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COMPRESSION BEHAVIOUR OF REINFORCED MASONRY WALLS: AN INVESTIGATION ON THE EFFECTS OF LATERAL RESTRAINING METHODS

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ABSTRACT

Compressive behaviour of reinforced masonry (RM) block walls is affected by the position of vertical bars inside the grouted cores and their lateral restraining methods. The current Australian Masonry Standard (AS3700-2018) specifies the contribution of vertical bars in the compressive strength of RM walls if the bars are surrounded by a grout annulus of a radius of at least two times the vertical bar diameter. However, without any lateral restrainers, it is difficult to position the vertical bars in the middle of the grouted cores to satisfy the grout annulus radius requirement, while the use of tie bars for restraining the vertical bars laterally is challenging and is not usually adopted on the construction sites. In this research, plastic restraining chairs have been employed in the construction of RM walls to restrain the vertical bars laterally in the middle of the grouted cores and their influence on the compressive behaviour have been evaluated. In total, eight RM walls were tested under concentric and eccentric compression loadings; of them, six walls were constructed with plastic restraining chairs, while two walls were constructed with lateral tie bars. Experimental results are presented in terms of the observed failure modes, compressive strengths, and the axial strain variations in the vertical bars. It was observed that the plastic chairs were able to restrain the vertical bars into position without compromising the compressive strengths in comparison to the RM walls where vertical bars were tied with the lateral bars.

KEYWORDS: *reinforced masonry, bar restraining chairs, concentric compression, eccentric compression, load-displacement*

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INTRODUCTION

Grouted hollow concrete block masonry with reinforcement is commonly used in the Australian and North American regions due to its better performance against seismic and wind actions. Since the walls are grouted with moderately high strength grout mix (normally higher than the block strength), reinforced masonry (RM) walls can resist high axial loads, which would facilitate the construction of taller masonry buildings [1-2]. The axial compression behaviour of RM walls is complex, as it involves the interaction mechanism of masonry (blockwork), grout annulus and vertical steel bars. Several studies in the past have investigated the in-plane shear behaviour of RM walls [3-5], while limited research studies have been focused on the axial compression behaviour.

To provide buckling restraint to the vertical reinforcements, lateral restrainers (tie bars) are recommended by the design standards [6-7], including the previous version of the Australian Masonry Standards (AS3700) [8]. However, due to the misconceptions about the adverse effects of lateral restrainers on the masonry bond strength and the difficulty of positioning them close to the vertical bars, the lateral restrainers are not well received by the practitioners. The available studies on the compression characteristics of RM walls or columns have not explicitly investigated the influence of lateral restrainers and their required spacing on the overall axial behaviour of RM walls [9-11]. The failure modes of the RM walls or columns under axial compression and the strain levels of the vertical steel bars at failure in most of the previous studies have indicated that no significant buckling of vertical bars have occurred in the absence of lateral restrainers, which implies that the stringent requirement of lateral restrainers is not entirely necessary [9-10]. This idea has been verified by the recent comprehensive experimental programme conducted at Queensland University of Technology (QUT), Australia, where the influence of slenderness and lateral restrainers were investigated by testing a total of 50 RM walls under axial compression. The results revealed that the failure modes, axial and lateral deformation characteristics of RM walls are not greatly influenced by the lateral restrainers and their spacing [12].

Subsequently, using the experimental findings of Song [12] and Zahra et al. [13], the design provisions of RM walls under axial compression have been revised in the current version of AS3700 [14], which emphasised the contribution of the vertical steel bars to the axial load capacity and the relaxation on the requirement of the lateral restrainers. One of the revised provisions requires the vertical steel bars must be surrounded by grout annulus of a radius of at least twice the diameter of the bar so that the vertical bar, with no lateral ties, can be designed to resist compression. Consequently, to facilitate the specific design requirement to ensure adequate grout annulus on-site, a product named ‘BlockAid’, as shown in Figure 1, has been introduced in the construction of RM walls. BlockAid is a bar locating seat or bar chair for blockwork, that facilitates precise placement of the horizontal and vertical steel bars in the hollow concrete block walls to achieve compliance with the design provisions. However, hitherto no systematic research studies have been dedicated to examining the implication of providing the BlockAid bar chairs in the grout annulus area to restrain the vertical bars on the compression resistance of RM walls.

Therefore, in this research, the effectiveness of the BlockAid bar chairs was investigated by testing eight RM walls under concentric and eccentric compression loading. The testing scheme, characterisation of constituent materials (block, mortar, grout and steel bar), construction of RM walls and testing protocols are explained under the experimental program section. The experimental findings are presented in the results and discussion section, which represents the observed failure modes, compressive strengths, and the axial strain variations in the vertical bars.

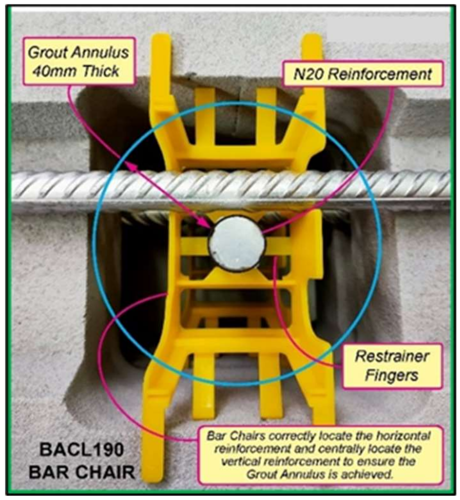


Figure 1: Schematic diagram of BlockAid bar chair

EXPERIMENTAL PROGRAM

The details of the experimental program are presented in this section.

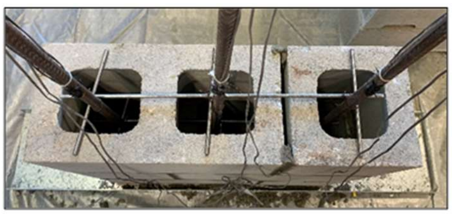
RM Wall Testing

Eight (8) RM walls were constructed in the laboratory and tested under compression loads without and with loading eccentricity. Out of the eight walls, six walls were constructed using BlockAid bar chairs in every alternative course. Three of these walls were subjected to concentric loading while the remaining three walls were subjected to eccentric compression loading. Two control specimens with 6 mm restrainer bars were also built for comparison. The testing scheme is presented in Table 1. Individual blocks, grout cylinders and prisms were also tested to determine their mechanical properties.

All the RM walls and prisms were constructed by a professional mason. The walls were constructed on a galvanised steel channel base, for the ease of moving the samples. A 6 mm plywood was placed on the steel channel; the location of vertical bars was marked on the plywood for accurate positioning. N16 steel vertical bars welded onto a steel chair were positioned at the marked locations. Wall ties were used according to the design specifications of AS3700 [8], with wall ties being applied on every block layer as shown in Figure 2(a) and the BlockAid bar chairs were placed on every second course, as presented in Figure 2(b). Before grouting, water was poured into the hollow cores of the wall specimen to ease the grouting process. The constructed samples are shown in Figure 2(c).

Table 1: Compression Testing Scheme

#	Specimen Type	Size	Number of samples
1	Hollow concrete blocks	390mm (Long) × 190mm (High) × 190mm (thick)	4
2	Grout cylinders	100mm (dia.) × 200mm (High)	5
3	Masonry prisms	390mm (Long) × 790mm (High) × 190mm (thick)	5
4	RM walls with 6mm restrainers (control)	590mm (Long) × 1390mm (High) × 190mm (thick)	2
5	RM walls with BlockAid bar chairs	590mm (Long) × 1390mm (High) × 190mm (thick)	6



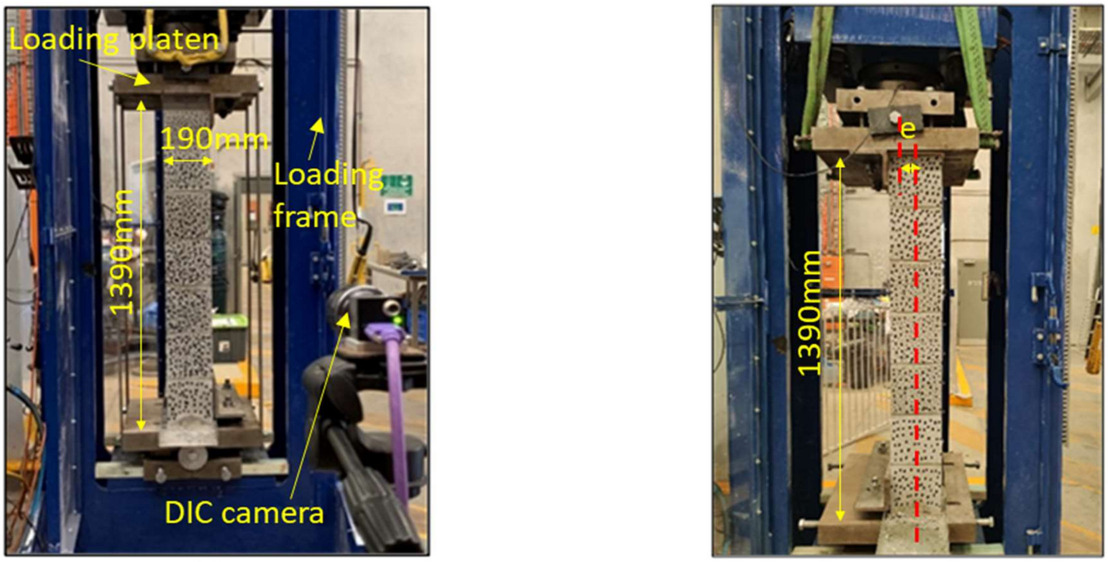
(a)

(b)

(c)

Figure 2: RM walls (a) sample with 6mm tie bars (b) sample with BlockAid bar chairs (c) constructed specimens

All the RM walls were cured for 28 days after grouting. An actuator with a 4000 kN capacity was used to apply the axial load to the walls. All the RM walls were tested under a uniform displacement controlled compression loading rate of 1 mm/min. The test setup for concentric and eccentric compression are shown in Figure 3. The steel strains in the proximity of chairs were measured through the installed strain gauges. The axial deformation of the walls under increasing load and failure modes were measured using the digital image correlation (DIC) technique. To facilitate the DIC measurements the surface of test specimens were speckled with black dots. High-resolution monochrome images of the test specimens were captured at regular intervals of 5 frames per second during the compression testing. The images were then correlated using a DIC software and the strain and deflection of the specimens were derived. For the eccentric compression tests, two specimens were tested under a loading eccentricity of e = 63 mm, i.e. one-third of the wall thickness (t/3), while one specimen was tested under a loading eccentricity of e = t/6 = 32 mm.



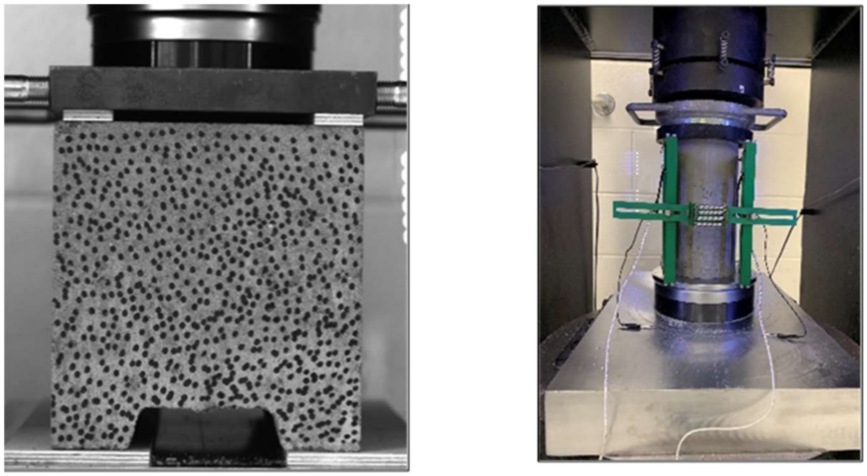
(a) (b)

Figure 3: Compression test details (a) concentric loading (b) eccentric loading

Mechanical Properties of Constituent Materials

Four hollow concrete blocks were randomly selected and tested as per AS/NZS 4456 [15] specifications to determine their compressive strengths. Two 40 mm wide × 6 mm thick plywoods were placed between the face shells of the block and the steel loading platen as shown in Figure 4(a) to ensure uniform compression loading on the face shells. A 2000 kN INSTRON machine was used to apply the uniform displacement controlled compression loading, with a loading rate of 1 mm/min. The average strength of blocks was 15.4 MPa with a coefficient of variation (COV) of 4%.

A premixed grout having 220 mm slump and 7 mm maximum aggregate size was prescribed for the grouting. A slump test was performed before grouting the specimens – the slump tested on the site was 230 mm. Five grout cylinders of dimensions 100 mm diameter × 200 mm high were also prepared and cured for 28 days to measure its compressive strength. Each grout specimens were filled in three layers, where each layer was tamped 25 times as per the AS1012.9 [16] specifications. These cylinders were then tested after 28 days of curing as shown in Figure 4(b). The average grout compressive strength of 36 MPa with a COV of 9% was recorded from the tests.



(a) (b)

Figure 4: Testing of (a) blocks and (b) grout cylinders

M3 type masonry mortar was used in the construction as specified in AS3700 [14]. 16 mm diameter N16 normal ductility deformed bars, as shown in Figure 5(a) was used as the vertical reinforcement. To avoid direct contact between the steel loading platen and the reinforcing bars, which can cause bowing of the bars, each vertical reinforcing bar was welded to a four-legged 25mm high steel chair, as shown in Figure 5(b). A 25 mm cover was maintained between the top of the steel bar and the top surface of the masonry wall specimen. Each RM wall specimen comprised of 3×1340 mm long vertical reinforcement bars, which were positioned in the grouted cores at a spacing of 190 mm centre to centre. Strain gauges were attached to the vertical bars to capture their performance during testing. Four walls were constructed with two strain gauges on the middle vertical reinforcement only, whilst the other walls had two strain gauges on all three vertical reinforcement bars. The strain gauges were installed at around mid-height (670 mm) at both the front and far face of the bars, as shown in Figure 5(c). The strain gauges were sealed using black silicone for waterproofing, mechanical protection and insulation. The average yield stress of bars was specified as 550 MPa by the supplier.

(a) (b) (c)

Figure 5: Reinforcing bars (a) prepared bars (b) bar welding (c) strain gauging

Masonry Prism Testing

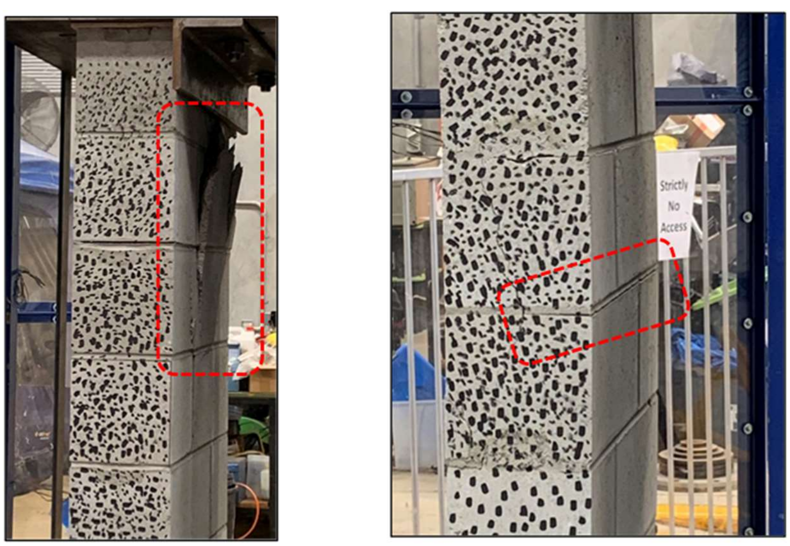
For measuring the compressive strength of masonry prisms, a total of two ungrouted and four grouted, four courses high stack bonded masonry prisms of dimensions 390 mm long × 790 mm high × 190 mm thick were constructed using the chosen blocks and mortar. All the masonry prisms were tested by strict adhering to test guidelines specified in Appendix C of AS3700 [14]. The compressive strengths of the masonry prisms are presented in Table 2.

Table 2: Masonry prisms test results

Sample #	Ungrouted prism strength (MPa)	Grouted prism strength (MPa)
1	8.65	26.99
2	9.40	23.35
3	-	25.64
Mean	9.02	25.33
COV	6%	7%

RESULTS AND DISCUSSION

The general failure mode observed in the concentrically loaded walls was the vertical splitting of the face and web shells. These cracks became evident once the loading reached close to 80% of the peak load. As the load reached ultimate capacity, these cracks became larger until the walls failed by crushing of concrete near mortar joints and web splitting, as shown in Figure 6(a). Under eccentric loads, the failure of walls occurred due to the opening of mortar joints at the tension side and crushing of concrete on the compression face, as shown in Figure 6(b).



(a) (b)

Figure 6: Failure modes under compression (a) concentric loading (b) eccentric loading

The maximum (peak) loads for the tested walls under concentric and eccentric compression tests are summarised in Table 3.

Table 3: Peak load capacity for compression tests

Sample #	Concentric compression capacity (kN)	Eccentric compression capacity (kN)
Control	3100	920 (e = 63mm)
BlockAid 1	2814	926 (e = 63mm)
BlockAid 2	2504	866 (e = 63mm)
BlockAid 3	3031	2041 (e = 32mm)

The mean strength of BlockAid wall samples under concentric compression was determined as 2785 kN with a COV of 10%. Under an eccentricity of e = 63 mm, the compression capacity was recorded as 896 kN with a COV of 5%. For e = 32 mm, the peak capacity was 2041 kN (3.3 times larger than for e = 63 mm). It can be observed that the difference of maximum concentric compression strength between the control wall with standard 6 mm restrainer bars (3100kN) and BlockAid wall (3031kN) is only 2.2%, which is negligible. Under eccentric compression loading, the maximum capacities are almost the same for the control and the BlockAid specimens.

Axial load-displacement relations of the RM walls and the steel strain variation of the reinforcing bars with the axial displacement of the walls were also measured to identify any buckling or dislodgement of the bars. Typical load-displacement curves of the control specimens and BlockAid specimens under concentric compression loading are presented in Figure 7(a) and 7(b), respectively. It can be observed from the load-displacement curves that the behaviour of control walls and BlockAid walls is quite similar with similar peak and post-peak softening trends. The steel strain variations with increasing displacement were also similar for both type of samples (see Figure 7(c) and 7(d)); the failure of both types of walls was recorded at a corresponding strain of around 1200 microstrain, which was less than the yield strain of the vertical bars of the 2500 microstrain. It is important to mention here that the Australian standards AS3700 [14] consider yield strength of 500 MPa for the vertical steel bars corresponding to yield strain of 2500 microstrain in the compression capacity equation of RM walls. However, a reduction factor of 0.4 is applied with the steel bars contribution to account for non-yielding bars. The behaviour of the vertical reinforcement is in agreement with the experimental findings of Song [12].

Figure 8 shows the axial load-displacement and the steel strain variation with the axial displacement obtained from the specimens tested under eccentric compression loading. Again, similarities in the load-displacement trends can be observed. The steel strains under eccentric compression loading in the BlockAid walls were found to be much lower than the control walls, which is perhaps due to the restraint provided by the chairs against tension in bars under eccentricity.

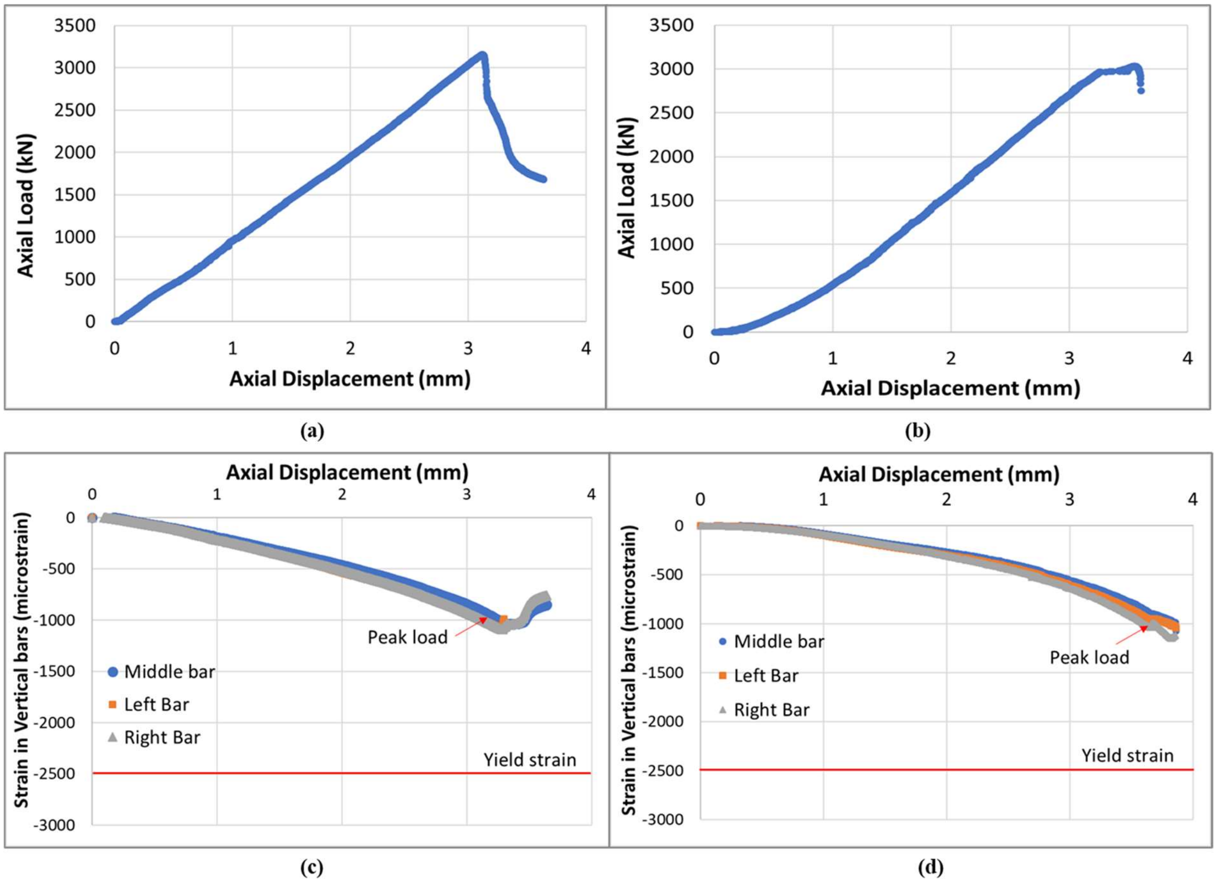


Figure 7: Concentric compression results (a) load-displacement of control wall (b) load-displacement of BlockAid wall (c) steel strain in control wall (d) steel strain in BlockAid wall

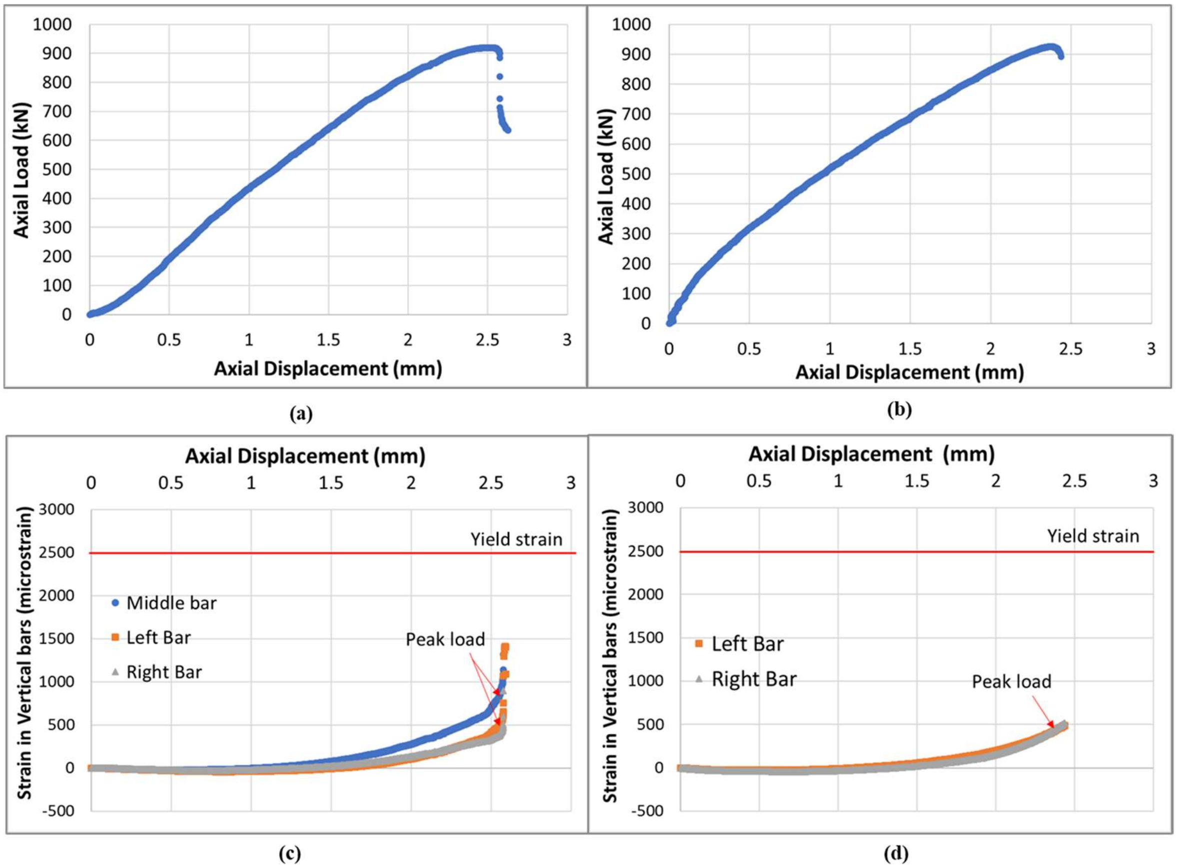


Figure 8: Eccentric compression results (a) load-displacement of control wall (b) load-displacement of BlockAid wall (c) steel-strain in control wall (d) steel strain in BlockAid wall

CONCLUSIONS

The influence of BlockAid bar chair lateral restrainers on the compressive behaviour of reinforced masonry (RM) walls has been investigated in this paper. A total of eight RM walls were constructed and tested under vertical compression loading, of them, six walls were constructed using BlockAid bar chairs, while two control walls were constructed using 6mm restrainer bars. A control wall and three walls with BlockAid bar chairs were tested under concentric compression loading, whilst the remaining three walls with BlockAid bar chairs and second control wall were tested under varying degree of eccentric compression loading.

The mechanical properties of the constituents, i.e., block, mortar, masonry prism and steel were also evaluated. The results indicate that the BlockAid bar chairs had no detrimental effect on the structural performance of RM walls under compression loading. Under concentric loading, the average compression capacity of the RM wall with BlockAid bar chair was only 2.2% lower than the control walls. The presence of the BlockAid bar chair did not influence the steel vertical strain corresponding to the maximum compression load of the concentrically loaded walls and the compression capacity of the eccentrically loaded walls.

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