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SHEAR OF CONCRETE MASONRY WALLS

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ABSTRACT
The behaviour of plain and bed joint reinforced concrete masonry walls subject to monotonic in-plane lateral (shear) load was examined. Tests were carried out on 18 walls (1.6 m long by 1.4 m high) with different levels of axial stress and different ratios of horizontal reinforcement. The results show that the bed joint reinforcement did not increase the shear strength of the masonry walls but rather decreased the shear strength, especially under low levels of axial loads. This finding is in contrast to many codes around the world which specify that the shear strength of a wall be determined by adding the strength of the masonry in shear to the strength of the shear resisting steel. The results show that there was negligible strain in the reinforcement until the masonry cracked - that the horizontal steel was activated only after the wall had cracked. Thus, the role can be summarized as increasing the ductility of the shear walls after failure; that is, after the peak load had been reached.

KEYWORDS: bed joint reinforcement, concrete masonry, monotonic loading shear strength.

INTRODUCTION
Masonry shear walls are the main structural elements that resist lateral loads applied to a masonry building. The shear resistance of reinforced masonry walls can be attributed to several complicated mechanisms including the shear resistance of the masonry, aggregate interlocking and the shear steel. The current Canadian Code [1] states that the shear resistance of a masonry wall can be calculated as the sum of two components: the shear resistances of the masonry and the steel. This concept is supported by Brunner and Shing [2] who developed an equation to calculate the shear resistance of a masonry wall taking into consideration the contribution of the shear resistance of the horizontal steel. However, the experiments carried out by Shing et al. [3] showed that horizontal steel is only activated after the initiation of cracking in the masonry walls. This result can be understood in that the extensional strain in the horizontal direction in laterally loaded masonry will be small, and if compatibility occurs between the reinforcement and the masonry, the strain in the steel will also be small. Thus one can query whether the bed joint reinforcement can contribute to the shear strength of the masonry, as it will not be subject to tensile stress until after the masonry has cracked. We decided to investigate this issue.

A parameter that is well known to affect the shear strength of masonry walls is the axial stress. For example, during their experiments, Voon and Ingham [4] observed that increasing the axial load delays the initiation of cracks and increases the shear resistance of the wall. The effect of this parameter on the contribution to the overall shear strength by the bed joint reinforcement was therefore also investigated.

Here, we describe the testing of 18 plain or bed joint reinforced concrete walls. The main variables in the experimental program were the level of axial compressive stress, and the amount of bed joint shear reinforcement. Bed joint reinforcement was used alone to isolate the effect of this variable. As far as we are aware, this is the first time that the effect of bed joint reinforcement on lateral load resistance has been examined as an independent, isolated variable. In other tests, bed joint reinforcement has always been used in conjunction with vertical reinforcement [eg: 3, 5].

EXPERIMENTAL PROGRAM

Eighteen partially grouted concrete masonry walls were tested under monotonic in-plane loading. The walls were 1.6 m long and 1.4 m high. The masonry shear wall specimens were either plain or contained various amounts of bed joint reinforcement as shown in Table 1. The walls were tested under 3 levels of axial compressive stress to assess the influence of this factor.

Table 1: Test Matrix for Masonry Shear wall Specimens.

Specimen number	Horizontal steel	Axial Compressive Stress (MPa)	Compressive Strength of Grout (MPa)	Compressive Strength of Mortar (MPa)
W1	-	2	21.6	6.7
W2	-	2	21.6	6.7
W3	-	3	21	4.8
W4	-	3	20	4.3
W5	-	4	21	4.8
W6	-	4	20	4.3
W7	4 #4.9	2	25	4.6
W8	4 #4.9	2	25	4.6
W9	5 # 4.9	3	23.2	7.7
W10	5 # 4.9	3	23.2	7.7
W11	5 # 4.9	4	23.2	7.7
W12	4 #4.9	4	25	4.6
W13	4 #3.7	2	23.7	6.5
W14	4 #3.7	2	25.1	7.3
W15	4 #3.7	3	23.7	6.5
W16	4 #3.7	3	25.1	7.3
W17	4 #3.7	4	23.7	6.5
W18	4 #3.7	4	25.1	7.3

MATERIAL PROPERTIES

Hollow concrete masonry units of nominal dimensions 400*200*200 mm and average compressive strength of 23.5 MPa were used in the construction of the walls. All the walls were constructed in face-shell bedding by the same experienced mason with type S mortar [1]. Six 50 mm mortar cubes were taken from each batch of mortar and tested for compressive strength. Six 100*200 mm cylinders were taken from each grout mix, with three being tested at an age of 7 days and the other three being tested at 28 days to obtain the compressive strength of the grout. Prisms built with the walls had an average compressive strength of 15 MPa based on the net areas of the block and grout.

The mortar joints were tooled to obtain concave mortar joints - this tooling increased the density of the mortar at the edge of the joints. Ladder type bed joint reinforcement wires of one of two different diameters (3.7 mm and 4.9 mm) were used in twelve walls. The average yield stress for five specimens of the smaller diameter wire was 530 MPa. For the bigger diameter reinforcement, three specimens demonstrated the expected load displacement curve with an average yield stress of 560 MPa, while the other two specimens broke suddenly without yielding at the welding joints, giving ultimate stresses of 470 MPa and 490 MPa. The sudden failure could be due to the effect of welding which can result in stress concentration at weld points. The load displacement curves for the two different diameter wires used are shown in Figure 1.

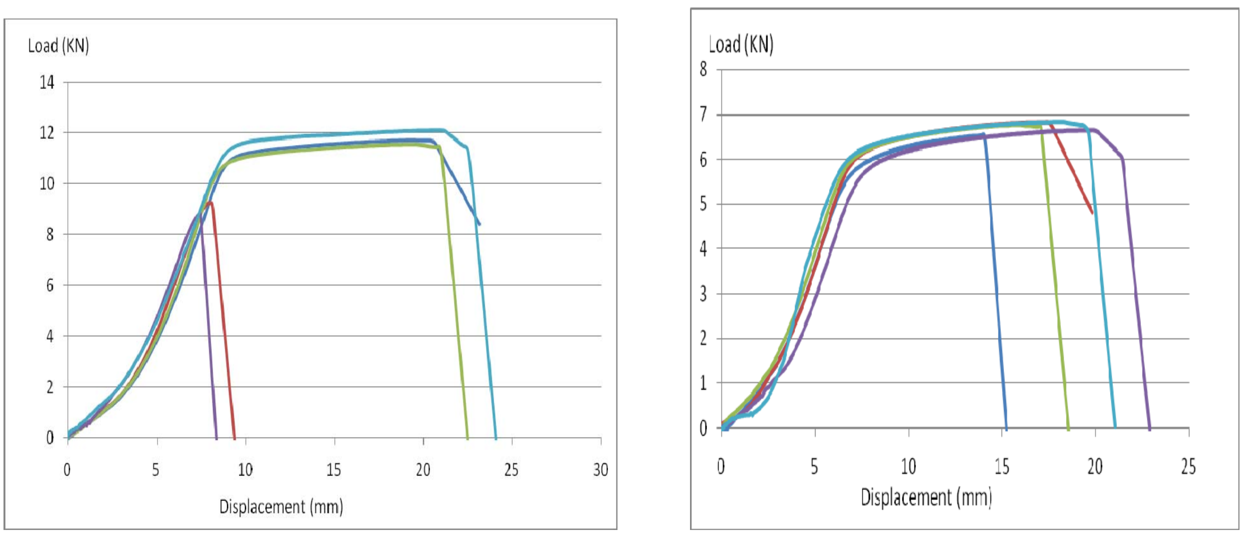
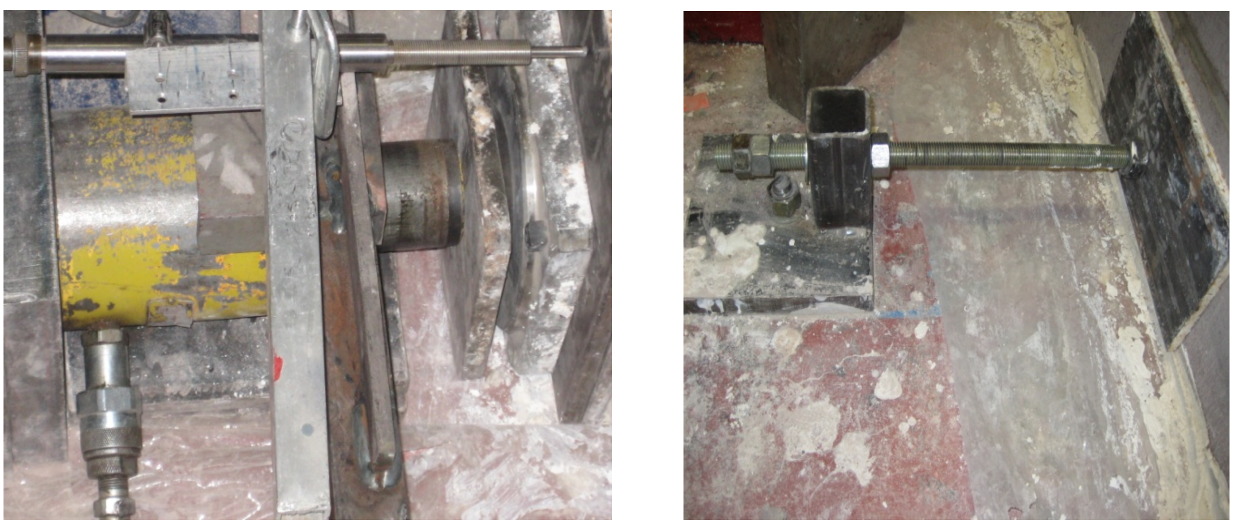


Figure 1: Load-Displacement curves for the ladder reinforcement used: a) D=4.9 mm and b) D=3.7 mm.

TEST ARRANGEMENT AND INSTRUMENTATION

All the specimens were tested in the rig shown in Figure 2. Fibreboard (Tentest) was placed on top of the wall, followed by a double I-Beam to spread the load from the centrally placed actuator over the whole length of the wall. The double I-beam was supported laterally by two rods bolted to the frame columns to prevent the beam from moving laterally under high loads. In order to hold the wall at the bottom, a 25 kN load was applied (in-plane) to the wall by means of a hydraulic jack (Figure 3a), where the load passes from the jack through a spherical seat to the wall. This load was applied to hold the wall in place on the load floor, and prevent it slipping. This was needed as the walls were not built on concrete bases with starter bars for vertical reinforcement.

Figure 2: Test Setup.



(a) (b)

Figure 3: Mechanical Fixation at the bottom of the wall.

Vertical reinforcement was not considered in these tests. Flexural failure by yielding of such bars through lifting of the heel of the wall was thus avoided. The intent was to find the diagonal shear strength of the masonry. Four small rods and four plates were installed on the sides of the walls near the ends at the bottom of the walls (two plates and two struts to each side) to hold the bottom of each wall from displacing laterally under high compressive load (also shown in Figure 3b).

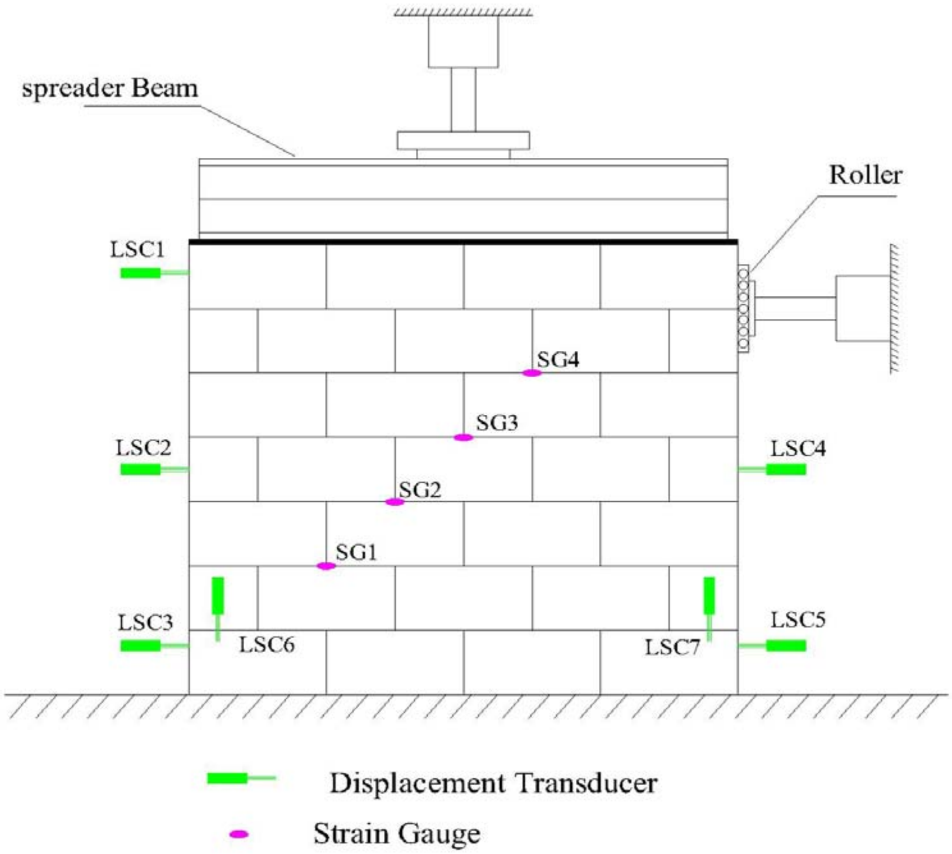


Figure 4: Distribution of Strain Gauges and Displacement Transducers.

Displacement transducers were installed to monitor the lateral displacement up the height of the wall and the base uplift. Strain gauges were attached to the bed joint reinforcement at different locations along the length of the reinforcement to provide readings roughly along the wall diagonal, as shown in Figure 4. The objective was to measure the tensile strain in the bars, with readings expected to increase rapidly after diagonal cracking.

Axial (vertical) load was applied by means of a MTS- servo-controlled hydraulic actuator of one Mega Newton maximum capacity and 250 mm maximum stroke. The horizontal load was applied by means of a second actuator with 500 kN maximum capacity and 150 mm maximum stroke. The horizontal load was applied to the upper two courses in the wall. In this arrangement (with the lower course being fixed by the hydraulic jack) the aspect ratio of the wall tends to be 0.5 (0.8/1.6).

Vertical load was first applied at a rate of 1 kN/s until the load for the required level of axial stress was reached. The actuator was then placed in force control so that the level of required axial stress was maintained and the lateral load was applied in displacement control at a rate of 0.1 mm/s. The lateral displacement was increased until the wall cracked and the maximum lateral load had dropped by 10 % of the peak magnitude. The load, displacement and the strain in the bed joint reinforcement were collected on a PC using the LABTECH data acquisition program. The time obtained to drop from the peak load to 90 % of the peak load "Dropping Time" was used as a measure of ductility.

EXPERIMENTAL RESULTS AND DISCUSSION

The results were divided into three categories according to the level of axial stress - 2 MPa, 3 MPa and 4 MPa. All the walls behaved mainly in shear as intended and failed by the formation of diagonal cracks, basically parallel to the compression strut. Typical load versus lateral displacement curves for walls with and without bed joint reinforcement are provided in Figure 5. The failure loads were all similar and the results showed that the horizontal steel was activated after the walls had been cracked. A typical graph for the strain gauge readings during a test is shown in Figure 6. Note that small compressive strains can be expected in the bed joint reinforcement which is lying in the main compression strut in the specimens.

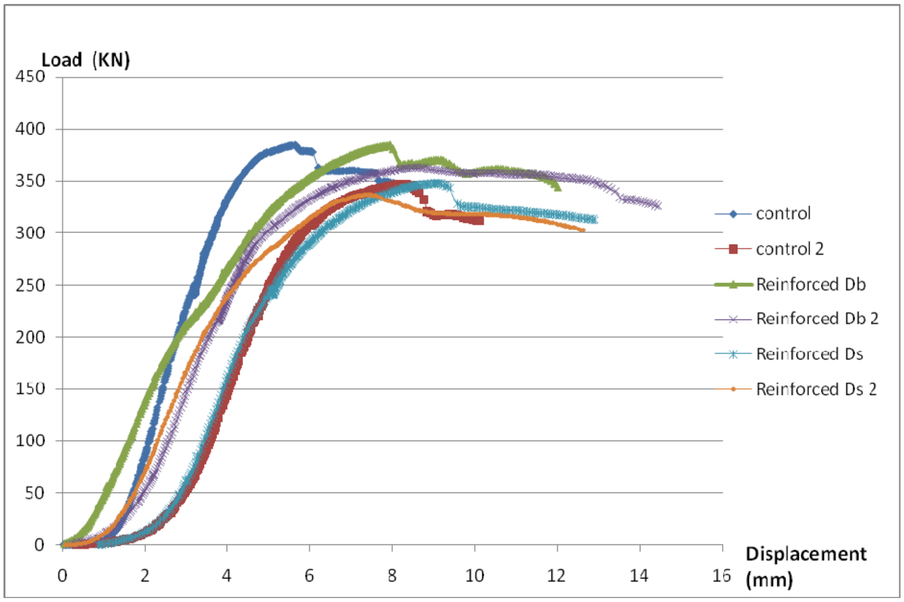


Figure 5: Typical Lateral Load –Displacement Curves for different types of walls. These are for an axial stress of 3 MPa.

EFFECT OF SHEAR REINFORCEMENT

The results obtained for walls subject to an axial stress of 2 MPa are given in Table 2. The results show that when using bed joint reinforcement the maximum load was 15% less than the loads obtained from plain walls.

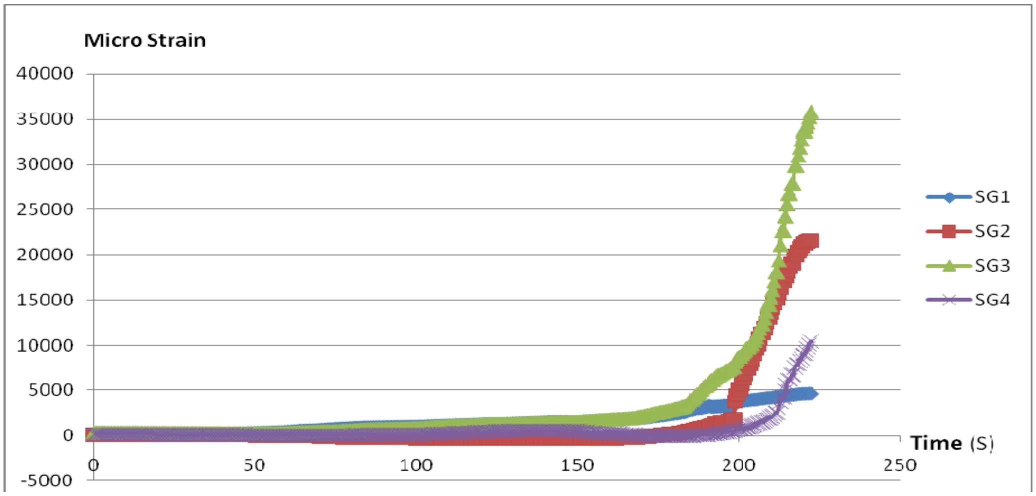


Figure 6: Typical graph for strain gauge readings in a masonry wall during a test

Table 2: Results from walls subjected to an axial stress of 2 MPa.

	Control		**Reinforced**			
			D=4.9 mm		**D=3.7 mm**	
Compressive strength of Grout (MPa)	21.6	21.6	25	25	23.7	25.1
Max Load (kN)	318.5	302.9	257.4	265.9	270.1	261.1
Displ at Max Load (mm)	22.8	12.7	8.3	9.8	8.1	8.11
Max Displacement (mm)	25.6	20.7	16.6	15	16.32	11.21
Vertical Displ. (mm)	19.6	6.5	3.1	3.67	1.4	0.79
Total Time (s)	76.5	64.5	262	242	249.5	201.5
Dropping Time (s)	2.5	20.5	90	57	103.5	35.5

For the walls subject to an axial stress of 3 MPa, there was an 11 % reduction in the maximum load when bed joint reinforcement was used compared to plain walls. The results also showed that the ductility of the walls was much higher when bed joint reinforcement was used compared to plain walls. The displacements to the peak load were similar, but the displacements to obtain the defined 10 % drop in load were substantially different - those of walls containing bed joint reinforcement being much larger than those for plain walls. Thus the ladder reinforcement appears not to increase strength, but to improve ductility. The results obtained from testing walls with an average axial stress of 3 MPa are presented in Table 3, with the displacements being related directly to dropping time.

For the walls subjected to an average axial stress of 4 MPa, the maximum loads when using bed joint reinforcement were only 8 % less than the maximum loads for the plain walls. Also, as in case of the 2 MPa and 3 MPa walls, the results showed that the ductility of the walls with bed joint reinforcement was much higher than the plain walls. The results for the 4 MPa walls are presented in Table 4.

Table 3: Results from walls subjected to an axial stress of 3 MPa.

	Control		Reinforced			
			D=4.9 mm		D=3.7 mm	
Compressive strength of Grout (MPa)	21	20	23.2	23.2	23.7	25.1
Max Load (kN)	384.4	419.6	384.2	362.3	347.9	337.1
Displ at Max Load (mm)	5.6	8.8	8	8.6	9.8	7.4
Max Displacement (mm)	8.1	9.6	12	14.4	12.9	12.6
Vertical Displ (mm)	1.9	6	4	2.4	2	1.6
Total Time (s)	197	205.5	239	253	232.5	219
Dropping Time (s)	28.5	2.5	42	60.5	39.5	57.5

Table 4: Results from walls subjected to an axial stress of 4 MPa.

	Control		Reinforced			
			D=4.9 mm		D=3.7 mm	
Compressive strength of Grout (MPa)	21	20	23.2	25	23.7	25.1
Max Load (kN)	459.5	433.6	437	393	414.6	393.8
Displ at Max Load (mm)	12	8.8	8.1	10.5	7.6	12.1
Max Displacement (mm)	13.8	10.8	12.4	12.4	11.4	15
Vertical Displ. (mm)	3.8	3.1	5	0.7	0.8	1.5
Total Time(s)	387	237.5	252.5	244.5	222.5	258
Dropping Time (s)	16	20	44	18	40.5	32.5

The results indicate that bed joint reinforcement does not increase the shear strength of the masonry walls but possibly decreases that strength, more so with low axial stresses than higher ones. The reductions in maximum load were 15%, 11% and 8% corresponding to axial stress levels of 2 MPa, 3 MPa and 4 MPa respectively. However, we recognize that the results are limited and lie within the range of variability that often occurs with masonry: more tests are needed to determine whether or not the result is statistically significant. The important feature is that the bed joint reinforcement did not increase the strength of the masonry. These results are in accord with those of Hatzinikolas et al. [6] who observed a similar, significant decrease in the ultimate compressive strength of masonry walls when bed joint reinforcement was included in the construction. Thus, these results support the notion that bed joint reinforcement does not have a positive effect with regard to the strength of masonry.

The results therefore call code equations which consider the shear resistance of masonry walls as the sum of two components into question. In many codes, the shear resistance of masonry is determined from $V_r = V_m + V_s$. Where V_m and V_s are the masonry shear resistance and steel shear resistance respectively. The experimental results here show clearly that the horizontal steel is substantially not stretched, and is therefore not activated in terms of providing resistance to the load, until the wall had been cracked. Thus the shear strength of a wall with only bed joint reinforcement is defined by the shear strength of the masonry under the axial load applied.

Normally, a shear wall will be designed with both vertical and bed joint reinforcement, so it would appear from these results to have become pertinent to examine the contribution of vertical reinforcement to shear strength separately from bed joint reinforcement, and to reconsider the code equations and what contributes to strength.

The major effect of bed joint reinforcement is to increase the ductility of the walls after failure. This is reflected in the time required for the load to drop to 90% of the peak load. When bed joint reinforcement was used, this time was considerably longer than for plain walls. The ductility provided would be useful under seismic loading to absorb energy and prevent catastrophic failure of the masonry.

EFFECT OF AXIAL STRESS

The increase in the axial stresses resulted in a significant increase in the shear resistance of the masonry walls due to the change in angle for likely crack formation and the increase of friction forces on the sliding bed joints with increasing the vertical load. With small vertical loads the wall tends to slide along the bed joints as the horizontal steel creates sliding planes along the bed joints, whereas with the higher axial stress, cracking tended to be more diagonal and lie within the units. For the plain walls, the increase in axial stress from 2 MPa to 3 MPa resulted in a 29% increase in the shear strength of the wall, with a further increase to 44% when the axial stress applied was 4 MPa.

For the walls with the small diameter, ladder-type, joint reinforcement, the increases in shear strength were 28% and 52%, corresponding to the increases in axial stress from 2 MPa to 3 MPa and from 2 MPa to 4 MPa respectively. Similarly, for the walls with the larger diameter reinforcement, the increases in shear strength were 43% and 59%. The increases in shear strength are due to the increase in aggregate interlocking forces that increase with the axial load applied to the wall. This effect was clearly noticed when the vertical (axial) load was removed at the end of each test, in that the cracks became wider. This widening reflects the effect of the confinement caused by the vertical load. Typical load versus Time curves for walls with different levels of axial stress are provided in Figure 7.

CONCLUSIONS

From the experiments carried out on the 18 walls, the following conclusions can be drawn:

- Bed joint reinforcement does not increase the shear strength of concrete masonry walls, but may actually decrease it, especially at low axial stress. The effect decreases gradually with increasing axial stress. These results are in contrast with the method for estimating the shear strength of masonry found in many codes in that the shear resistance of bed joint reinforcement did not increase the overall shear resistance of these masonry walls.
- The load-carrying capacity of the steel used in bed joint reinforcement is activated only after the wall has cracked.
- A major beneficial effect of bed joint reinforcement is to increase the ductility of the wall after failure – in the post peak region of behaviour.
- Axial compressive load has a significant influence on the in-plane shear resistance of masonry walls as it increases the friction forces on the sliding planes.

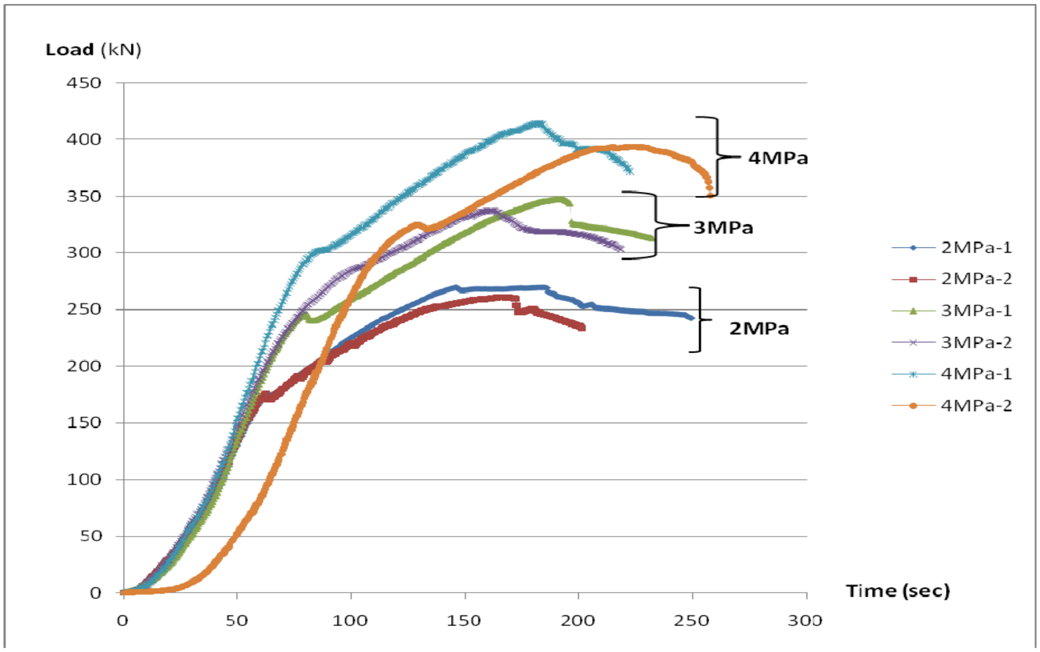


Figure 7: Typical Lateral Load –Time Curves for different axial stress levels. These are for walls with bed joint reinforcement of diameter 3.7 mm.

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