Influence of blockaid chairs on compression and out-of-plane behaviour of reinforced masonry walls

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ABSTRACT

Changes in Australian Masonry Standards and National Code of Construction for reinforced masonry (RM) under compression impress the need of a grout annulus and vertical bar confinement using 6 mm tie bars. Maintaining the verticality and centricity of reinforcement and restraining them with the tie bars is challenging and time consuming. BlockAid have designed masonry bar chairs to align and restrain the reinforcing bars central in the block cores. This paper presents an investigation to ascertain the performance of BlockAid bar chairs in supporting the reinforcing bars in the RM walls subject to vertical compression and out-of-plane loads. The mean compressive strength in the fully grouted RM walls with BlockAid bar chairs was determined equivalent to the control specimen which sustained maximum load of 3100kN, compared to 3030kN for the BlockAid sample. Strain in the vertical steel bars, with BlockAid bar chairs, remained compressive throughout the loading with no evidence of buckling. The out-of-plane test results of BlockAid walls were similar in terms of failure modes, load-displacement behaviour and steel strain variations. These observations conclude that BlockAid bar chairs are effective in restraining the vertical bars against buckling and do not compromise the compression and bending capacity of RM walls.

1. Introduction

Reinforced masonry (RM) walls are employed in masonry buildings for resisting earthquakes and cyclonic wind actions effectively. For this reason, these have been widely researched in the past for their lateral shear and bending resistance against lateral dynamic actions (Mojiri, Tait, and El-Dakhakhni 2014; Bolhassani, Hamid, and Moon 2016; Shrive et al. 2018; Calderon, Arnau, and Sandoval 2019; Noor-E-Khuda and Dhanasekar 2020). However, their response under axial compression behaviour, which is a primary force on these elements, was explored by limited researchers (Khalaf, Hendry, and Fairbairn 1993; Isfeld et al. 2019; Song 2020; Zahra et al. 2021a). In the masonry design standards, the RM walls are designed with lateral restrainers to prevent the buckling of vertical reinforcement under compression loads. According to recent revisions in Australian Masonry Standards (AS3700-2018), the vertical bars should be placed in the centre of grouted cores as such an annulus grout thickness not less than twice the diameter of vertical reinforcing bars should be maintained for considering the contribution of vertical bars in the compression capacity. To achieve this compliance, it is necessary that the vertical bars remain straight and central in the block cores when the grout is poured (Zahra et al. 2021b).

BlockAid bar chairs (BlockAid 2020) are designed to accurately position the horizontal and vertical reinforcement in reinforced masonry block walls. These bar chairs can provide an effective solution to keep the bars straight in the required position under compression loads as shown in Figure 1. An experimental study was conducted at QUT previously (Dhanasekar 2018), in which RM walls were constructed using BlockAid bar chairs for maintaining the annulus grout requirements around the bars and were tested under concentric and eccentric compression. It was concluded that the bar chairs maintained the grout annulus requirements without any adverse effect on the compression capacity of the walls. However, Australian National Code of Construction (NCC-2019) requires RM members in compression to be restrained by 6 mm diameter bars to laterally restrain the vertical reinforcement in addition to the annulus grout diameter requirements. Practically, this kind of lateral arrangement is not very efficient and is generally not followed on construction sites due to the large amount of time required to restrain the vertical bars laterally using 6 mm tie bars. Consequently, BlockAid have revised their chair design with two restrainer fingers to snug fit the vertical bars and restrain them laterally as shown in Figure 1.
BlockAid bar chairs are designed for both ‘Non-Centrally Located (BANCL)’ and ‘Centrally Located (BACL)’ reinforcements, with the vertical steel location determining the correct product for the application as shown in Figure 2. Non-centrally located bar chairs are designed to support the vertical and horizontal bars to resist out-of-plane bending especially in the retaining masonry wall structures. The BlockAid bar chairs are made of plastic and come in sizes suitable to either 190 mm or 290 mm thick walls; this research has used 190 mm thick blocks commonly available in Queensland. The aims of this research are:

1. To examine experimentally whether the improved version of BlockAid bar chairs for centrally located bars through the grout annulus around the vertical compression steel can restrain the bars laterally without compromising the compression capacity of the walls in concentric and eccentric compression loads.
2. To ascertain the out-of-plane capacity of RM walls with BlockAid bar chairs for the non-centrally located vertical and horizontal bars.

To achieve these aims, a test scheme was designed to test the RM walls under compression and out-of-plane loads to ascertain the benefits of the novel BlockAid bar chairs. Twelve medium high walls with a limited effect of slenderness were constructed – of which four each were tested under concentric compression, eccentric compression and out-of-plane bending. To prove the hypothesis that the intrusion of the BlockAid bar chairs would produce a beneficial effect on the response of masonry walls to axial compression (concentric and eccentric) and out-of-plane bending behaviours, wall samples without bar chairs having 6 mm diameter restrainer bars under compression while tie wires were used to tie the horizontal and vertical bars to test under bending for comparison. In addition, the strains in the reinforcing bars were also measured to examine any premature buckling and effect of restraining provided by the BlockAid bar chairs. The results of these tests are presented in this paper.

2. Experimental programme

In total, twelve block walls were constructed by a professional mason, of which nine (9) walls were built with BlockAid bar chairs in every alternative bed joint. The remaining specimens were built without bars chairs as control specimens with standard 6 mm diameter restraining bars in compression, while tie wires were used to tie the horizontal and vertical bars to test under out-of-plane bending. More details are presented in the following sub-sections.

2.1. Construction materials and properties

For the construction of the walls, grout, blocks, mortar, reinforcement bars were required. All individual materials were tested for their properties.

2.1.1. Grout

Premix grout of compressive strength of 25MPa, 220 mm slump and 7 mm aggregates was employed...
in this testing scheme. Slump test was conducted to ensure the slump was as prescribed – the slump tested on site was 230 mm. Five grout cylinders (100 mm diameter × 200 mm high) were also filled in three layers, with 25 tamps at each layer. These cylinders were then tested after 28 days of curing as shown in Figure 3(a). A 2000kN INSTRON machine was used to apply a uniform compression displacement at the rate of 1 mm/min. Grout strength is presented in Table 1.

2.1.2. Blocks

Full concrete blocks of size 390 mm (length) × 190 mm (thickness) × 190 mm (height) and half concrete blocks of size 190 mm (length) × 190 mm (thickness) × 190 mm (height) were sourced. Four full blocks were randomly selected and tested to determine the compressive strength in consistent with AS/NZS 4456 (2003). These blocks were tested under face-shell loading by placing 40 mm wide × 6 mm thick plywood along the full length of the block (390 mm) as shown in Figure 3(b). The test results are listed in Table 2.

2.1.3. Mortar

M3 Mortar in the mix ratio by volume of cement (1): lime (1): sand (6) was used for the construction of the stack bonded prisms and the RM walls. The mortar was mixed and applied by a professional mason.

2.1.4. Reinforcing bars

Reinforcing bars (16 mm diameter – N16 and 12 mm diameter – N12 normal ductility deformed bars) were sourced. The reinforcement bars were visually inspected upon delivery to ensure the straightness and quality of these bars. The bars are shown in Figure 4(a). To avoid direct contact between the steel loading platen and the reinforcement bars, the vertical reinforcement bars were welded to a four-legged steel chair which was 25 mm high. At the top, the steel bar finished 25 mm lower than the top surface of the masonry wall specimen. This was to ensure direct contact between the loading platens and the bars were avoided to prevent bowing as shown in Figure 4(b).

The preparation of the reinforcement is vital for successful testing and data recording. Each wall had three 1340 mm long vertical reinforcement bars at 190 mm c/c spacing. Bars in all loaded walls were strain gauged. Four walls had two strain gauges on only the middle vertical reinforcement, 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 front and far face of the bars as shown in Figure 4(c).

Prior to installing the strain gauges, the steel bar was milled to an adequate depth to achieve a flat surface. Cyanacrylate was applied onto the sticky tape with the strain gauge and pressure was applied for 60 s to keep the gauge attached onto the bar. Polymer resin coating was then applied on top of the gauges as a protective layer. Additionally, a hot glue gun was used to seal the strain gauges at a cool temperature. Finally, the strain gauges were sealed by black silicone for waterproofing, mechanical protection and insulation. The tensile testing of bar samples is shown in Figure 4(d) and the stress–strain curves of three tested

| Sample # | Compressive strength (MPa) |
|----------|----------------------------|
| 1        | 15.79                      |
| 2        | 15.34                      |
| 3        | 14.46                      |
| 4        | 15.99                      |
| Mean     | 15.39                      |
| COV      | 4%                         |

| Sample # | Compressive strength (MPa) |
|----------|----------------------------|
| 1        | 36.53                      |
| 2        | 41.11                      |
| 3        | 36.15                      |
| 4        | 33.73                      |
| 5        | 33.09                      |
| Mean     | 36.12                      |
| COV      | 9%                         |

Figure 3. Testing of grout and blocks.
N16 bars are shown in Figure 4(e). The yield stress of bars was determined as 550 MPa on an average.

2.1.5. Masonry prisms

Four course high stack bonded ungrouted and grouted masonry prisms of size 390 mm (length) × 790 mm (height) × 190 mm (thickness) were constructed using the chosen blocks and mortar; three of them were grouted. Testing of prisms was consistent with Appendix C of AS3700 (2018). Results are shown in Table 3.

2.2. Construction of walls

For compression tests, eight (8) RM walls were developed in the QUT lab for concentric and eccentric tests. Three (3) walls each for concentric and eccentric compression testing were built with BlockAid bar chairs while two control specimens with 6 mm restrainer bars were developed for comparison. For out-of-plane testing, four (4) RM walls were developed with one wall as ‘control’ without BlockAid bar chairs and 3 walls with BlockAid bar chairs in every alternative bed joint. Testing scheme for all the tests is presented in Table 4.

A professional mason was hired to construct all the walls. The construction of the walls began with a galvanised steel channel as the base. This channel simplifies the process of moving the walls from the fabrication mat to the loading frame. A 6 mm thick plywood was placed centrally onto the steel channel and the first layer of blocks were positioned on the plywood. The desired location of the steel bars was marked on the plywood with a marker aligning through the plastic bar chairs, then the N16 steel vertical bars welded onto a steel chair were positioned at the marked location. Wall ties and plastic bar chairs were used according to the wall specification, with wall ties being applied on every block layer as shown in Figure 5(a) and plastic bar chairs were placed on every second course as can be seen in Figure 5(b). For out-of-plane bending samples, the same procedure was adopted for construction, except the BANCL190 bar chairs were used with 3 N16 vertical bars and 3 N12 horizontal bars in the tension side as shown in Figure 5(c,d) for the control and BlockAid samples. Strain gauge wires were carefully extracted all towards one end of the wall and escorted through a hole before sealing the hole up with grouting. Prior to grouting, water was poured in the wall specimen to ensure the grout smoothly filled up the cores. The constructed samples are shown in Figure 5(e).
Table 4. Testing scheme of RM walls.

| #  | Specimen type                                      | Test description                                         | # of samples |
|----|---------------------------------------------------|----------------------------------------------------------|--------------|
| 1  | RM wall: 590 mm (long) × 1390 mm (high) × 190 mm (th.) [control sample with 6 mm tie bars] | Concentric compression test with strain gauges in all 3 N16 vertical bars | 1            |
| 2  | RM wall: 590 mm (long) × 1390 mm (high) × 190 mm (th.) [control sample with 6 mm tie bars] | Eccentric compression test with strain gauges in all 3 N16 vertical bars (e = t/3) | 1            |
| 3  | RM wall: 590 mm (long) × 1390 mm (high) × 190 mm (th.) [with bar chairs for centrally located bars] | Concentric compression test with strain gauges in all 3 N16 vertical bars | 3            |
| 4  | RM wall: 590 mm (long) × 1390 mm (high) × 190 mm (th.) [with bar chairs for centrally located bars] | Eccentric compression test with strain gauges in all 3 N16 vertical bars | 3            |
| 5  | RM wall: 590 mm (long) × 1390 mm (high) × 190 mm (th.) [with bar chairs for non-centrally located bars] | 4-point bending test with strain gauges in all 3 N16 vertical and 3 N12 horizontal bars | 3            |
| 6  | RM wall: 590 mm (long) × 1390 mm (high) × 190 mm (th.) [control with tying wires] | 4-point bending test with strain gauges in all 3 N16 vertical and 3 N12 horizontal bars | 1            |

2.3. Testing of walls

The samples were cured for 28 days after pouring of grout. The tests were carried out as per the scheme provided in Table 4. As previously described, reinforcing bars were instrumented to measure the deformations and strains when the specimens were subjected to loads to determine if unrestrained bars and/or restrained bars had any dislodgement or otherwise affecting the walls behaviour. Strain gauges were attached to the vertical and horizontal steel bars for measuring the steel strains. Individual test details for compression and out-of-plane bending are in the following sub-sections.

2.3.1. Compression tests

All RM wall samples were tested in a 4000kN capacity compression testing frame under uniform compression at the rate of 1 mm/min. The test set-up for concentric and eccentric compression are shown in Figure 6. The steel strains in the proximity of chairs were measured and the capacity of walls was compared with similar walls previously tested in Zahra et al. (2021b) with 6 mm diameter restraining bars in both lateral directions without any chairs. Deflection and failure mode were also measured through digital image correlation (DIC) technique (Zahra and Dhanasekar 2018; Asad et al. 2019). DIC is a unique technique in which the surface of samples is speckled with black dots and monochrome images of samples are captured at a regular interval (5 frames per second for this project) during the test. The images are then correlated using a DIC software to calculate the

![Figure 5. RM walls construction details.](image-url)
strain and deformation field with respect to the first image of sample without any load.

For eccentric compression tests, the eccentricity of one-third of thickness (t/3) which corresponds to 63 mm was adopted for two samples with BlockAid bar chairs, while one of the samples was tested for the eccentricity of t/6 = 32 mm.

2.3.2. Out-of-plane bending tests
Out-of-plane bending tests were also conducted in the same machine with a different loading set-up. Four-point loading assembly was developed as shown in Figure 7 to apply the out-of-plane bending loads on the RM wall specimens.

The deflections under out-of-plane bending tests were measured using three linear variable displacement transducers (LVDTs) as shown in Figure 7. Similar to compression tests, the steel strains were also measured through the installed strain gauges in the horizontal and vertical bars.

3. Results and discussion
The behaviour of tested walls was examined in terms of failure modes, failure strengths, load-displacement curves and steel strain variations. The results are discussed in detail in this section.

3.1. Compression test results
The general failure mode observed in the concentrically loaded walls was 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 8(a). Under eccentric loads, the failure of walls occurred due to opening of mortar joints on the tension side and crushing of concrete on the compression face (see Figure 8(b)). The failure mode is consistent with the previous tests conducted by Dhanasekar (2018) and in the test campaign which provided input into the 2018 edition of AS3700-2018 (Zahra et al. 2021b).

The maximum (peak) loads for the tested walls under concentric and eccentric compression tests are summarised in Table 5. The mean strength of BlockAid wall samples under concentric compression was determined as 2785kN while under eccentricity of e = 63 mm as 896kN. 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%. Whereas under eccentric compression the maximum capacities are almost same for the control and BlockAid samples.

It is important to mention that these results are much higher than the similar walls tested by Zahra et al. (2021b) where the average concentric compression capacity of 1237kN and eccentric compression capacity of 610kN was obtained. The reason for such a large difference (two-fold) can be attributed to the difference in materials strength including block strength (12% higher) and grout strength (44% higher) for the current tests.

Additionally, the experimental compression capacities were also compared with the predictions of AS3700 (2018) for compression strength using the design capacity Equation (1).
The mean strength of masonry \( f_m = 9 \text{ MPa} \), mean strength of grout \( f_{cg} = 36 \text{ MPa} \), yield stress of steel \( f_{sy} = 550 \text{ MPa} \), steel bar area \( A_s = 600 \text{ mm}^2 \), bedding area \( A_b = 600 \times 30 \times 2 = 36,000 \text{ mm}^2 \), grout area \( A_g = 58,500 \text{ mm}^2 \), grout strength factor \( k_c = 1.2 \) and \( \alpha_r = 0.4 \) for RM walls were input in Equation (1). The reduction coefficient \( k_{es} \) was calculated using Equation (2) separately for concentric and eccentric compression capacities.

\[
F_d \leq k_{es} \left[ f_m A_b + k_c \left( \frac{f_{cg}}{1.3} \right)^{0.55+0.005f_{sy}} A_g + \alpha f_{sy} A_s \right]
\]

(1)

The slenderness and eccentricity ratios in the above equation were set as \( S_{cr} = 190/1390 = 7.32 \) and \( \epsilon = 63 = 0.33 \).

The results are tabulated in Table 6.

The experimental results (control with 6 mm diameter restrainers and BlockAid bar chairs) have yielded a higher strength in comparison to the latest code predictions which shows that the BlockAid bar chairs can be used as an alternative to 6 mm diameter ties for restraining the vertical bars. These results confirm that with the use of BlockAid bar chairs, the walls can exhibit adequate margin for the safety factor to account for uncertainties in construction and materials quality. Load displacement curves and steel strain variations were also measured to verify any buckling or dislodgement of the bars. Typical results of the
control specimens and BlockAid specimens under concentric compression are presented in Figure 9. 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 trends. The steel strain variations with increasing displacement are also very similar for both kind of samples with maximum compressive strain of around 1200 microstrain (lesser than the yield strain of 2500 microstrain) in vertical bars which is in agreement to the previous test results for similar walls (Zahra et al. 2021b).

Figure 10 shows the load deflection and steel strain variations of the eccentric wall samples. Again, the similarities in the load-displacement trends can be observed. However, the steel strains under eccentric compression in the BlockAid walls were found much lower than the control walls, perhaps due to restraint provided by the chairs against tension in bars under eccentricity.

3.2. Out-of-plane bending test results

For all tested walls under out-of-plane bending, similar failure mode was observed with cracking at the points of load application as marked in Figure 11. The cracking was symmetric about the centreline of the wall specimen. The inclined cracking protruded from the point of load applications to the bottom side of the specimen. Vertical cracks in tension side of the tested walls were also observed.

The ultimate strength or load capacity of walls under bending is listed in Table 7. The ultimate load of the control specimen was measured only 2.5% higher than the mean strength of the BlockAid wall specimens which is consistently same as in compression tests. The ultimate deflections for both kind specimens were around 9 mm.

Figure 12 shows the load deflection and steel strain variations in the horizontal and vertical bars. The load-deflection behaviour of the control wall and BlockAid walls was found similar. The measured steel strains in the vertical bars under bending were observed closer to the yield strains for all bars in all tested walls, while strains in the horizontal bars were much lower at around 250 microstrain due to not directly bending under loads. The vertical steel bars, which were predominantly experiencing tension almost reached the yielding strain but did not undergo higher than yielding strains due to cracking progression in the masonry.
Figure 9. Load displacement and steel strains under concentric compression.

Figure 10. Load displacement and steel strains under eccentric compression.

Figure 11. Failure mode of walls under out-of-plane bending.
4. Conclusions

This research paper presents an investigation on the behaviour of RM walls with novel BlockAid bar chairs installed to support and restrain the reinforcing bars to achieve compliance with AS3700 (2018) and NCC (2019). In total, 12 samples were tested under concentric compression, eccentric compression and out-of-plane bending loads. Based on the construction and testing of these RM walls, the following conclusions have been made:

1. The use of BlockAid bar chairs ensures the straightness and correct positioning of the vertical reinforcement as desired in the compression design provisions of AS3700-2018.
2. Under the test regime, no adverse effect on the load carrying capacity of the RM walls under compression and out-of-plane loading was obvious.
3. The variation of steel strain under concentric compression loads show no difference between the control walls with 6 mm restrainer bars and the walls with BlockAid bar chairs. However, under eccentric compression, the tensile strains in bars with bar chairs were much lower than the control wall showing the effectiveness of bar chairs in restraining the vertical bars against excessive bending.
4. The compression capacity of the tested walls was 2.6 times higher than the AS3700-2018 predictions. This demonstrates that the BlockAid bar chairs can provide adequate safety against uncertainties in construction and material quality.
5. Out-of-plane bending behaviour of RM walls with and without bar chairs were similar in terms of steel strains and load displacement responses. This also proves that the BlockAid bar chairs can be effectively used to restrain/support the vertical and horizontal bars in the retaining structures without the need of wire tying the horizontal and vertical bars.

The results in this paper show that the use of BlockAid bar chairs can expedite the construction of RM walls with adequate restraint and correct positioning of reinforcing bars within the grouted cores to efficiently achieve compliance to AS3700 (2018) and NCC (2019).

Disclosure statement

No potential conflict of interest was reported by the author(s).

Table 7. Ultimate load capacity for bending tests.

| Sample # | Ultimate load (kN) | Failure deflection (mm) |
|----------|--------------------|-------------------------|
| Control  | 364                | 9.1                     |
| BlockAid 1 | 383              | 9.4                     |
| BlockAid 2 | 337              | 10.2                    |
| BlockAid 3 | 344              | 8.1                     |
| Mean     | 355                | 9.2                     |

Figure 12. Load displacement and steel strain variations for bending tests.
Notes on contributors

**Tatheer Zahra** is a focused, motivated and result oriented Lecturer in Civil Engineering with 10 years experience in undergraduate and postgraduate teaching, research, project supervision and industrial services. Tatheer has proudly represented the Queensland University of Technology in Australia and overseas as an outstanding Science, Technology, Engineering and Mathematics (STEM) female candidate, teaching and presenting papers. Tatheer continues to grow her teaching and research skills with excellence in concrete and masonry structures and new genre composite materials.

**Christopher Rafferty** is one of the founding directors of BlockAid Pty Ltd, a company that designed and developed bar chairs for reinforced masonry to ensure best practice construction in order to achieve compliance to building Standards and Codes and provide confidence in this versatile building material for all stakeholders.

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