INFLUENCE OF MATERIAL PROPERTIES AND VERTICAL PRE-COMPRESSION ON THE SHEAR BEHAVIOUR OF MORTAR JOINTS

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ABSTRACT

The influence of mortar type on the shear behaviour of bed joints subjected to simultaneous shear and normal pre-compression was investigated. The test specimens were manufactured of solid clay bricks combined with a typically strong, cement rich respectively a typically weak, lime rich mortar. The tests were carried out under deformation control, which enabled both the elastic and softening plastic properties of the joints to be observed. The elastic shear deformation of the joints with the weak mortar was 2-4 times larger than in the case with the strong mortar. Joints with the weak mortar exhibited less pronounced shear softening than the joints with the strong mortar. Results of the investigations suggest that a shift from the strong to the weak mortar might improve the resistance to cracking of a horizontally restrained wall by 30-60 %.

Key words: Masonry, mortar, cement, lime, shear, strength, deformation, dilatancy.

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INTRODUCTION

Design of masonry has mainly been concerned with provision of sufficient resistance against loads threatening the structural integrity of buildings. This has created a tendency to maximize the strength of both units and mortars, which often renders masonry with low ductility. In such masonry, there is an increased demand for movement joints to accommodate for differential thermal movements and shrinkage. As the understanding of the physical phenomena influencing cracking of masonry is generally poor among practitioners, movement joints are often used in excess. Movement joints need maintenance and lead to a fragmentation of masonry structures, which is considered unfavorable from architectural point of view.

Development of micro-level modeling strategies in the last decade has led to a better understanding of the cracking of masonry subjected to in-plane tension loads (CUR (1997), Lourenço (1996), Gottfredsen (1997), van Zijl(1999), Molnár (2000)). The shear properties of mortar joints have, among others, been identified as key-parameters. As a complement to the modeling, suitable test set-ups, able to deliver elastic softening-plastic shear parameters of mortar joints, have been developed by van der Pluijm (1993) and Gottfredsen (1997).

As the main objective of the shear tests was model development and verification, generally few material combinations were tested. In Hansen et al. (1998), different unit/mortar combinations were tested regarding in-plane horizontal ductility. Weak mortars were reported to produce more ductile shear behaviour compared to strong mortars. However, generalizations based on the results in Hansen et al. (1998) are difficult to make due to the insufficient number of replicates in the tests.

The purpose of the present research is to provide better insight in the shear behaviour of joints built with massive clay bricks and typically strong respectively weak mortars. The test results can be used to evaluate the influence of mortar quality and vertical pre-compression on the structural response of masonry subjected to shear loads and horizontal tension in its own plane. This constitutes an essential step towards more rational design rules concerning design of movement joints. The paper presents the results of 31 deformation controlled shear tests on mortar joints subjected to simultaneous vertical pre-compression and shear.

MATERIALS AND METHODS

The shear tests in the present work were carried out on specimens consisting of two bricks and one mortar joint. The tests were performed at three different levels of normal pre-compression. The testing arrangement was similar to those used by van der Pluijm (1993), Gottfredsen (1997) and Hansen et al. (1998).

Materials

One type of solid clay bricks and two types of mortar were used. The bricks were of type Haga red, manufactured by extrusion. The tensile strength and the static modulus of elasticity were determined from direct tension tests on full size bricks. The dynamic modulus of elasticity was determined by measurement of the natural resonance frequencies in the flexural mode, prior to the tension tests. The mechanical properties of the bricks are presented in Table 1.

Table 1. Mechanical properties of massive clay bricks (Molnár 2000).

Parameter	Value	Dimension	Number of tests	Coefficient of variation [%]
Dimensions	218x119x60	mm^3	-	-
Density	1870	kg/m^3	-	-
Initial rate of suction	2.55	$kg/m^2/min$	-	-
Compressive strength	35*	N/mm^2	-	-
Tensile strength	2.5	N/mm^2	6	9.4
Static modulus of elasticity	13400	N/mm^2	6	3.7
Dynamic modulus of elasticity	13900	N/mm^2	6	5.8

* Compressive strength according to the manufacturer.

Two mortars, here described as B and D respectively, were used in the experiments. Mortar B is the most frequently used pre-mixed mortar in Sweden. The binder in mortar B is masonry cement, composed of approximately 75% Portland cement, 25% filler of grounded limestone and air-entraining additives. The filler is used to reduce the cement content whereas the air-entraining additive is used to improve workability. Mortar D is a pre-mixed lime (hydraulic) cement mortar, introduced to the Swedish market in the 1990s. The flexural and compressive strength of the mortars were determined on prisms 40*40*160 mm according to procedures described in RILEM (1994). Mortar composition and mechanical properties are shown in Table 2.

Table 2. Composition and standard properties of mortars (Molnár 2000).

Mortar	Composition Parts by weight	Compressive strength [N/mm^2]	Flexural strength [N/mm^2]
B	masonry cement/sand 100/600	6.0	1.1
D	Portland cement/lime/sand 25/75/750	3.0	0.9

Specimens

The specimens used in the present work were so called couplets, consisting of two bricks and one mortar joint, see Fig. 1. The preparation of the bricks before manufacturing of specimens involved:

- grinding of one bed face, in order to facilitate the gluing to the steel plates;
- saw-cutting to the desired length of 180 mm;
- repeated cleaning of the surface by high-pressure water, in order to eliminate the dust originating from sawing;
- drying at a temperature of 18-20 C and a relative humidity (RH) of 40-50 % during 3 weeks.

Two types of specimens, with mortar B and D respectively, were manufactured. The specimens were cured for 2 weeks at 18-20 C and RH 90 %. Until testing, i.e. farther 6-9 weeks, the specimens were stored at 18-20 C and RH 40-50 %.

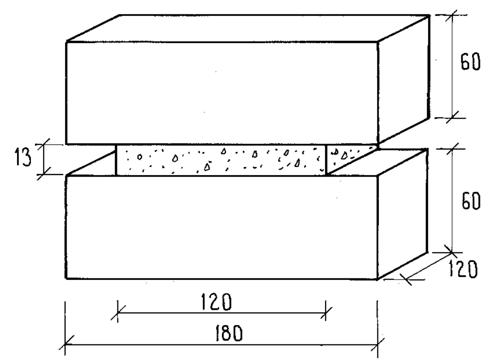

Figure 1. Shear specimen

Test set-up

The shear test set-up was similar to those used by van der Pluijm (1993), Gottfredsen (1997) and Hansen et al. (1998), see Fig. 2. An approximately uniform shear distribution in the mortar joint is obtained by introducing an axial force through two L-shaped steel frames. The desired normal pre-compression is generated by springs attached to the L-shaped frames.

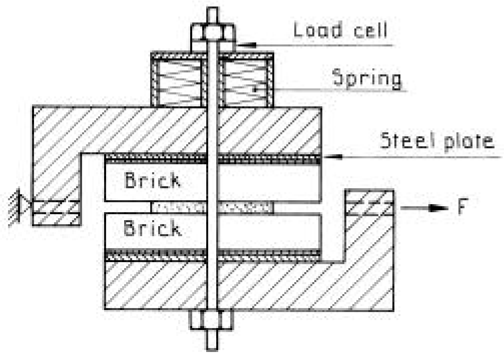

Figure 2. Shear test set-up adopted from v. d. Pluijm (1993) and Gottfredsen (1997).

Before testing, two steel plates were glued to the specimens by means of an epoxy-based glue. Next, the specimens were assembled in the L-shaped steel frames and fastened by screws. The pre-compression force was generated by means of a steel frame and two spiral springs. The stiffness of the springs was 500 N/mm, which was chosen so that no larger deviation than 6 % from the target pre-compression value should occur due to the normal expansion of the mortar joints during shear softening.

The whole arrangement was fixed in a testing machine of MTS type with hinged connections. The tests were conducted under constant deformation rate, with the mean tangential deformation of the mortar joint as a guiding input. The chosen deformation rate was 0.036 mm/min.

Six LVDTs as shown in Fig. 3 measured the tangential and normal deformations of the mortar joint. The supports of the LVDTs were glued to the bed face of the bricks, which enabled the shear deformation of the joint to be recorded directly. The testing machine recorded the axial force.

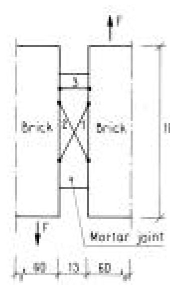

Figure 3. Measurement of the tangential (LVDT 1&2) and normal (LVDT 3) displacements.
LVDT 4-6 on the opposite side not shown.

The mean value of the tangential (shear) displacement d is calculated as

$$d = \frac{(d_1 - d_2) + (d_4 - d_5)}{4} \quad (1),$$

where the d_n values are readings from the diagonally placed LVDTs in Fig. 3. By placing the LVDTs diagonally, the readings systematically underestimate the tangential displacements by 2.3 %. The normal displacement is calculated as the mean of the readings from LVDTs 3 and 6.

Test program

Altogether 31 tests were carried out, consisting of two material combinations, at three different levels of normal stress, with five or sex replicates for each material and normal stress combination, see Table 3. At the time of testing, the specimens were 8-11 weeks old. In the following sections, specimens with mortar type B and D are referred to as series B respectively series D.

Table 3. Test program - shear tests on bed joints

	Number of tests		
Normal stress level [N/mm²]	0.22	0.56	0.84
Series B	6	5	5
Series D	5	5	5

RESULTS AND DISCUSSION

Representative load-shear displacement curves from the deformation controlled shear tests are presented in Fig. 4. In most of the tests, the behaviour was linear elastic up to 30 % of the peak load. Thereafter, the joints behaved more or less non-linearly. In all tests, failure occurred in the brick mortar interface, with no discernible cracks in the bricks. In three cases, all in series B, unstable behaviour was observed in the post-peak stage. Series B exhibited a steeper descent of the softening branch of the stress-shear displacement curves at every pre-compression level than series D.

Along the softening branch of the load deformation curves, sudden load drops of vibration type could be observed. The phenomenon is known as stick-slip motion, see Oden & Martins (1985) and Giannakopoulos (1989) for more details.

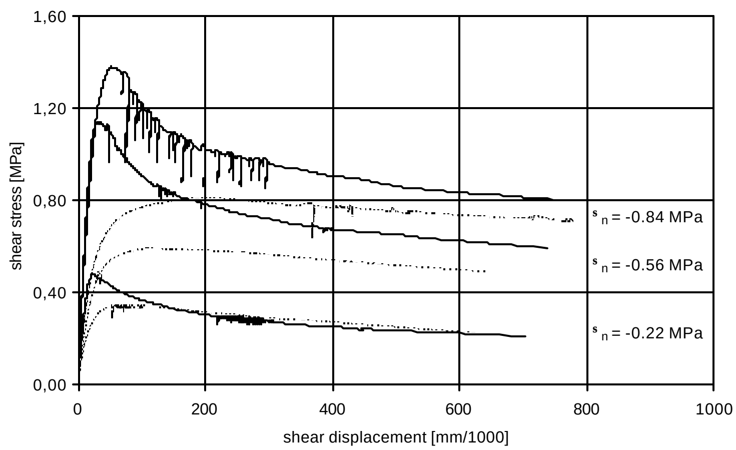

Figure 4. Load-displacement curves from the shear tests at different levels of normal pre-compression. Series B - continuous lines; series D - dotted lines.

Fig. 5 presents normal versus shear displacement curves from the shear tests. The normal uplift generally started at shear displacements corresponding to the peak load and did not reach its maximum when the shear tests were terminated. The normal uplift for the joints in series B was twice as high as in series D. High normal pre-compression resulted in low normal uplift and vice versa, regardless mortar type.

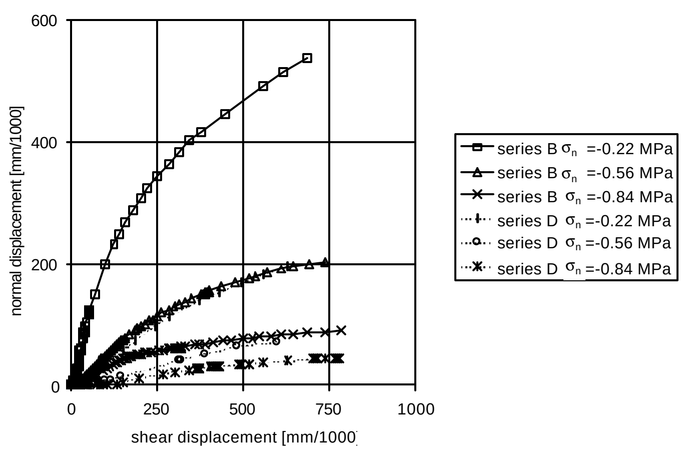

Figure 5. Typical normal versus shear displacement curves.

The test results are analyzed as follows in terms of properties determined, either directly or derived, from the load deformation curves. Fig. 6 shows a load tangential deformation curve and the definition of the properties to be analyzed.

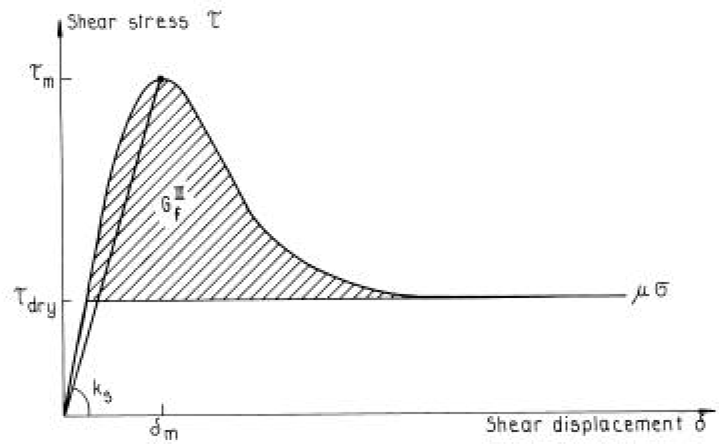

Figure 6. Typical load displacement curve from deformation controlled shear tests. d_m - tangential displacement at peak load; t_m - maximum shear load carried by the joint; s_n - normal stress; m - coefficient of dry friction; t_{dry} - shear load at constant dry friction; k_s - secant shear stiffness of the joint; G_f^{II} - mode II fracture energy.

Pre-peak parameters

Up to load levels of approximately 30 % of the peak load, the joints exhibited a nearly linear elastic behaviour. However, from levels corresponding to 70 % of the peak load and upwards, the behaviour of the joints was non-linear. From the load deformation curves obtained in the tests, the shear stiffness of the joints was determined. Choosing secant stiffness seemed convenient, as it gives a realistic estimate of the shear deformation at the peak load. The secant stiffness k_s is calculated as

$$k_s = \frac{F_{max}}{A_j d_m} \quad (2),$$

where F_{max} are the peak load, A_j the joint area and d_m the tangential displacement at peak load. The obtained shear stiffness values are presented in Table 4.

Table 4. Shear stiffness values of the joints determined from the shear tests.

Normal pre-compression	Series B k_s	c.v.	Series D k_s	c.v.
[N/mm²]	[N/mm³]	[%]	[N/mm³]	[%]
0.22	26	56	6.1	57
0.56	27	32	4.6	38
0.84	24	23	4.0	8

It can be observed, that the joints in series B are 4-5 times stiffer in shear compared to the joints in series D. In both cases, the variability in k_s is highest at low pre-compression levels and decreases with increasing pre-compression. In series D the joint stiffness k_s decreases with increasing normal pre-compression. This may be the result of an early onset of plastic deformations in the mortar.

The value of shear displacement at peak load d_m indicates the tangential deformation capacity of a joint before cracking. From Fig. 7 it can be observed, that at pre-compression levels of 0.22 MPa joints in series D can deform twice as much than joints in series B before cracking. At pre-compression levels of 0.56 MPa and 0.84 MPa, this difference in elastic deformation capacity increases to a factor 3 and 4 respectively.

The results of the tests suggest that the choice of mortar type significantly influence the behaviour of horizontally constrained walls subjected to imposed deformations. If the proportion of mortar joints in masonry is roughly estimated to 15 %, a shift from the strong to the weak mortar in the present study enhances the elastic deformation capacity of a wall in the horizontal direction by 30-60 %. This means, that the capacity of the restrained wall to resist shrinkage or temperature changes is enhanced to the same extent.

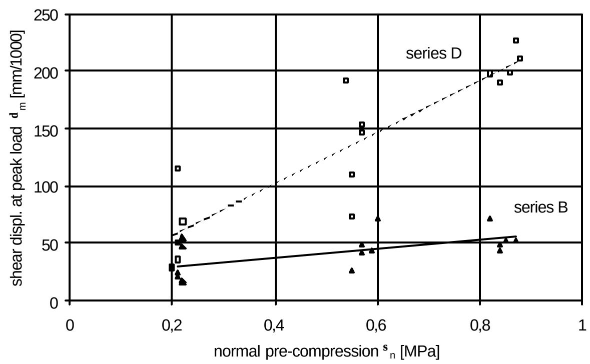

Figure 7. Shear displacement at peak load d_m versus normal pre-compression.

Strength parameters

The shear strength of the joints t_m is calculated from the maximum axial force F_{max} and the area of the mortar joint A_j as

$$t_m = \frac{F_{max}}{A_j} \qquad (3).$$

In Fig. 8 the shear strength values are plotted against the applied normal pre-compression. By performing a linear regression, the parameters of the Coulomb failure criterion, the cohesion c and the coefficient of internal friction $\tan j$, are determined. The results are presented in Table 5.

Figure 8. Shear strength of the joints as a function of the normal pre-compression.

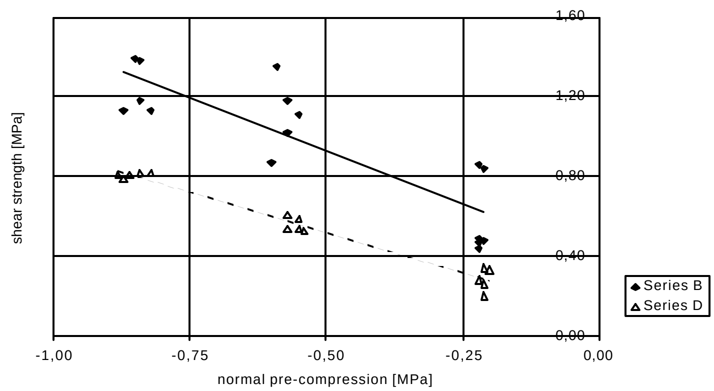

Table 6. Shear strength parameters for the joints determined by linear regression.

	Cohesion c	Coefficient of internal friction $\tan j$
	[N/mm²]	[-]
Series B	0.40	1.06
Series D	0.11	0.82

The linear regression indicates an essential difference between the two mortars regarding cohesion, with values four times higher in series B than in series D. Compared to similar mortars in Gottfredsen (1997), both mortars in the present work exhibit low cohesion.

Post-peak parameters

After the peak, the shear load carried by the joint specimen gradually diminishes to a (theoretically) constant level t_{dry}, known as dry friction, see Fig. 6. In the present work, the plateau reported by van der Pluijm (1993) and Gottfredsen (1997) in the post-peak stage of the load displacement curves could not be observed. Especially at pre-compression levels of 0.56 and 0.84 MPa, the load displacement curves exhibited a sloping tendency when the tests were terminated. This might be caused by the fact that cohesion softening of the mortar joints was not completed when testing was stopped. The coefficient of dry friction m_{dry}, calculated at tangential displacements of 0.6 mm, varied between 0.84 and 1.05.

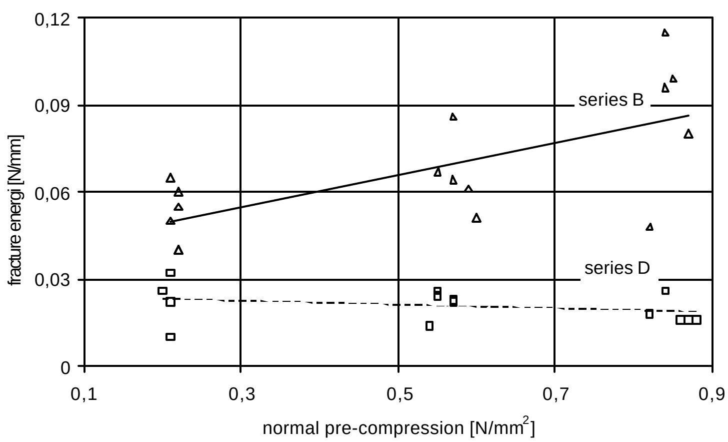

Figure 9. Mode II fracture energy as a function of the normal pre-compression.

The cohesion softening of mortar joints is often characterized by the mode II fracture energy G_f^{II}. This is defined as the area enclosed by the load displacement curve and the level of dry friction t_{dry}. Fig. 9 presents the mode II fracture energies plotted against the normal pre-compression. For series B a linear dependence was found, whereas series D showed no dependence on the normal pre-compression. The softening behaviour of the joints was most pronounced in series B, at low levels of pre-compression. Least softening was observed in series D at high levels of pre-compression. Generally, the shear behaviour of the joints in series D showed similarities with an elasto-plastic material.

Normal uplift - dilatancy

Granular materials like soils, concrete and mortars subjected to shearing beyond the elastic stage exhibit a normal uplift along with the shear displacement. The normal uplift is explained by the dislocation taking place in the granular material at the onset of cracking and during the relative tangential movement of the two surfaces in the crack. The described normal uplift is known as dilatancy/dilatation in the literature.

The magnitude of normal pre-compression has a significant influence on the normal uplift of joints in shear. At the same amount of shear displacement, high levels of normal pre-compression correspond to low values of normal uplift and vice versa.

Another parameter influencing the normal uplift of joints during shear deformation is the mortar type. Series B exhibited twice as large normal uplift at every pre-compression level compared to series D. This fact can be explained by differences in cohesion and grading of the sand in the two mortars.

Van Zijl & Rots (1998) analyzed the influence of normal confinement on the shear behaviour of mortar joints. In a series of FE analyses, cases with total confinement and no confinement at all were simulated with different levels of dilatancy. At total confinement combined with non-zero dilatancy, no upper limit for the maximum load could be obtained. The effect of dilatancy at zero confinement was negligible. However, the effect of dilatancy was not verified on experimental data with documented normal stiffness of the testing equipment.

In the present work the normal pre-compression in the shear tests was generated by two spiral springs mounted in parallel. The total stiffness of the springs was 500 N/mm, which resulted in an increase of the normal pre-compression by 1 and 6 % at pre-compression levels of 0.84 MPa and 0.22 MPa respectively. It can be concluded that the confining effect of the springs was not significant and thus the tests can practically be considered as unconfined.

CONCLUSIONS

Deformation controlled shear tests with three different levels of normal pre-compression were carried out on mortar joints built with typically strong (cement rich) resp. weak (lime rich) mortars. The tests showed that:

- The strength of the mortar joints could be described by the Coulomb failure criterion. The cohesion c was four times higher (0.40 vs. 0.11 MPa) in the joints with strong mortar compared to joints with weak mortars.

- The shear displacement at peak load was 2-4 times larger in the case of joints with weak mortar compared to joints with strong mortars. Increasing levels of normal pre-compression resulted in higher values of the shear displacement at peak load.

- The secant shear stiffness k_s of the joints with weak mortar decreased with increasing normal pre-compression.

- Joints with strong mortar exhibited more shear softening compared to joints with weak mortar. The post-peak behaviour of the joints with weak mortar showed similarities with an elasto-plastic material.

- Concerning dilatancy, joints with strong mortar showed twice as high values as joints with weak mortars.

REFERENCES

CUR (1997) – "Structural masonry: an experimental/numerical basis for practical design rules". Edited by Rots, J.G. A. A. Balkema, Rotterdam, The Netherlands.

Giannakopoulos, A.E. (1989) – "The return mapping method for the integration of friction constitutive relations". Computers and Structures, Vol. 32, pp. 157-167.

Gottfredsen, F.R. (1997) – "Laterally loaded masonry – properties and behaviour". Ph.D. thesis, SBI report 289, Danish Building Research Institute, Hoersholm, Denmark.

Hansen, K.F., Nykänen, E. and Gottfredsen, F.R. (1998) - "Shear behaviour of bed joints at different levels of precompression". Masonry International, The British Masonry Society, Stoke-on-Trent, UK, Vol. 12, No. 2, pp. 70-78.

Lourenço, P.B. (1996) – "Computational strategies for masonry structures". Dissertation, Delft University of Technology, Delft, The Netherlands.

Molnár, M. (2000) - "In-plane tension behaviour of horizontally loaded masonry". Licentiate thesis, Report TVBK-1018, Lund University, Lund, Sweden.
RILEM (1994) – "Technical recommendations for testing and use of construction materials". E&FN Spon, London, UK.

Van der Pluijm, R. (1993) – "Shear behaviour of bed joints". Proceedings of the 6th North American Masonry Conference, Philadelphia, pp. 125-136.

Van Zijl, G.P.A.G. & Rots, J.G. (1998) – "Towards numerical prediction of cracking in masonry walls".

Computer methods in structural masonry - 4, ed. by Pande, G.N., Middleton, J., Kralj, B., pp. 94-102. E & FN Spon, London, UK