Behaviour of Stack Bonded Masonry Under Concentrated Compression Loading

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ABSTRACT

Stack bonded (or stack pattern) masonry is a form of construction in which the masonry units in successive courses are aligned vertically above one another. This bonding pattern leads to continuous vertical joints resulting in a weak form of construction, which is vulnerable to cracking along the continuous vertical joints. Despite its inferior structural performance compared to more traditional bonding patterns, it has a history of being used in architectural feature applications. Furthermore, its popularity has increased again in recent years as architects push the boundaries of what is possible in masonry facades. In response, new code provisions which require the use of bed joint reinforcement were introduced to AS3700 - Masonry Structures in 2018 [1] to help inform the structural design of stack bonded masonry subjected to out-of-plane bending. However, its performance under concentrated compression loading is yet to be studied. The current paper presents an experimental study designed to investigate the relative performance of stack bonded masonry, with and without bed joint reinforcement, compared to traditional running (stretcher) bonded masonry, when subjected to concentrated compression loads. For running bonded masonry, AS3700 [1] allows strength enhancement immediately beneath a concentrated load due to the confinement provided by the surrounding masonry and assumes concentrated loads will disperse through the masonry at 45° to the horizontal. However, due to the presence of the continuous vertical joints in stack bonded masonry, it remains unclear whether these assumptions still apply. The current study investigates these aspects with a view to assessing the suitability of the current code provisions for applications involving stack bonded masonry. While it was found that unreinforced stack bonded masonry has limited ability to disperse concentrated loads, the use of the AS3700 [1] prescribed quantities and distribution of bed joint reinforcement is effective in achieving a performance similar to that of unreinforced running bonded masonry.

KEYWORDS

concentrated compression load, masonry, stack bond, stack pattern

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INTRODUCTION

Past experimental and numerical modelling research has shown that when unreinforced masonry (URM) is subjected to concentrated compression loading the failure mode involves vertical cracking initiating as a perpend crack beneath the concentrated load, usually several courses below the point of load application where there exists a state of vertical compression combined with biaxial tension [2]. The crack then propagates vertically through units and joints in the case of running (stretcher) bond, extending towards the loading location and the base of the wall. For short loading plates the crack tends to be directly beneath the centre of the plate. For longer loading plates the cracks tend to occur beneath one or both ends of the plate. Confinement due to surrounding less stressed masonry leads to strength enhancement immediately beneath the load. Enhancement up to three times the strength under uniaxial compression has been observed in some cases, depending on the loaded area ratio, wall aspect ratio and load location in relation to the end of the wall [3]. Most design codes allow for the strength enhancement and require that designers check for failure via crushing immediately beneath the concentrated load, as well as failure (via crushing or buckling) in a dispersed zone at wall mid-height [4]. Assumptions regarding the angle of load dispersion range from 45° to 60° to the horizontal, although some studies indicate that these angles may be non-conservative [5].

AS3700 [1] provides an equation for strength enhancement (up to a factor of 2) immediately beneath the concentrated load, which depends on the loaded area ratio and the proximity of the load to the end of the wall. The loaded area ratio is defined as the area of bearing between the concentrated load and the masonry divided by the effective area of dispersion of the concentrated load at the wall mid-height. In determining the area of dispersion, the concentrated load is assumed to disperse at an angle of 45° to the horizontal and the dispersed length (L_e) is limited by the end of the wall and by intersection with the dispersion zone of another concentrated load (Fig. 1.)

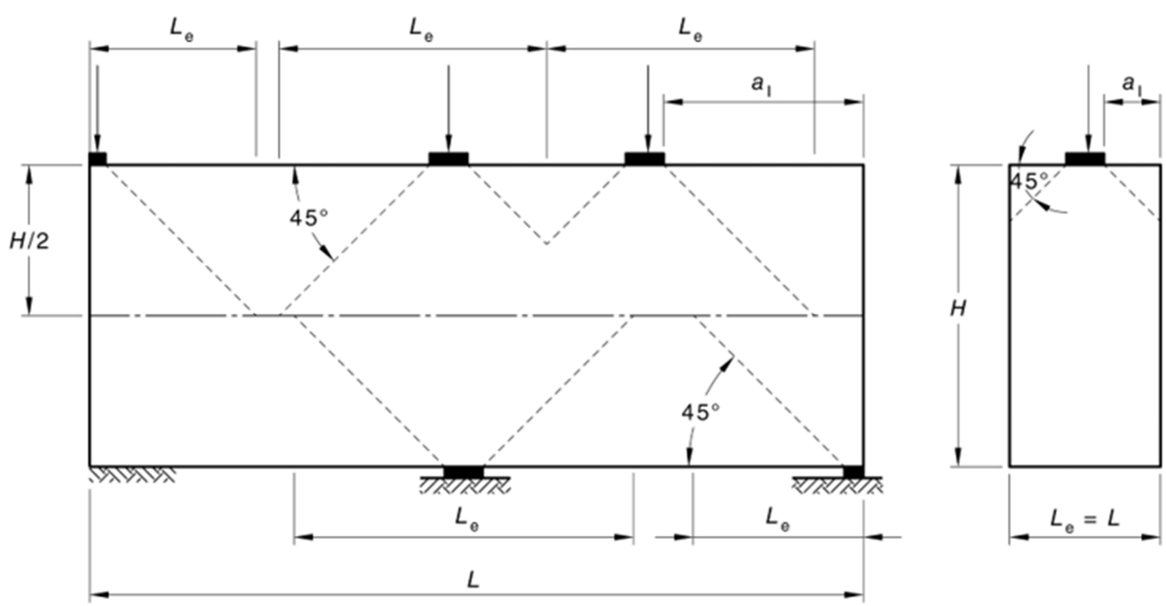


Figure 1: Loading Positions and Effective Areas of Dispersion [1]

In the case of unreinforced stack bond, a vertical crack initiating beneath a concentrated load will propagate unhindered through continuous perpends. Furthermore, the vertical shear transfer required to disperse the concentrated load along the length of the wall is expected to be less effective in stack bond due to the continuous vertical joints. In fact, AS3700 [1] (consistent with other design standards) defines unreinforced continuous vertical joints as the “structural end of a member”, effectively ending the zone of dispersion at the joint. This means for example, that a concentrated load applied to a single vertical stack of units must be resisted by that single stack alone.

Based on research by the authors [6,7,8] new provisions were introduced to AS3700 [1] in 2018, requiring the use of bed joint reinforcement to improve the robustness and out of plane bending capacity of stack bonded masonry. It is reasonable to expect that such bed joint reinforcement could also contribute to shear transfer across vertical mortar joints in stack bonded masonry, helping to facilitate the dispersion of concentrated compression loads along the length of a wall, much in the same way that the overlapping of units does in running bonded masonry. The current study aims to investigate these aspects by comparing the relative performance, when subjected to concentrated compression loads, of stack bonded masonry, with and without bed joint reinforcement, to traditional running bonded masonry.

EXPERIMENTAL PROGRAM

Materials and Test Specimens

A total of eight (8) masonry wall specimens were constructed by an experienced mason using extruded clay bricks (230 mm long x 76 mm tall x 110 mm wide) using 10 mm thick 1:1:6 (cement:lime:sand by volume, as per AS3700 [1]) (or approximately 1:0.5:7.6 by mass) mortar joints. All bed joints were fully bedded and perpend joints fully filled. The walls were 11 units (2630 mm) in length, 15 courses (1280 mm) in height and a single masonry unit (110 mm) thick. For each mortar batch mixed during the wall construction, three x 6-unit high masonry prisms were constructed for compressive strength testing in accordance with AS3700 [1].

The test program considered four wall types, with two nominally identical specimens for each type. Two walls (Specimens RU1 and RU2) were constructed in unreinforced running bond with half unit overlap between successive courses. Six walls were constructed in stack bond (stack pattern). Of the six stack bonded walls, two were left unreinforced (SU1 and SU2), two were reinforcement with the AS3700 [1] specified minimum quantity of bed joint reinforcement (SRL1 and SRL2) and two were reinforced with greater than minimum reinforcement (SRH1 and SRH2) by placing additional layers of bed joint reinforcement in the courses immediately beneath the point of application of the concentrated load. Bed joint reinforcement consisted of a single layer of Ancon AMR/S/D3.0/W60 ladder type reinforcement, which consists of two stainless steel plain wires of diameter 3.0 mm, spaced 60 mm apart, connected by cross wires at 450 mm centres. Fig. 2 shows the dimensions and reinforcement details for the test specimens. For solid and cored unit (fully bedded) masonry laid in stack bond pattern, AS3700 [1] requires that bed joint reinforcement be placed in bed joints at centres not exceeding 6 times the wall thickness and having a reinforcement area not less than 0.00035 times the gross vertical cross-sectional area of the wall. The reinforcement arrangement shown in Fig. 2 for specimens SRL1 and SRL2 meets this requirement. Note that the reinforcement diameters are shown oversized for clarity in the side elevation views in Fig. 2.

The specimen naming convention is such that the first letter indicates the bonding pattern (R for running, S for stack), the second letter indicates the presence of reinforcement (U for unreinforced, R for reinforced), The third letter, if used, indicates the reinforcement quantity (L for “low” = AS3700 minimum requirement, H for “high” = greater than AS3700 minimum) and the number indicates which of the two specimens of each type is being considered.

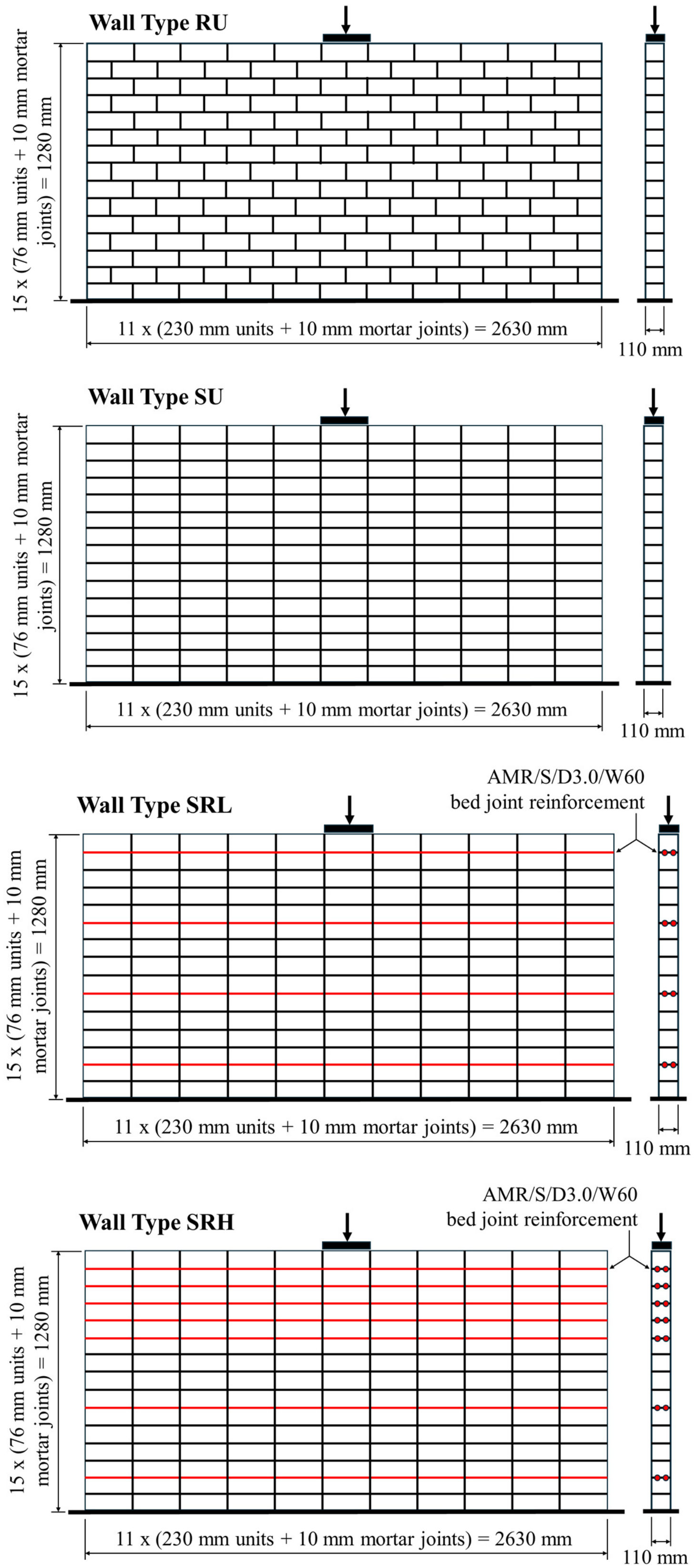


Figure 2: Test Specimen Dimensions and Reinforcement Details

Test Setup and Procedure

The test setup is depicted schematically in Fig. 3a and a typical test is shown in Fig. 3b. The testing reaction frame was designed to provide an unobstructed view of the front face of the wall panels, so that digital image correlation (DIC) could be used to determine displacements and strains in the masonry during each test. The DIC technique involves using a high-resolution camera to take photographs prior to, and at regular (5 second) intervals during testing which are later compared using the software VIC-2D to determine strains and displacements relative to the initial unloaded reference image. The DIC results were used to visualise the progression of damage and failure mode, and the degree of load dispersion along the length of the wall in each specimen.

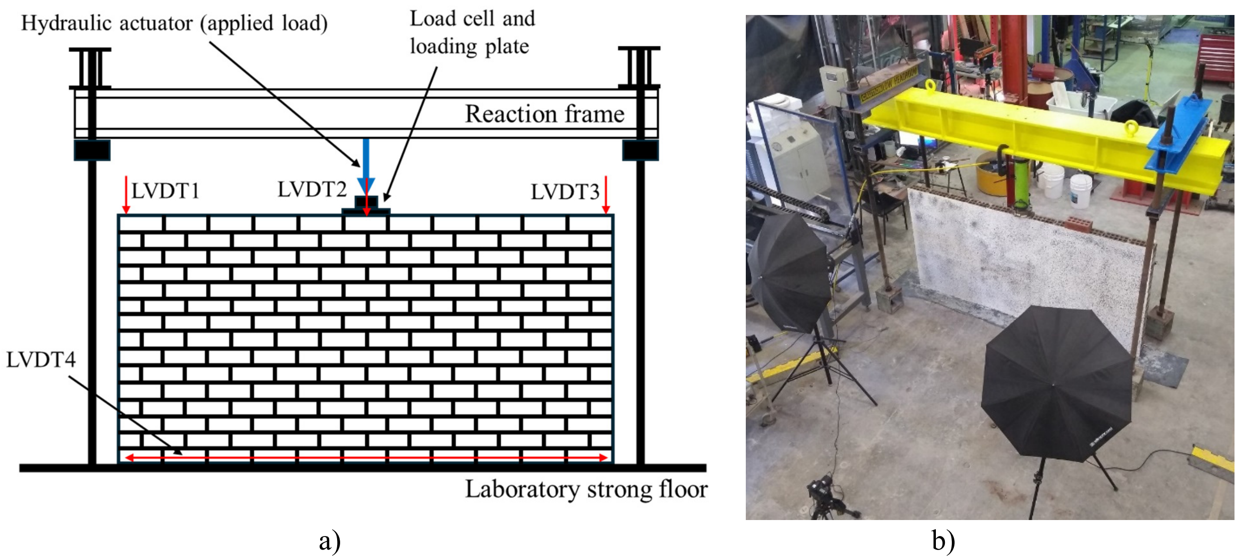


Figure 3: Test Setup

The concentrated compression load was applied via a 230 mm x 110 mm steel loading plate which was positioned to exactly cover one full masonry unit (brick) at the mid-length of the wall. This arrangement was the same for all eight specimens. The load was applied slowly using a hand operated hydraulic pump. The application of load was neither completely displacement control, nor completely load control. The applied load was recorded using a load cell placed directly above the loading plate.

For the very first wall specimen tested (SU1), the specimen was placed on top of a line of load cells (one beneath each masonry unit), in an attempt to measure directly, the dispersion of load along the length of the wall. This technique proved problematic due to challenges in achieving a uniform load along the length of the wall prior to application of the concentrated load. Hence this technique was not used for subsequent tests, with the walls being founded directly on the laboratory strong floor and relying solely on DIC for assessing the load dispersion. In addition, linear variable differential transformers (LVDTs) were used to record displacements at regular intervals during each test (Fig. 3a). Vertical displacements were recorded at the point of application of the concentrated load (LVDT2), and at each end of the wall (LVDT1 and LVDT3), and horizontal displacement was recorded along the base of the wall (LVDT4).

RESULTS AND DISCUSSION

The experimental results are summarised in Table 1 and plots of applied concentrated compression load versus vertical displacement at the loading plate are shown for all specimens in Fig. 4. The concentrated load was applied sufficiently slowly as to allow cracking to propagate in a relatively controlled manner prior to reaching peak load. However, once peak load was achieved the wall specimens experienced sudden failure, such that the unloading branches could not be recorded. This is evidenced by the straight sections with no data markers in the post peak branch of the load versus displacement plots in Fig. 4. These post peak sections are included here to show that many of the walls retained residual compressive capacity post failure, and in the case of Specimen SU1, the load was able to increase further following an initial load drop upon the first vertical crack appearing. The post peak branch is not shown for Specimen SRH1 because LVDT2 measuring vertical displacement dislodged from its mounting point upon failure.

Table 1: Summary of Experimental Results and Strength Predictions

Spec. ID	Peak Load (kN) (1)	Ave. Peak Load (kN) (2)	f_b (MPa) (3)	f_m (MPa) (4)	Strength enhance-ment factor (3) / (4) (5)	f'_m (MPa) (6)	AS3700 pred. capacity (kN) (7)	AS3700 design capacity (kN) (8)	Pred. / Exp. (7) / (1) (9)	Design / Exp. (8) / (1) (10)
RU1	193	246	7.6	9.9	0.77	6.3	315	150	1.6	0.8
RU2	298		11.8	12.8	0.92	7.4	407	176	1.4	0.6
SU1	186	162	7.4	14.7	0.50	9.7	467	231	2.5	1.2
SU2	138		5.5	13.2	0.41	8.4	420	200	3.0	1.4
SRL1	342	305	13.5	12.8	1.06	7.4	407	176	1.2	0.5
SRL2	267		10.6	14.6	0.72	8.1	464	193	1.7	0.7
SRH1	263	259	10.4	14.6	0.71	8.1	464	193	1.8	0.7
SRH2	256		10.1	15.8	0.64	9.9	502	236	2.0	0.9

Notes: (3) = average stress immediately beneath bearing plate at peak load, (4) = mean uniaxial compressive strength of masonry from prism tests, (6) = characteristic uniaxial compressive strength of masonry from prism tests.

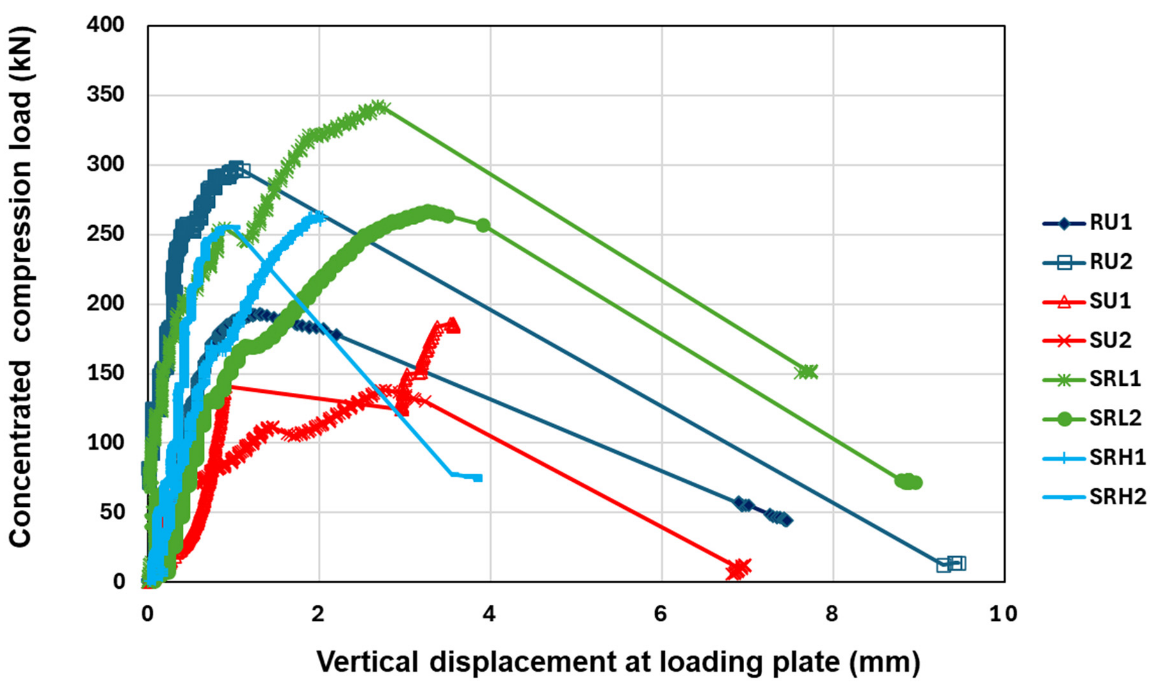


Figure 4: Concentrated Compression Load versus Vertical Displacement

Specimen type RU

Specimens RU1 and RU2 (unreinforced running bond pattern) were included in the experimental program as control specimens for comparison with the stack bonded walls. RU1 failed via local crushing beneath the loading plate combined with stepped and horizontal cracking which extended along the bed joints in the upper courses of the wall and through to one end of the wall. This observed horizontal cracking provides clear evidence of the ability of the running bond pattern to transfer vertical shear arising from the concentrated load to the masonry either side of the load and hence disperse the concentrated load along the length of the wall as assumed in design codes. Fig. 5a shows a DIC image of vertical strain prior to peak load indicating the dispersion of load along the wall length and Fig. 5b shows the final failure pattern. By contrast, Specimen RU2 failed via vertical cracking which initiated at the base of the wall in line with the loading plate and then propagated vertically to combine with a region of crushing beneath the loading plate. Despite this different failure pattern, observations of vertical strain contours captured using DIC (Fig. 5c) do show, similarly to RU1, that the load was dispersed along on the length of the wall either side of the concentrated load throughout the various stages of loading. The final failure pattern is shown in Fig. 5d.

Specimen type SU

Specimens SU1 and SU2 (unreinforced stack bond pattern) would not be permitted under AS3700 [1] due to the requirement for bed joint reinforcement in any stack bonded masonry. The behaviour of these two specimens confirmed the limited load bearing ability of this form of masonry, with the average of the peak loads resisted by the SU specimens (162 kN) being 34% lower than that of the RU specimens (246 kN) (Table 1). Specimen SU1 experienced a single vertical crack extending from one edge of the loading plate, followed soon after by a second vertical crack from the other edge of the loading plate to form a single isolated stack of units resisting the concentrated load. Specimen SU2 experienced three vertical cracks: the first appearing beneath one edge of the loading plate, the second appearing one unit length away from the edge of the loading plate on the opposite side, and then a third from the other edge of the loading plate, again isolating a single stack of units which then crushed near the base of the wall (Fig. 5e). Vertical strain contours captured using DIC indicate limited dispersion of the load along the wall prior to the cracks forming, which highlights the inability for the continuous unreinforced vertical joints to transfer vertical shear arising from the application of the concentrated load, and hence the limited ability to disperse the load to the surrounding masonry.

Specimen type SRL

Specimens SRL1 and SRL2 contained the AS3700 [1] minimum required bed joint reinforcement for stack bonded masonry (Fig. 2). However, it should be noted that the reinforcement centre to centre spacing (344 mm), slightly exceeds the AS3700 [1] upper limit (300 mm) for achieving "monolithic structural action" across the continuous vertical joints in the stack pattern. This means that the continuous vertical joints would technically still be considered as the "structural end of the wall" and hence define the limit of dispersion of the concentrated load. Despite this, the presence of the reinforcement in the SRL specimens resulted in a marked improvement in the structural behaviour of these specimens compared to the unreinforced stack bonded (SU) specimens. The average of the peak loads recorded for the two SRL specimens (305 kN) was almost twice that for the unreinforced (SU) specimens (162 kN) and 24% greater than that for the running bonded (RU) specimens (246 kN) (Table 1). SRL1 developed vertical cracks (initiating at the base) extending to either edge of the loading plate at an applied load of approximately 250 kN. However, the presence of the bed joint reinforcement allowed the wall to resist additional load, with the peak load being defined by crushing at the base of the wall beneath the loading point (Fig. 5f). SRL2 displayed similar behaviour, with vertical cracks extending beneath both edges of the loading plate, combined with crushing within the masonry stack beneath the loading point. In addition, horizontal cracks developed just above wall mid-height (Fig. 5g). As for SRL1, first cracking did not define the peak load, with SRL2 also being able to resist higher load beyond the appearance of the first cracks. This behaviour indicates that the presence of bed joint reinforcement bridging the cracks allowed redistribution of the concentrated load within these specimens. This behaviour can be seen as steps and changes of slope in the loading branches for SRL1 and SRL2 in Fig. 4. Inspection post testing of the deformed shape of the upper most layer of reinforcement provides clear evidence of the action of the reinforcement in transferring shear across the vertical cracks (Fig. 5h).

Specimen type SRH

Specimens SRH1 and SRH2 contained additional reinforcement (compared to the SRL specimens) so that every joint in the upper five courses was reinforced (Fig. 2). The rationale was to provide additional reinforcement close to where the concentrated load was applied to more effectively disperse the concentrated load along the wall length. Contrary to expectations, the results indicate that this did not occur. The average of the peak loads recorded for the SRH specimens (259 kN) was lower than that for the more lightly reinforced SRL specimens (305 kN) and only marginally greater than that for the RU specimens (246 kN).

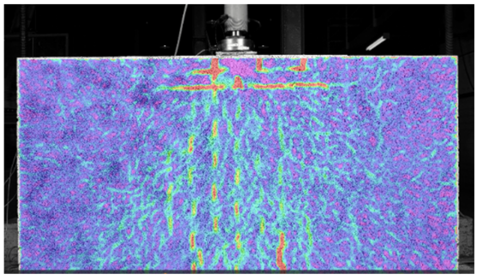
The cracking behaviours for the SRH specimens were similar to those observed for the SRL specimens, with vertical cracks developing beneath each edge of the loading plate, combined with crushing of the masonry within the central stack of units (Fig. 5i). The presence of multiple layers of reinforcement near the top of the walls had the effect of reducing the relative vertical displacement across the cracks compared to the SRL specimens. This is evidenced by the significantly smaller vertical displacements at peak load (SRH compared to SRL in Fig. 4) and visibly reduced deformation of the reinforcement in the upper most bed joint (Fig. 5j compared to Fig. 5h).

The reason for the lower average peak load for SRH compared to SRL specimens remains unclear, however, it is noted that the difference is only 15% (comparable to the expected variability of masonry compression strength [9,10]) and there is significant variability between the peak loads for the repeat specimens within each wall type (Table 1 and Fig. 4).

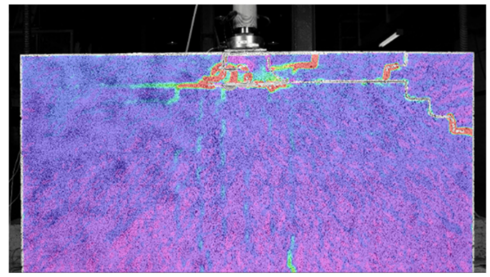
Strength Enhancement Factor

As noted in the introduction, past research has reported strength enhancement for the masonry immediately beneath a concentrated compression load which arises due to the confinement provided by the surrounding masonry. To assess this effect in the current study, the average stress (f_b in Table 1) immediately beneath the loading plate at peak load was determined for each specimen by dividing the peak load by the area of the bearing plate. This was compared to the mean uniaxial compressive strength obtained from prism testing in accordance with AS3700 [1], for the batch of mortar used to construct that wall specimen. The strengths, and the strength enhancement factors, are reported in Table 1, columns (3), (4) and (5). Contrary to expectation, in most cases the mean uniaxial strength from prism testing exceeded the average stress beneath the bearing plate at peak load, implying that there was in fact no measurable strength enhancement. While this was unexpected, the strength enhancement factors for the SU specimens are clearly much lower than those for RU, SRL and SRH, highlighting the reduced effectiveness of load dispersion and confinement by surrounding masonry for these specimens.

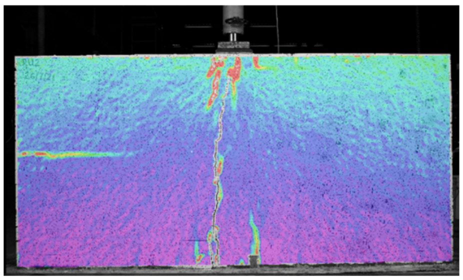
The reasons for the lack of strength enhancement, even in the case of RU specimens, are not completely clear. However, it is noted that the concentrated bearing (strength enhancement) factor (k_b) determined in accordance with AS3700 [1] (see next section) for the loading plate and wall dimensions tested in the current study is just 1.26, implying that for this size loading plate, the strength enhancement is not expected to be large. Hence the effects of strength enhancement may simply be lost within the general variability of material strengths across the wall and prism specimen results.



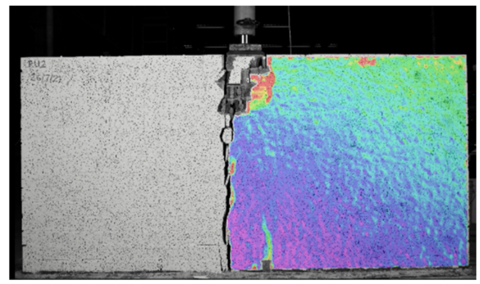
a) RU1 - load dispersion prior to peak load



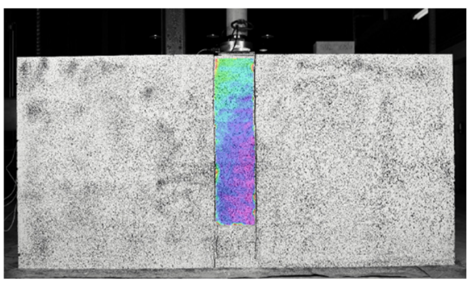
b) RU1 - final failure pattern



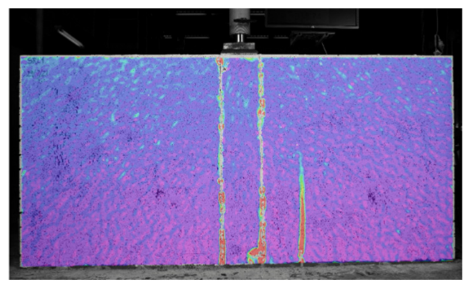
c) RU2 - load dispersion prior to peak load



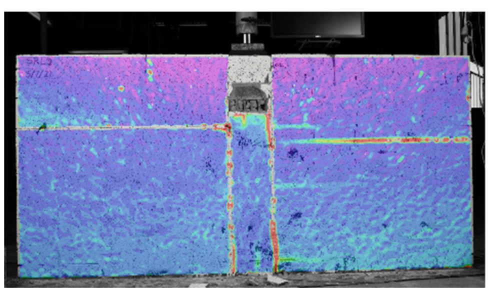
d) RU2 - final failure pattern



e) SU2 - final failure pattern

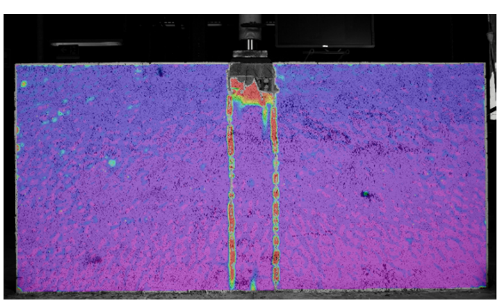


f) SRL1 – just prior to peak load

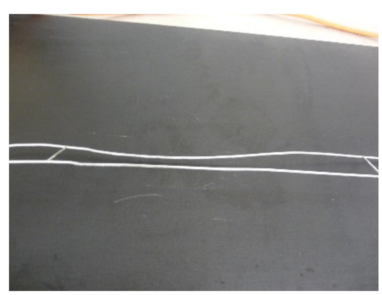


g) SRL2 – final failure pattern

h) SRL1 – top layer of reinforcement post failure



i) SRH1 - final failure pattern



j) SRH2 - top layer of reinforcement post failure

Figure 5: Cracking and Failure Behaviour of Wall Specimens

AS3700 Strength Predictions

Columns (7) and (8) in Table 1 show calculated values of load capacities under concentrated compression load determined in accordance with AS3700 [1]. The reported capacities are the lesser of two values: one defined by crushing immediately beneath the concentrated load (which includes a strength enhancement factor) and another defined by general compressive failure via crushing or buckling in the zone of load dispersion at wall mid-height. In all cases, the capacity for crushing immediately beneath the concentrated load governed. The “AS3700 predicted capacity” (Column (7) in Table 1) is a best estimate of load capacity based on the values of mean masonry compressive strength (f_m) from the prism tests and a capacity reduction factor $\varphi = 1$. The “AS3700 design capacity” (Column (8) in Table 1) is based on characteristic masonry compressive strengths (f'_m) and $\varphi = 0.75$. Columns (9) and (10) show ratios of the predicted or design capacities and the experimentally observed capacity for each specimen. The values AS3700 predicted / experimental capacities are all significantly greater than 1 indicating that the AS3700 [1] best estimate over predicts the observed wall specimen capacities by a large margin. The ratios of AS3700 design / experimental capacities for RU1 and RU2 (for which the AS3700 [1] provisions are intended) are 0.8 and 0.6, indicating safe designs for the running bonded wall type. The ratios of design / exp. also imply safe designs for all SRL and SRH specimens, indicating that the presence of bed joint reinforcement may allow designers to adopt the current code assumptions related to concentrated compression load design. However, the ratios of AS3700 design / experimental capacities for SU1 and SU2 are 1.2 and 1.4 respectively, confirming that unreinforced stack bonded masonry has limited capacity to disperse concentrated compression load and cannot be designed using the current code assumptions.

CONCLUSIONS

The study aimed to investigate the relative performance of stack bonded masonry, with and without bed joint reinforcement, compared to traditional running bonded masonry, when subjected to concentrated compression loads. The following conclusions can be drawn:

- Specimens RU1 and RU2 (unreinforced running bond pattern) displayed the ability of the running bond pattern to transfer vertical shear arising from the concentrated load to the masonry either side of the load and hence disperse the concentrated load along the length of the wall as assumed in design codes.
- The behaviour of the unreinforced stack bonded specimens (SU1 and SU2) confirmed the limited load bearing ability of this form of masonry, the average peak loads resisted being 34% lower than that of the RU specimens. DIC results indicated limited dispersion of the load along the wall prior to the cracks forming, highlighting the inability for the continuous unreinforced vertical joints to transfer vertical shear arising from the application of the concentrated load.
- The presence of the AS3700 [1] minimum required bed joint reinforcement in the SRL specimens resulted in a marked improvement in the structural behaviour compared to the unreinforced stack bonded (SU) specimens. The average peak load recorded for the SRL specimens was almost twice that for the unreinforced (SU) specimens and 24% greater than that for the running bonded (RU) specimens. This behaviour indicates that the presence of bed joint reinforcement bridging the cracks allowed redistribution of the concentrated load within these specimens.
- The inclusion of additional bed joint reinforcement immediately beneath the concentrated compression load (Specimen type SRH) did not improve the peak load resisted compared to the SRL specimens. The reasons for this are not fully understood and are the subject of ongoing research.

- There was no measurable strength enhancement observed immediately beneath the concentrated load for any of the specimens. However, this is thought to relate in part to the choice of loading plate and wall dimensions as the AS3700 [1] enhancement factor for the tested dimensions is close to unity.
- Load capacity predictions determined in accordance with AS3700 [1] significantly over-estimated the observed strengths for the unreinforced stack bonded (SU) specimens confirming that assumptions related to strength enhancement and load dispersion cannot be relied upon for this form of masonry. However, the results indicate that for stack bonded masonry containing the AS3700 [1] minimum specified bed joint reinforcement, the design assumptions related to concentrated compression loading can potentially be adopted.

ACKNOWLEDGEMENTS

This research was conducted in the Civil Engineering laboratories of The School of Engineering at The University of Newcastle. The assistance of the laboratory staff is gratefully acknowledged, as is the support of Think Brick Australia, Brickworks Ltd and Ancon Building Products Pty Ltd.

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