RESPONSE OF REINFORCED CONCRETE MASONRY WALLS TO ECCENTRIC COMPRESSION

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ABSTRACT

Reinforced concrete masonry walls are used extensively in multi-level buildings of heights up to 15m and they are also employed in the basement of taller buildings. In such applications, eccentricity in vertical loads are unavoidable; this research has been carried out with a view to understanding the response of the concrete masonry walls under concentric and eccentric compression. Compression capacity of the reinforced masonry walls are normally determined with no regard to the area of the compression steel reinforcement although some limited experimental studies in the literature exhibit contribution of the steel reinforcement to the capacity of the reinforced masonry. With a view to examining the contribution of the vertical reinforcing bars with and without lateral restraining steel bars, thirty-six walls of 1400mm high × 600mm long × 190mm thick walls have been constructed and tested under concentric and eccentric compression. Several sensors were fitted to the wall surfaces and reinforcing bars to monitor the strain levels and potential instability of the wall due to slenderness and/or eccentricity in the loading. The data are presented in this paper and the performance of the reinforced masonry walls to concentric and eccentric compression observed from the experiments is described.

KEYWORDS: *reinforced concrete masonry, concentric compression, eccentric compression.*

INTRODUCTION

Compared to the number of available papers on structural columns and walls under axial compression, eccentric compression tests are rare; however, in the last five years the authors have found five experimental studies involving eccentric compression on structural columns/ walls [1 - 5]. There are more studies (concentric and eccentric compression tests) on short prisms (600mm to 800mm high) – these studies are not considered in this paper so that the focus would be set on walls of reasonable heights (1m or taller). Havez et al [1] tested reinforced concrete "walls"

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(305mm wide × 203mm thick cross section) of height 1.83m under eccentricities of $^t/_6$, $^t/_3$ & $^t/_2$ (where *t* is thickness of wall) and examined the beneficial effect of the polyvinyl chloride (PVC) sheeting encasing the reinforced concrete. Four main reinforcing bars were used with full lateral restraining stirrups (ties) similar to the common designs of rectangular reinforced concrete columns. They found that despite the presence of lateral ties, the main steel did not always yield in the tested normal RC walls – however, the steel reinforcement in all the PVC encased RC walls yielded, but the PVC buckled. A similar innovation is reported in Vardy and McDougal [2] where they examined the capacity of plastered straw bale under eccentric and concentric compression. Bernat et al [3] examined the beneficial effect of textile reinforced mortar (TRM) rendering to existing clay brick walls under eccentric compression; the TRM rendered walls were shown to exhibit much higher ductility under eccentric compression compared to un-rendered URM walls. Kottb et al [4] and Sheehan et al [5] examined the effect of eccentric compression on the high strength concrete column and concrete filled elliptic steel column respectively. Supinyeh and Hamez [6] investigated steel fabric embedded concrete walls under eccentric compression. Insight into the load transfer mechanism under eccentric compression of the solid clay brick masonry is reported through experiments on short prisms and analytical modelling by Brencich and de Felice [7] and Cavaleri et al [8]. These studies used walls or columns of maximum height 1.5m. The national concrete masonry association, USA [9] reported results of two 6m (20') high grouted reinforced masonry walls of length 1.2m (48") and thickness of 200mm (8"); one wall was tested under concentric compression and the other wall was tested under an eccentricity of one-sixth of the thickness of the wall. The review of literature shows that there exists gap in the in-depth understanding of the response of reinforced masonry walls containing single vertical reinforcing bars at mid thickness to compressive loading. The Australian masonry structures standard AS3700 [10] provide stringent requirement of detailing lateral retraining bars to the centrally positioned main reinforcing steel to qualify the wall be designed as reinforced masonry; those walls that do not satisfy the requirement are currently designed as unreinforced masonry with lower capacity reduction factor. Such a stringent regulation is not found in the Canadian masonry structures standard S304.1 [11], Eurocode 6 [12] and the masonry society joint committee standard [13]. This research is, therefore, formulated to uncover the rationale of the stringent provisions in the AS3700 [10] through an extensive experimental campaign. This paper reports testing of thirty six 1.4m high reinforced masonry walls under concentric and eccentric compression.

EXPERIMENTAL INVESTIGATIONS

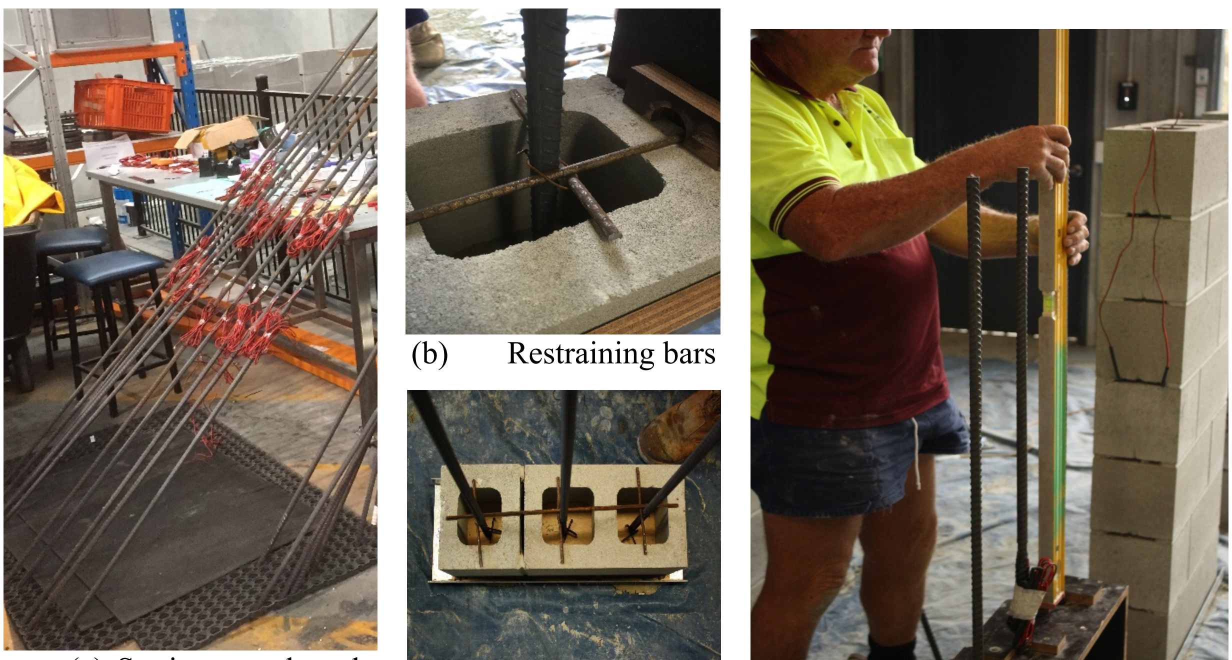
The experimental investigation reported in this paper included examination of the effect of the following parameters:

- The lateral restraining bar details
    - Restraining bars along only the length direction of wall with the vertical spacing of 800mm/ 400mm/ 200mm
    - Restraining bars along both the length and the thickness directions of the wall with the vertical spacing of 800mm/ 400mm/ 200mm

- Eccentricity in loading to thickness of wall ratios of $e/t = 0; (1/6) \& (1/3)$

The gross dimensions of the wall and the specified grout strength (20MPa) were kept constant. The average strength of the two-cell hollow concrete blocks was 13.45MPa (CoV 24%). The average hollow masonry prism strength was 8.34MPa (CoV 18%) and the grouted masonry prism strength was 9.06MPa (CoV 12%). All strength calculations were performed using the net area.

Non-coiled steel bars donated by the Steel Reinforcement Institute of Australia (SRIA) were first cut to the required size, strain gauged and kept ready prior to construction of the masonry shell (Fig. 1a). A 25mm high chair was used to ensure the bottom end of the vertical steel reinforcing bar do not contact the loading plate (Fig. 1c); similarly the top end of the bas was kept 25mm below the top surface of the wall. Load transfer to the steel bars was thus ensured through the bond between the grout and the bar and not through direct contact with the loading platen to avoid premature buckling of the reinforcing bars.



(a) Strain gauged steel bars

(b) Restraining bars

(c)View of chairs

(c) Checking verticality

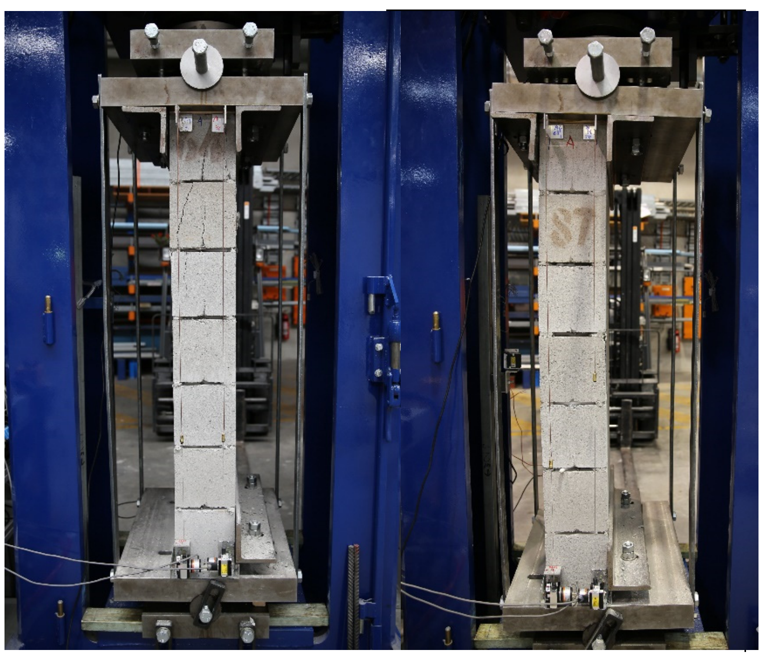
Figure 1: Process of Construction of Reinforced Masonry Wall Specimens

Hollow concrete blocks of 390mm long × 190mm high × 190mm thick were face shell bedded using 10mm thick 1:1:6 (cement : lime : sand) mortar in the construction of the 600mm long × 1400mm high × 190mm thick wall. A 6mm thick plywood plate was positioned on a steel "C" section that acted as a lifting beam to transport the wall from the construction site to the test frame. The positions of the reinforcing bars were marked on the plywood. Vertical steel bars were positioned at these marked locations exactly on chairs and the lateral restraining bars were tied to the vertical bar at specified spacing such that the ends of these restraining bars along the thickness direction were embedded in the mortar joints for 20mm length (mortar joints were 30 mm – 32 mm wide covering the face shell thickness) (Fig. 1b). The position and the alignment of the vertical steel were carefully assessed by the mason throughout the construction process (Fig. 1d).

The three hollow cores in each wall were poured with the grout of specified strength 20MPa and specified slump 220mm for ease of pour. The specimens were grouted on two different days; each grout pour was sampled in three 100mm diameter × 200mm high steel moulds for assessing the 28-day compressive strength. Slump cone tests were also conducted – consistency of 220mm slump was obtained.

The grout was rodded carefully without dispositioning the vertical and/ or the lateral restraining steel bars as well as the wires connecting the strain gauges on the vertical steel bars. Grout was filled flush with top surface of the wall specimens and the grouted walls were wrapped in plastic sheet to cure for 28 days. A day ahead of testing, the plastic sheet was removed. The grout was fund to had shrunk leaving a small depression of 2mm – 3mm; this depression was levelled using a mix of sand and araldite. The mix was smeared along the whole length and width of the top surface of the wall as a capping layer of 3mm – 5mm thickness. A 6mm thick plywood capping was positioned on top of the araldite – sand mix layer.

The finished specimen was moved to the test site and positioned under the loading frame. Fig. 2(a) shows the setup of a concentrically loaded wall and Fig. 2(b) shows the setup of an eccentrically loaded wall.



(a) Concentric Loading (b) Eccentric Loading

Figure 2: 1.4m Tall Walls During Testing

The following sensors were setup carefully.

- String-pots to measure the overall deformation of the specimen: four string pots, one at each corner of the specimen, were positioned.
- Laser: Three lasers were positioned pointing at the one-fourth, mid and three-fourth heights of the wall to measure the out-of-plane deformation (if any) in the direction of the thickness of the wall.
- Digital Images at regular frequency of 0.1Hz: to monitor stress states at web shells using the digital image correlation (DIC) method.
- The lead wires from the strain gauges on the steel bars were hooked onto the data acquisition computer.

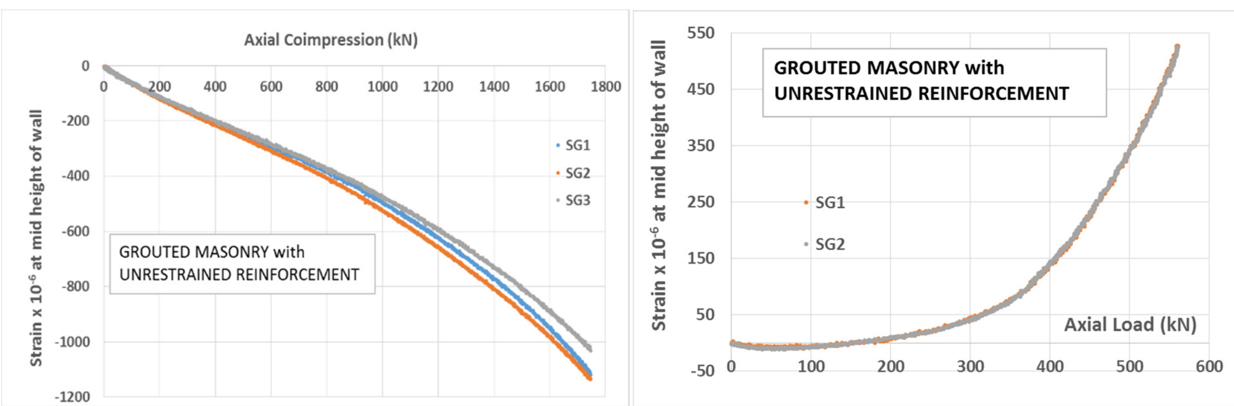
The load was applied using a displacement controller. Vertical displacement was increased at a slow rate of 0.01mm/ sec and was continued until the vertical load dropped by 20% or the wall exhibited instability.

RESULTS AND ANALYSIS

The experiment generated a huge set of data; only very limited results obtained from the dataset is presented here and analysed.

Strain in Vertical Reinforcing Steel Bars

Strain in the unrestrained vertical steel bars embedded in grout in walls under concentric and eccentric loadings are shown in Fig. 3.

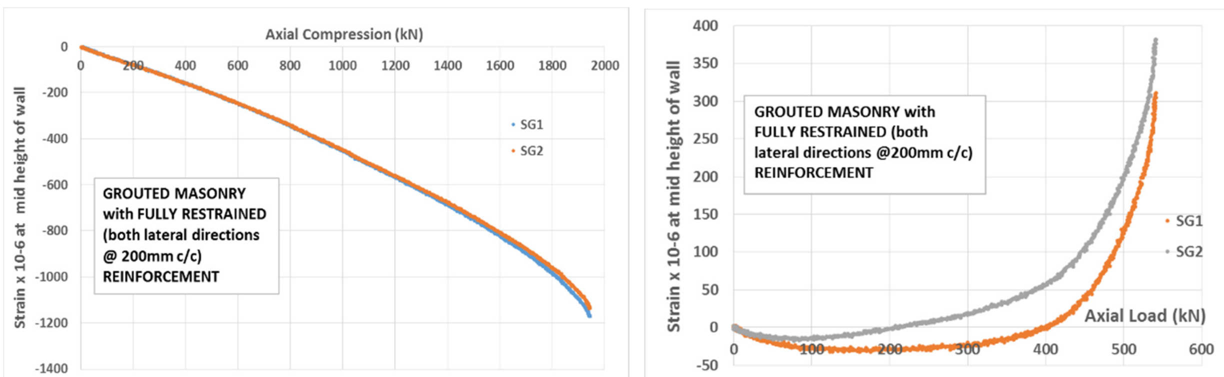


(a) Under concentric loading (b) Under eccentric loading

Figure 3: Strain in unrestrained vertical steel bars embedded in grout

The steel bars in walls under concentric loaded were provided with three strain gauges (60° rosette pattern) at mid height and the steel bars in walls under eccentric compression were provided with two strain gauges (with a face-shift of 180°) at mid height. Therefore, three traces of steel strains are presented for the wall under concentric loading and for the eccentrically loaded wall, only two traces are presented. It can be seen that the axial compression has caused monotonically increasing compressive strain in the steel bars till the failure (peak load) of the wall, whilst the eccentric loading up to approximately 1/3rd of the ultimate load (~200kN) caused small compressive strain, which then changed to rapidly increasing tensile strain. Steel remained elastic at the time of failure of the wall specimen in both the concentrically loaded wall (ultimate load ~1100kN, Fig. 3a) and the eccentrically loaded wall (ultimate load ~580kN, Fig. 3b). The steel strain of the wall subject to eccentric compression is lower than that of the steel strain of the wall subject to concentric loading because under eccentric loading the ultimate load was low.

The strain in the vertical steel bars laterally restrained in both directions is shown in Fig. 4. One of the strain gauges in the wall under concentric compression delaminated and hence only two traces are presented. The two strain gauges in the eccentrically loaded wall survived and hence both traces are presented.



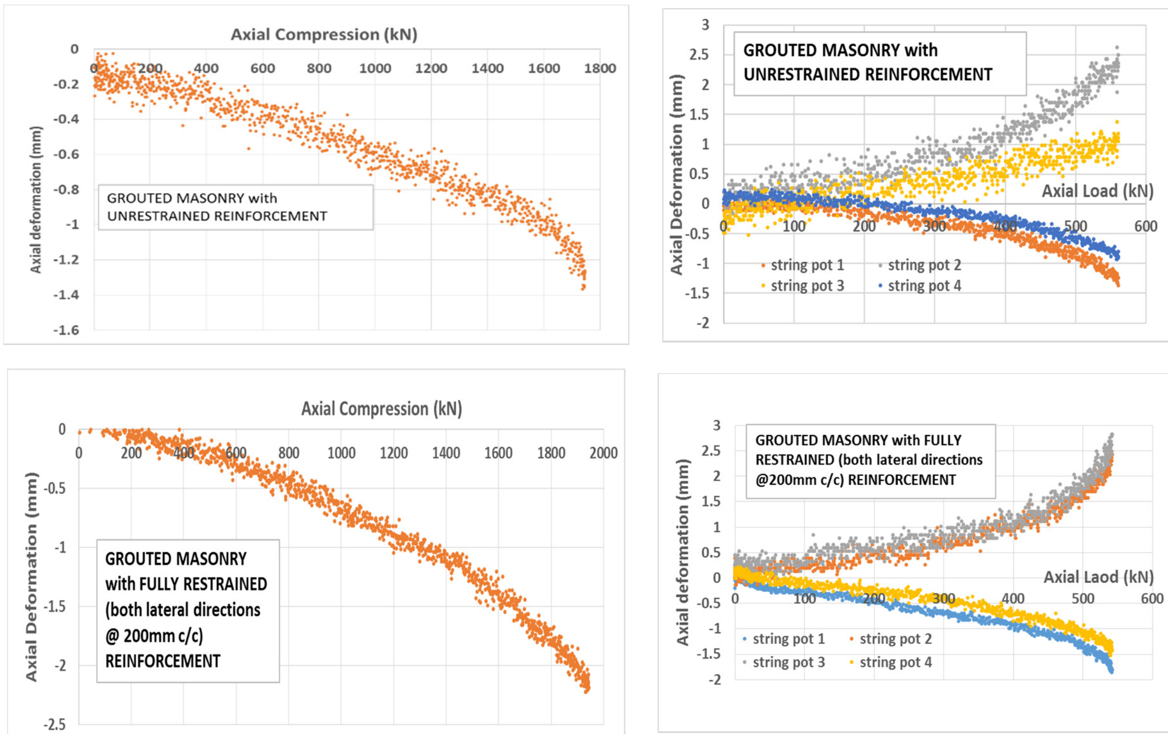
(a) Under concentric loading (b) Under eccentric loading

Figure 4: Strain in fully restrained vertical steel bars embedded in grout

The striking similarity between Figs 3 and 4 for both the concentric (Figs 3a and 4a) and eccentric (Figs 3b and 4b) loaded walls clearly illustrates that the detailing of lateral restraining steel bars does not contribute to improved response of the vertical reinforcing steel bars. Under concentric compression, the laterally restrained vertical reinforcing bars attained maximum strain of approximately ~1200 microstrain (Fig. 4a), which is just ~100 microstrain more than the case under no lateral restraining bars (Fig. 3a). Under eccentric loading, the maximum strain in steel was just + 380 microstrain (Fig. 4b – where the vertical bars had lateral restraining bars detailed), which is much lower than the + 520 microstrain (Fig. 3b) attained by the steel bars with no lateral restraining bars. Under eccentric loading, the wall whose strain response is presented in Fig. 4b, failed under ~520kN, which is 10.3% lower than the ~580kN for the wall whose response is presented in Fig. 3b. In both cases (unrestrained in Fig 3 and restrained in both directions in Fig 4), the vertical steel reinforcing bar remained elastic when the failure of masonry occurred. From these observations, it can be concluded that the detailing of the lateral restraining steel bars do not improve the response of the vertical steel reinforcing bars. Considering the effort and time required to detail such lateral restraining bars and the associated costs of the labour, there appears no significant benefit achieved. Further, in wall structures, ignoring the contribution of the vertical reinforcing bars seems highly conservative and restricts the concrete masonry designers effectively competing with other reinforced products.

Axial Shortening of the Reinforced Masonry Walls

Traces of the string pot data are plotted in Fig 5 for walls under concentric and eccentric loading. The traces of the four string pots for the concentrically loaded specimens were averaged and hence a single trace is shown for the wall containing unrestrained and the fully restrained (both directions @ 200mm c/c) vertical steel reinforcement in Fig. 5a. The traces of each of the string pots are shown separately for wall specimens subject to eccentric compression.



(a) Under concentric loading (b) Under eccentric loading

Figure 5: Axial deformation of the Reinforced Masonry Walls

The traces of the eccentrically loaded walls show extension (positive displacement) and contraction (negative displacement) of the two opposite surfaces of the walls once the load level increased beyond 200kN. The response under tension was noisier than that under compression owing to cracking.

Under the concentric compression, the two walls (one with unrestrained and the other with the fully restrained vertical steel reinforcement) exhibited similar slope. Approximately 0.6mm deformation occurred in both walls under 1000kN axial compression. Under the eccentric compression, both walls in Fig. 5b have exhibited maximum elongation of approximately 2.8mm and maximum contraction of 1.8mm. There is no obvious influence of the type of reinforcement detail to the overall behaviour of the wall from these structural responses. These data again confirms the insignificant influence of the need for restraining the steel reinforcing bars to improve the response of the reinforced masonry walls as anticipated in the AS3700 (2011).

EFFECT OF ECCENTRICITY TO THE RM WALL COMPRESSION CAPACAITY

The ultimate load obtained from the 36 walls was analysed to examine the effect of the eccentricity to the vertical compression. As stated before, the 36 walls were grouted in two batches. Although 20MPa grout of 220mm slump with maximum size of the aggregate limited to 12mm was specified for each batch, the cylinder strengths obtained from each batch was different as below: (1) Batch#1: 33MPa and (2) Batch#2: 35MPa. The grout strength delivered was significantly higher than specified. As the maximum grout strength was limited to 1.3 times the strength of the masonry block in the AS3700-2011 [10], for the specified strength of 15MPa blocks, a maximum of 20MPa grout was considered appropriate and hence specified. As the grout strength was different in two batches, the ultimate loads of the 36 walls obtained from the experiment were rationalised using the grouted masonry strength formula provided in AS3700-2011 [10]. The average strength of the 18 concentric loaded walls was used to non-dimensionalise the experimentally obtained and subsequently rationalised ultimate load capacities of the 36 walls. The data obtained are plotted against the eccentricity-to-thickness ratio of the wall in Fig. 6.

The vertical axis of the figure shows the non-dimensionalised ultimate load of each wall $\left(\frac{P_u}{Ave\left(P_{u,e=0}\right)}\right)$. The horizontal axis show the eccentricity-to-thickness ratio $\left(\frac{e}{t}\right)$. A regression line of $\left(1.0-1.8\frac{e}{t}\right)$ was fitted with a goodness of fitting of 83%. The trendline obtained is close to the theoretical line of $\left(1.0-2.0\frac{e}{t}\right)$. The theoretical line is also plotted in the figure; the experimental data for eccentrically loaded walls plotted above the theoretical lines. Therefore, it can be concluded that the theoretical line can be used conservatively for the design of reinforced masonry walls subject to eccentric compression.

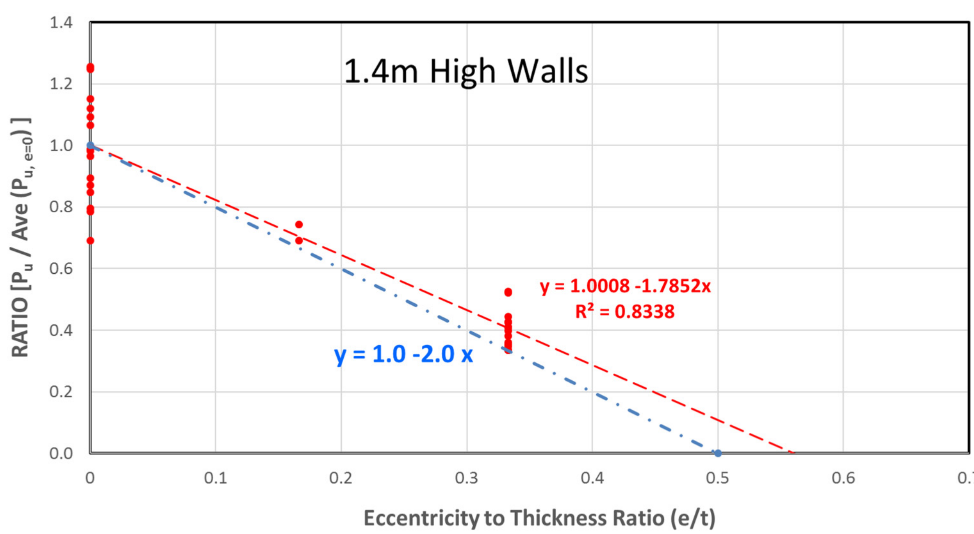


Figure 6: Effect of Eccentricity to Ultimate Load on 1.4m High Reinforced Masonry Walls

CONCLUSIONS

Effect of eccentricity to reinforced masonry walls has been reported. As the Australian Masonry Structures Standard AS3700-2011 [10] differentiate the wall based on the presence of lateral retraining steel at close intervals either as unreinforced masonry or as reinforced masonry, walls were detailed with varied spacing of the restraining bars in either one lateral direction (along the length of wall) or in both directions (length and thickness directions). Walls containing unrestrained steel bars were also tested. Eighteen walls each were tested in concentric and eccentric compression respectively. The main reinforcing steel was strain gauged and the axial deformation of the wall was monitored using four string pots, one each at one corner for the full height of the wall. The following conclusions were made:

1. Detailing of the lateral restraining steel bars to the main steel reinforcement did neither improve the response of the wall nor increased the axial strain.
2. Main vertical reinforcement did not yield at the time of the grouted masonry attaining maximum (ultimate) load.
3. The 1.4m high walls tested in this research exhibited a linear reduction in ultimate load with the increase in eccentricity.
4. The ultimate load of the 1.4m walls under eccentric compression was found marginally higher than the theoretical reduction of $\left(1.0 - 2.0\frac{e}{t}\right)$, justifying usage of the theoretical reduction factor in the design conservatively irrespective of the presence or absence of the lateral restraining bars.
5. Usage of grout whose strength is much higher than the $1.3 f'_{uc}$ limit imposed in the AS3700 (2011) did not adversely affect the response of the wall. As no other international standard has such a restriction, it is recommended that the AS3700(2011) allows the designers to take advantage of the higher strength grout to design grouted reinforced masonry for higher loaded structures.

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