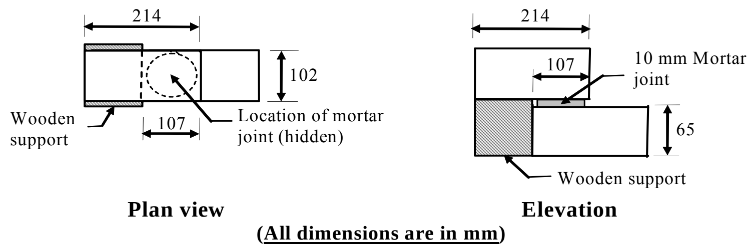

Figure 3. Example of the Method Used in Constructing the Z-shaped Shear Specimen (Circular Mortar Joint)

Testing of Z-shaped Shear Specimens and Theory Used to Determine f_{vko}

Five specimens of each block/mortar combination were constructed and tested at 28 days of curing. Figure 4 shows the loading and support arrangement used for testing the specimens. Dental plaster was used as a packing material and 10 mm square steel bars were used at all loading and supporting points. The reason of using dental plaster was to eliminate the uneven surfaces of block at these points. Once the dental plaster was hardened, the specimens were loaded to failure by applying displacement at a rate of 1 mm/min.

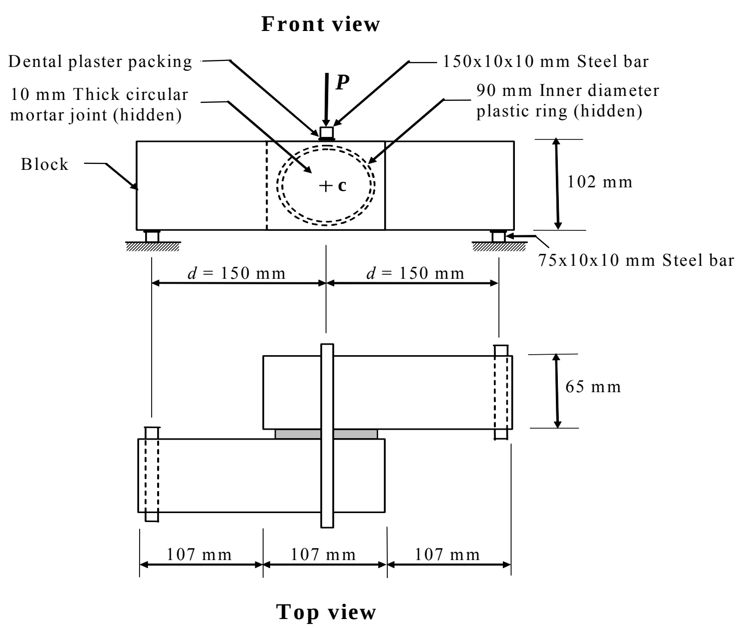

Figure 4. Load and Support Arrangements for Testing the Z-shaped Shear Specimens

The Z-shaped specimen is a simply supported loaded at mid span. The loading subject the specimen to shear and bending stresses. At ultimate load these stresses reach their maximum values and the Z-shaped specimen could fail by shear or bending. But due to the way the specimen was constructed whereby the only medium connecting the two blocks together is the mortar joint the maximum moment about Point c, which termed in this paper as torque (T), would move from Point c to Point t and a new torsion mode of failure (Figure 5) is created which breaks the bond between one of the blocks and the mortar joint by torsion shear stresses.

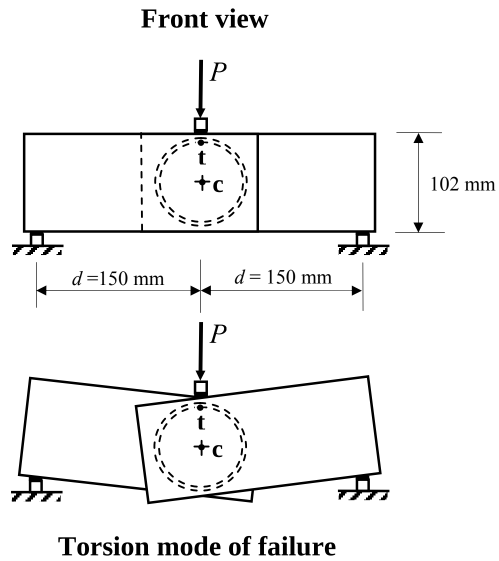

Figure 5. Observed Torsion Mode of Failure

Based on the torsion mode of failure a free body diagram (Figure 6) for the top block at the start of loading was drawn showing the applied load (*P + 2W*), weight of block (*W*), reaction force at support (*P/2 + W)*, to the right hand side under steel bar), resultant of shear stresses across the mortar joint (*P/2+ 2W*), to left hand side under mortar joint), and the resultant of moment about Points c or t (torque *T*). At the start of loading, the torque *T* rotates around the centre of the mortar joint (Point c), but at failure the torque moves to Point t. Based on this the value of f_{vko} was calculated using the theory of torsion for a circular shaft (Stephens 1982) and given by equations (2-6):

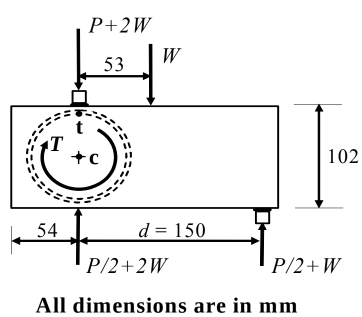

Figure 6. Free Body Diagram for Top Block

Density of concrete (ρ) = 2400 Kg/m^3
Volume of one block (V) = 0.214 x 0.102 x 0.065 = 0.00142 m^3
Mass of one block (M) = 2400 x 0.00142 = 3.41 kg
Weight of one block (W) = 3.41 x 9.81 = 33.45 N

The torque (T) about the centre of the circular mortar joint (Point c), at the start of testing, moves to Point t at failure is given by:

$$\mathrm{T} = \left[\left(\frac{P}{2} + W\right)d - 53W\right] = \left[\frac{Pd}{2} + 97W\right] \qquad (1)$$

The polar second moment of area about Point c (J_c) is given by:

$$J_c = \left[\frac{\pi R^4}{2}\right] \tag{2}$$

Since at failure, the torque moves to Point t, the polar second moment of area about Point t (J_t) is given by:

$$J_t = J_c + \pi R^2 \left(R^2\right) = \left[\frac{3\pi R^4}{2}\right] \tag{3}$$

Since, the section modulus of a circular area about Point t (Z_t) is given by:

$$Z_t = \frac{J_t}{R} = \left[\frac{\frac{3\pi R^4}{2}}{R}\right] = \left[\frac{3\pi R^3}{2}\right] \tag{4}$$

Therefore, the initial shear bond strength, f_{vko}, including the blocks self weight, is given by:

$$f_{vko} = \left[\frac{T}{Z_t}\right] = \left[\frac{\frac{Pd}{2} + 97W}{\frac{3\pi R^3}{2}}\right] \tag{5}$$

And the initial shear bond strength, f_{vko}, without the blocks self weight, is given by:

$$f_{vko} = \left[\frac{T}{Z_t}\right] = \left[\frac{\frac{Pd}{2}}{\frac{3\pi R^3}{2}}\right] = \left[\frac{pd}{3\pi R^3}\right] \tag{6}$$

Where:
d = Distance between the applied load and support (for specimens tested d = 150 mm).
P = Applied load (N).
R = Radius of circle (for specimens tested R = 45 mm).

Example of Calculation
In order to show the differences between the values of f_{vko} with and without including the blocks self weight, this example was carried out for a specimen with circular mortar joint built with 1:2:8 mortar:

Failure load (P) = 2505 N
f_{vko} with blocks self weight = 0.445 N/mm^2 ≈ 0.45 N/mm^2
f_{vko} without blocks self weight = 0.438 N/mm^2 ≈ 0.44 N/mm^2

As can be seen, that including the blocks self weight has minor effect on the value of f_{vko}, therefore, to simplify calculations and to produce conservative designs, the weight of the blocks should be ignored in calculation.

Test Method and Apparatus Used to Determine μ

Figure 7 shows the simple sliding apparatus used to determine the coefficient of external friction, μ. This is a simpler version of an apparatus used by Riddington and Jukes in 1994. It consists of a wooden base and a steel plate hinged together at one end. To find μ the steel plate must be inclined first and supported by a wooded block. A failed specimen is then placed on the inclined steel plate and the inclination increased gradually until slip occurs. The piece of wooden block was then moved to support the inclined steel plate in its final position. Finally, the angle of inclination is measured using a protractor and the coefficient of external friction, μ, was determined by taking the tangent of this angle.

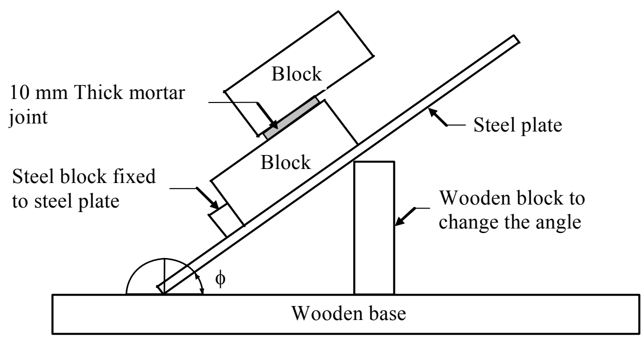

Figure 7. Apparatus Used to Determine the Coefficient of External Friction

Although, this test measures the coefficient of external friction, it had been found that this value gives a good indication as to the value of the coefficient of internal friction (Riddington and Jukes 1994).

RESULTS AND DISCUSSION

Effect of Joint Type and Mortar Strength on f_{vko}

Table 2 shows the experimental results obtained for all the specimens tested in this investigation. The table shows little difference in the initial shear bond strength, f_{vko}, observed between the circular-jointed and the rectangular-jointed specimens. The reason may be due to the small difference in area between the two types of joint, which means that the contribution to shear bond strength of the extra area resulted from using rectangular joint, is very small and almost negligible. Therefore using simple rectangular mortar joint instead of circular joint should be adopted in the construction of the Z-shaped shear specimens. Using rectangular joint makes the process of construction easier and quicker since there is no need for plastic ring to be placed between the two blocks.

Table 2. Results of Testing Z-shaped Shear Specimens Using Equation 6 (Means of 5)

Mortar type (C:L:S)	Joint type	Failure load (N)	Initial shear bond strength (f_{vko}) (N/mm^2)	C.V. (%)
1:2:8	Rectangular	2505	0.44	7.3
	Circular	2521	0.44	8.5
1:1:6	Rectangular	2482	0.43	10.0
	Circular	2545	0.44	17.1
1:½:5	Rectangular	2773	0.50	8.1
	Circular	2741	0.48	13.2
1:¼:3	Rectangular	3079	0.54	12.5
	Rectangular (cut face)	3385	0.59	12.8
	Circular	2937	0.52	11.6
	Circular (cut face)	3293	0.58	17.3

C:L:S = Cement: Lime: Sand mortar mixed by volume.
C.V. = Coefficient of variation.
Note: Test results from the sliding apparatus showed that there were no differences in the values of coefficient of external friction ($\mu = 0.87$) for the four types of mortar used in the investigation.

Figure 8 shows the initial shear bond strength, f_{vko}, against mortar cube compressive strength for both types of joint. The figure highlights the small differences in the values of f_{vko} between the circular-jointed and the rectangular-jointed specimens. It is also evident from the figure that increasing mortar compressive strength causes an increase in f_{vko}. The average shear bond strength for both types of joints using a mortar joint of the 1:¼:3 mix is 0.53 N/mm^2, compared to 0.44 N/mm^2 for the 1:2:8 mix, an increase of 20.5%. The mortar strength was thought to affect block-mortar shear bond strength because of the better mechanical bonding between the two materials as a result of using stronger mortar.

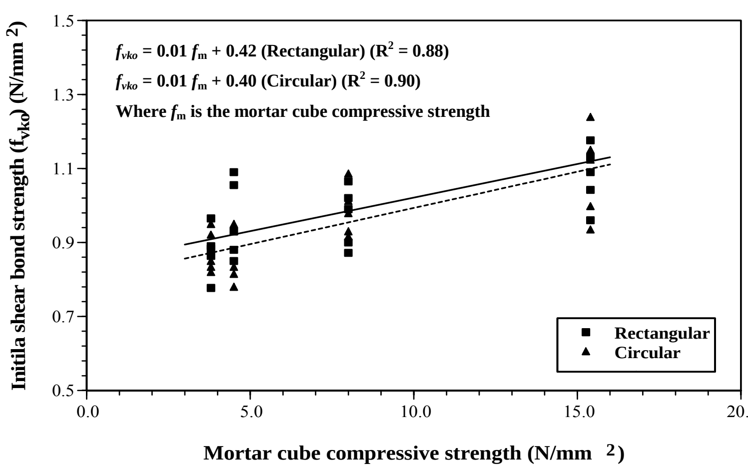

Figure 8. Initial Shear Bond Strength vs Mortar Cube Compressive Strength

Similar relationships and conclusions were observed between the initial shear bond strength, f_{vko}, and mortar cube splitting strength for both types of joint.

Initial Shear Bond Strength at Block Cut Face

The results in Table 2 for the 1:¼:3 mortar mix, compare the initial shear bond strengths, f_{vko}, of the specimens jointed by a mortar joint at the block cut faces. The table shows that the values of f_{vko} for the rectangular-jointed specimens are 0.54 and 0.59 N/mm^2 for the uncut and cut faces respectively. For the circular-jointed they are 0.58 and 0.52 N/mm^2 for the uncut and cut faces respectively. The shear bond strength at a cut face appears to be slightly higher than that at an uncut face. The most likely explanation is that the cutting operation resulted in exposing the finer pores in the concrete and increasing the number of pores per square millimetre compared to the uncut faces. This on the other hand provides a better "key" for shear bond resistance. More tests to produce micrographs using an electronic microscope are needed to confirm this finding.

Finally, the test results showed that there were no differences in the values of $\mu = 0.87$ for the different types of mortar used in the investigation.

CONCLUSIONS

1. The results of testing showed that the proposed Z-shaped shear specimen and test method are capable of determining the values of f_{vko} and μ for blockwork masonry bed joints.
2. The investigation showed that the new proposed Z-shaped shear specimen offers many advantages to determine f_{vko}. These are: easy to construct, light in weight, easy to set-up for testing, no eccentricity of loading effecting results, failure occurs in one interface, and test can be carried out on a large number of specimens to achieve reliable results.
3. The test results and observations showed that failure occurred by shear at a single block/mortar interface rather than by shearing of two interfaces, as is the case with triplet specimen.
4. The proposed specimen and test set-up reduce or even eliminate any eccentricities caused by the setting and loading procedures that have been shown previously to influence considerably the values of f_{vko} and their coefficient of variation in triplet specimens. On the other hand the proposed specimen and test method produced more representative values for f_{vko} and causes a noticeable reduction in the coefficient of variation.
5. There appears to be little difference in the values of f_{vko} between the circular-jointed and the rectangular-jointed specimens. It is therefore suggested that simple rectangular joints be adopted for the construction of the test specimens.
6. The results showed that the initial shear bond strength, f_{vko}, increases as the mortar compressive or tensile strength increases.
7. From comparison of results where cut faces were bonded with those where uncut faces were used, it appears that the process of cutting exposed the finer pores in the concrete so the number of pores per square millimetre is higher than the uncut surface. This resulted in a better mechanical bonding between the two materials and consequently an increase in shear bond strength.

Apart from its simplicity, the new proposed Z-shaped shear specimen and test method offers another advantage whereby the failed specimens can be reassembled and tested on a simple sliding apparatus to determine the coefficient of external friction, μ, which previous findings showed that it does give a good indication of the coefficient of internal friction.

REFERENCES

British Standards Institution, “Use of masonry: Structural use of unreinforced masonry”, *BS 5628: Part 1*, 2005, London.

British Standards Institution, “Methods of test for masonry. Determination of initial shear strength”, *BS EN 1052: Part 3*, 2002, London.

British Standards Institution, “Eurocode 6: Design of masonry structures: General rules for reinforced and unreinforced masonry structuers”, *BS EN 1996-1-1: Part 11*, *Eurocode 6 (EC 6)*, 2005, London.

Hendry, A.W. and Khalaf, F.M., “Masonry Wall Construction”, Spon Press, ISBN 0-415-23282-1, 2001.

Hendry, A.W., “Structural Masonry”, *Macmillan*, London, 1998.

Hamid, A.A. and Drysdale, R.G., “Behavior of Brick Masonry Under Combined Shear and Compression Loading”, *Proc. 2nd Canadian Masonry Symposium*, Ottawa, 1980, pp. 102-108.

Khalaf, F.M., “Simple Bending Test for the Determination of Masonry Bond Strength”, *Proc. 4th International Masonry Conference*, London, 1995, pp. 327-330.

Riddington, J.R. and Jukes, P., “A Masonry Joint Shear Strength Test Method”, *Proc. of the Institute of Civil Engineers (ICE) Journal*, Vol. 104, 1994, pp. 267-274.

Sinha, B.P., “Model Studies Relating to Load Bearing Brickwork”, *PhD Thesis*, University of Edinburgh, 1967.

Stephens, R.C., “Strength of Materials: Theory and Examples”, *Edward Arnold*, London, 1982.

Stöckl, S. and Hofmann P., “Tests on the Shear Bond Behavior in the Bed Joints of Masonry”, *Proc. 8th international Brick/Block Masonry Conference*, Dublin, 1988, pp. 292-303.