Spatial Correlation of Flexural Tensile Bond Strength in Unreinforced and Ungrouted Concrete Masonry Walls

Lewis J. Gooch[i], Chee Yin Lam[ii], Lyndsey G. Terry[iii], Mark J. Masia[iv], and Mark G. Stewart[v]

ABSTRACT

The flexural tensile bond strength of masonry is critical to defining the out-of-plane bending resistance of unreinforced and ungrouted masonry walls (URM). This is particularly relevant to concrete URM which is often utilised in the construction of retaining walls, load-bearing internal wythes of masonry cavity wall construction, and other structural elements typically subject to out-of-plane loading. Due to its dependence on workmanship, mortar quality and brick/block typology, the flexural tensile bond strength of masonry has been observed to be highly variable. Furthermore, previous investigations of the spatial variability of clay brick masonry indicate that the sequential nature of construction for masonry walls often introduces a correlation between the properties of adjacent mortar joints. Understanding this spatial variability will improve the accuracy of probabilistic models of URM and is an important consideration in a structural reliability-based analysis of URM performance. The current study presents a laboratory investigation in which three concrete masonry walls – two concrete block and one concrete brick – were sequentially deconstructed using the bond wrench test method. From this testing, the spatial variability of the flexural tensile bond strength of each wall specimen has been quantified. Furthermore, the spatial variability of mortar joint thicknesses has also been analysed to quantify the correlation between adjacent joint thicknesses, as well as to assess any relationship between the thickness and strength of individual mortar joints.

KEYWORDS

concrete block, concrete brick, flexural tensile strength, spatial variability, ungrouted, unreinforced

[i] Research Associate, The University of Newcastle, Callaghan, Australia, & University of Technology Sydney, Ultimo, Australia, lewis.gooch@newcastle.edu.au
[ii] Ph.D. Student, The University of Newcastle, Callaghan, Australia, cheeyin.lam@uon.edu.au
[iii] Ph.D. Student, The University of Newcastle, Callaghan, Australia, lyndsey.terry@uon.edu.au
[iv] Professor, The University of Newcastle, Callaghan, Australia, mark.masia@newcastle.edu.au
[v] Distinguished Professor, University of Technology Sydney, Ultimo, Australia, mark.stewart@uts.edu.au

INTRODUCTION

The application of stochastic numerical modelling strategies allows for accurate predictions of masonry behaviour to be determined without requiring expensive and time-intensive physical testing programs. However, an essential part of developing a suitable predictive model is the accurate representation of material parameters. Furthermore, the spatial variability of these properties – i.e.: how the material characteristics change throughout a modelled structure, such as the joint-to-joint bond strength within a masonry wall – is an important consideration, as weaker components within a masonry structure may initialise a cascading failure at a lower applied load than would be captured in a non-spatial analysis.

Previous investigations into the spatial variability of clay brick masonry properties, such as the flexural tensile bond strength by [1-3] and mortar joint thickness by [4, 5] based on the experimental data of [6], has allowed for the variations in material properties to be considered in stochastic numerical modelling strategies (see [7-10]). However, comparably few studies consider spatial variability in concrete masonry structures, such as [11, 12], and in these cases, the degree of correlation between properties has not been derived from experimental testing. The current study, therefore, presents a preliminary investigation into the spatial variability of flexural tensile bond strength and mortar joint thickness in three full-scale unreinforced concrete masonry walls (two ungrouted concrete block walls and one concrete brick wall). The spatial variability of these properties has been quantified via the autocorrelation coefficient, ρ, for application in stochastic numerical models. The value of ρ varies from ±1.0 (a full correlation, i.e.: a perfect linear (or negative linear) relationship such that determining the property of a single joint informs the correlated property for all adjacent joints), to ρ = 0 (no correlation, i.e.: the property of a given joint is independent of those of adjacent joints) [13]. These concepts are highlighted in Figure 1.

Figure 1: Indicative flexural bond strengths of clay brick masonry (shown in MPa) for various correlation coefficients [3].

The correlation coefficient, ρ_k, is determined for a given lag, k, representing the distance between data points in a set (in this case, the distance between bed joints under examination). The current study considers only the spatial correlation of adjacent bed joints, or of correlation between a given joint's strength and thickness, i.e.: $k = 1$ and $k = 0$, respectively.

As discussed by [13], the k^{th} autocorrelation function may be determined as per Equation (1), where N is the sample size, x_i and y_i are the i^{th} data points of the two sets under consideration (either the thickness or bond strength of adjacent joints, or the thickness and bond strength of a given joint), and $\bar{x}$ and $\bar{y}$ are the sample means of x and y, respectively.

$$(1)\quad \rho_k = \frac{\sum_{i=1}^{N-k}(x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^{N-k}(x_i - \bar{x})^2 \sum_{i=1}^{N-k}(y_i - \bar{y})^2}}$$

EXPERIMENTAL TESTING

Masonry Typologies

In this study, experimental tests were performed on three wall specimens, each of three distinct concrete masonry types: 190 mm × 190 mm × 390 mm concrete blocks, 140 mm × 190 mm × 390 mm concrete blocks, and standard Australian dimension concrete bricks (230 mm × 110 mm × 76 mm); see Figure 2. Furthermore, all wall specimens utilised the standardised [14] 1:1:6 (cement: lime: sand, by volume) mortar mix (or approximately 1:0.5:7.6, by mass), and were cured in ambient conditions beyond 28-days prior to testing.

Both concrete block walls utilised face shell bedding, i.e.: the mortar laid only on the outer flanges of the units (see Figure 2(a) and (b)). In this case, the flexural tensile bond strength is estimated in accordance with AS 3700 [14] considering the net bedded area as shown in Figure 2(a) and (b). The concrete brick walls utilised full bedding. Here, the bond strength was conservatively estimated by ignoring the unit perforations and considering the gross section properties of a 230 mm × 110 mm bedded area.

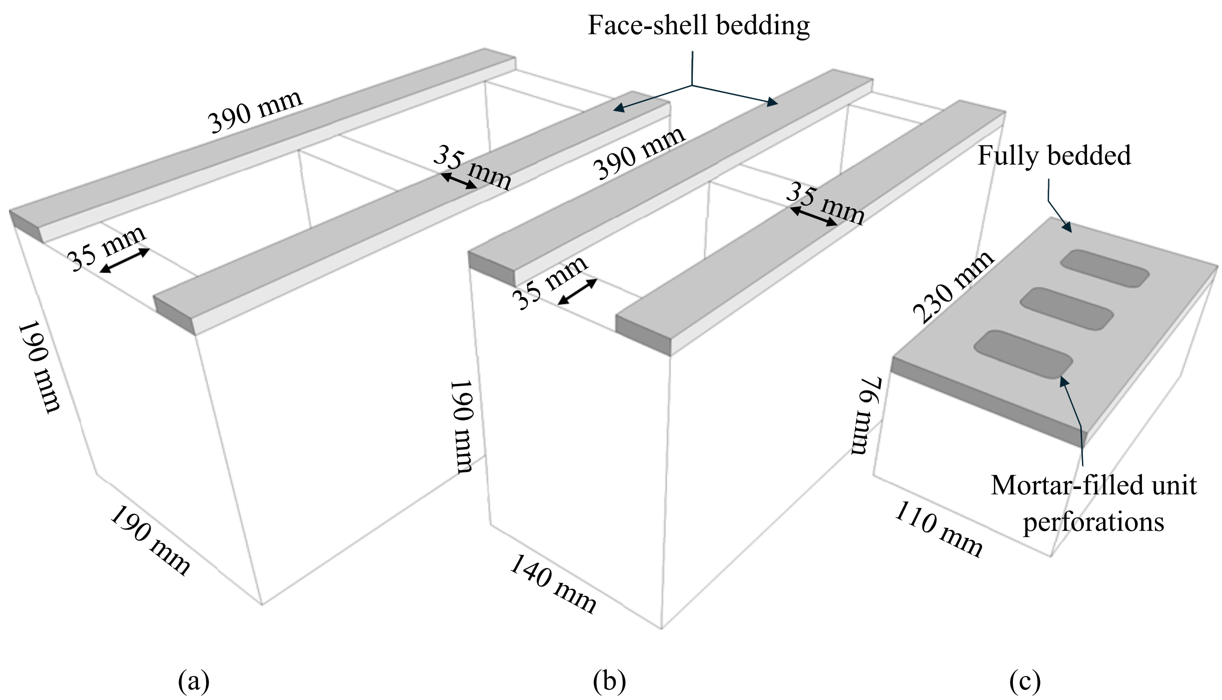
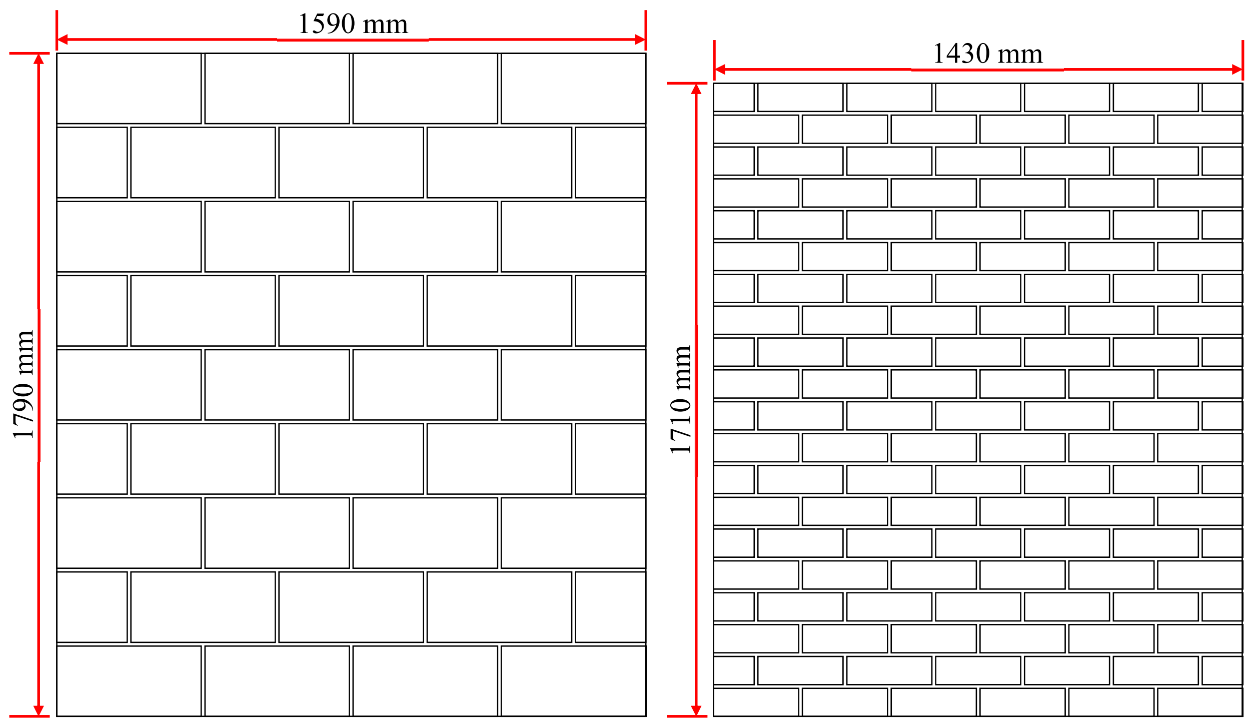


Figure 2: Concrete masonry unit and bedding types.
(a) 190 mm blocks, (b) 140 mm blocks, and (c) bricks

Wall Specimens

The concrete block walls utilised nine courses, laid in a running bond pattern. Each course maintained four full-sized blocks (or three full-sized and two half-sized blocks), as shown in Figure 3(a). Due to the limited number of units in each course, the accuracy of correlation coefficient on a course-wise basis is limited. On-going testing is considering a larger sample size of the presented specimens, and future studies into the spatial variability of concrete block masonry may consider shorter walls (fewer courses) and more units per course, as it is expected that the spatial correlation between successive courses would be negligible [1].

Furthermore, the concrete brick wall similarly utilised a running bond pattern, across a total of 20 courses – each with six full-sized (or five full-sized and two half-sized) bricks, as shown in Figure 3(b). As with the block walls, these course sizes do not represent a significant data set for the course-wise quantification of spatial variability. As such, the results of the current study should be considered as indicative only, and future investigations are planned.



(a) (b)

Figure 3: Nominal wall specimen geometries.
(a) 190 mm and 140 mm block walls, and (b) brick walls.

Bond Wrench Test Method

The flexural tensile bond strength of each bed joint was estimated using the bond wrench test method, as specified by AS 3700 [14]. This test involved first saw cutting the perpend joints adjacent to the bed joint to be tested. This was performed using a carbide-tipped hand saw or diamond-tipped reciprocating saw. A clamp was then attached to the brick or block to be tested, and a bending moment was applied by the gradual application of force. This test method is shown in Figure 4. Note that each wall specimen was bordered by a thin (<10 mm), non-structural parge (see Figure 4(b)) that remained after a series of water penetration tests that were performed on the walls as a part of an unrelated study. This was saw-cut in-line with the bed joints to be tested prior to the application of a bending moment and was present only on the compression edge of the tested joints, limiting its influence on the estimations of flexural tensile bond strength.

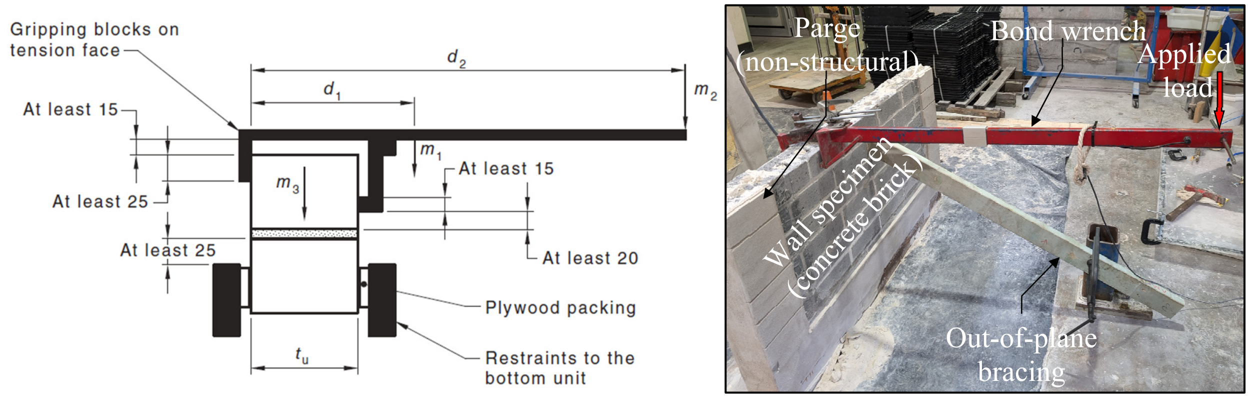


Figure 4: Schematic [14] and test set-up of the bond wrench test.

The force required to induce failure, m_2, was recorded, and the flexural tensile bond strength, f_{sp}, was estimated as:

$$(2)\ f_{sp} = \left(\frac{M_{sp}}{Z_d}\right) - \left(\frac{F_{sp}}{A_d}\right)$$

where M_{sp} is the applied bending moment about the centroid of the bedded area of the examined joint, estimated as per Equation (3), and Z_d is the section modulus of the bedded area about the axis about which the bending moment is applied. Similarly, F_{sp} is the applied compressive force, calculated via Equation (4), and A_d is the total bedded area. Note that Z_d and A_d are calculated based on the net cross-section for face-shell bedded masonry and the gross cross-section for fully bedded masonry (refer to Figure 2) in accordance with AS 3700 [14].

$$(3)\ M_{sp} = 9.81 m_2 \cdot \left(d_2 - \frac{t_u}{2}\right) + 9.81 m_1 \cdot \left(d_1 - \frac{t_u}{2}\right)$$
$$(4)\ F_{sp} = 9.81 \cdot (m_1 + m_2 + m_3)$$

For each individual test, only the value of m_2 is recorded. The remaining variables shown in Equations (3) and (4) are summarised in Table 1.

Table 1: Bond wrench test variables for each masonry type.

Masonry Type	Parameter	Value	Masonry Type	Parameter	Value
190 mm block	t_u	190 mm	Brick	t_u	110 mm
	d_1	469 mm		d_1	389 mm
	d_2	1380 mm		d_2	1300 mm
	m_3	16.2 kg		m_3	3.0 kg
140 mm block	t_u	140 mm	*All*	m_1	8.2 kg
	d_1	419 mm			
	d_2	1330 mm			
	m_3	11.9 kg			

RESULTS

Flexural Tensile Bond Strength

The flexural tensile bond strengths of the tested bed joints are summarised in Table 2. In comparison to clay brick masonry (see [1, 15]), the measured mean bond strengths for the concrete block walls were consistent between types and notably low, 0.05 MPa and 0.07 MPa, with high coefficients of variation (COVs) of 0.52 and 0.56, for the 190 mm and 140 mm blocks, respectively. Furthermore, a bond strength could not be measured for a considerable number of bed joints (31% of the 190 mm block, and 14% of the 140 mm block) as these failed under the self-weight of the bond wrench (equivalent to an applied flexural tensile stress of 0.018 MPa and 0.008 MPa for the 190 mm and 140 mm blocks, respectively) or were cracked due to the testing of courses above. These low bond strengths and correspondingly high COVs may be attributable to load-unload cycles induced from the application of the bond wrench on courses above. The limitation in the testing method was not addressed as it was not practical to rigidly restrain the wall specimens below each joint as it was being tested. It should be noted, however, that the results obtained from the joints in first course of each wall (that were not subject to load-unload cycles) are consistent with subsequent courses. Furthermore, the results obtained from the concrete brick wall were consistent with expectations, with a mean flexural tensile bond strength of 0.52 and COV of 0.43, despite the large number of joints per course (and correspondingly larger number of load-unload cycles for successive courses). This discrepancy in performance cannot be readily attributed to mortar batch quality or workmanship as all three wall specimens were constructed by the same individual bricklayer using the same standardised mortar mix. Similarly, each specimen was cured for a period in excess of 28-days (between two and four months), suggesting that age-time does not account for such a large difference in bond.

These low sample means and COVs for the block wall specimens likely limits the accuracy of the determined correlation coefficients presented in Figures 5 and 7, as the value of ρ_k is sensitive to the sample mean and standard deviation (refer to Equation (1)). This limitation is further exacerbated as the proportional error associated with the bond wrench test will be higher for lower bond strengths.

Table 2: Measured flexural tensile bond strengths.

Specimen	Flexural Tensile Bond Strength (f_{tb})		
	Sample Size	***Mean (MPa)***	***COV***
190 mm block	25	0.05	0.52
140 mm block	31	0.07	0.56
Brick	93	0.52	0.43

Further to the measured bond strengths, the correlation coefficient for adjacent flexural tensile bond strengths ($\rho_{k=1}$) has been determined for each course of the tested wall specimens. In the cases of the block walls, the determined values of $\rho_{k=1}$ are based on a limited data set, as each course had, at most, five measurable mortar joints. However, the results from these specimens were consistent with the concrete brick wall which maintained up to seven mortar joints per course, and maintained a similar range of values to that reported by [1] for clay brick masonry (see Figure 5). Here, values of $\rho_{k=1}$ ranged from -0.95 to 0.59, with a median value of -0.25 and -0.09 for the block and brick walls, respectively. This large spread in values for $\rho_{k=1}$ is not unexpected for masonry material properties that are typically highly variable. However, the median values of $\rho_{k=1}$ are indicative of a statistically independent relationship, rather than the weak correlation of $\rho_{k=1}$ = 0.4 observed by [1, 3] for clay brick masonry.

While a larger course-wise sample size of bond strengths should be examined to verify the observations made in this study, the results summarised in Figure 5 indicate that statistical independence may most accurately represent the spatial variability of flexural tensile bond strengths in concrete masonry structures.

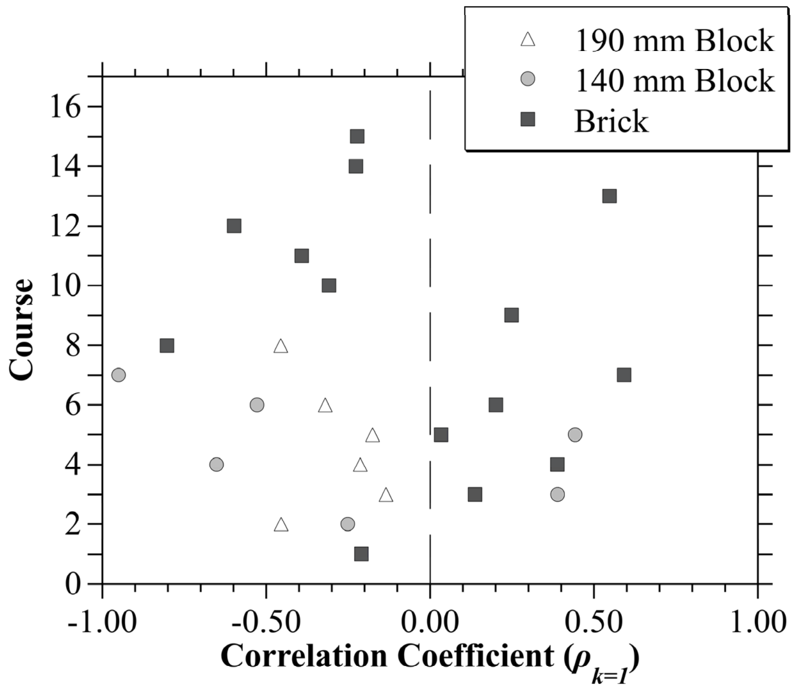


Figure 5: Correlation coefficients for adjacent (*k* = *1*) flexural tensile bond strengths.

Mortar Joint Thickness

The thicknesses (vertical height) of all of the mortar joints tested under flexural tensile loading were measured prior to failure – with some exceptions where joints were failed due to loading of courses above. The measured joint thicknesses are summarised in Table 3. These values indicate that the nominal joint thickness of 10 mm adopted for each specimen was reasonably well satisfied, with mean values ranging from 9.5 mm to 10.9 mm, and COVs between 0.11 and 0.13. Furthermore, it is notable that the determined COV for each wall specimen is lower than that for clay brick masonry, as reported by [6]. While the dataset presented by [6] is comprised of more than 1,700 individual joint measurements, the 217 joint measurements presented in the current study is still significant, suggesting that a greater level of precision was achieved for all three concrete wall specimens. Furthermore, the influence of unit height variability is negligible, as the variability of unit height is of the order of a COV = 0.02 [5].

Table 3: Measured mortar joint thicknesses.

Specimen	Mortar Joint Thickness (t_j)		
	Sample Size	*Mean (mm)*	*COV*
190 mm block	34	9.5	0.13
140 mm block	36	10.2	0.11
Brick	97	10.9	0.11

As with the measured flexural tensile bond strengths, the correlation coefficient between adjacent mortar joint thicknesses ($\rho_{k=1}$) has been determined. These results are indicative of a weak, or statistically insignificant correlation between mortar joint thicknesses, with values of $\rho_{k=1}$ ranging from -1.0 to 0.51 (see

Figure 6), and a median value of -0.17. This result is consistent with the findings of [4] for clay brick masonry, which found that course-wise correlation coefficients ranged from approximately -0.70 to 0.90, but were typically grouped close to $\rho_{k=1} = 0.15$. Hence, as with the flexural tensile bond strength, statistical independence may best represent the spatial variability of mortar joint thickness in concrete masonry walls.

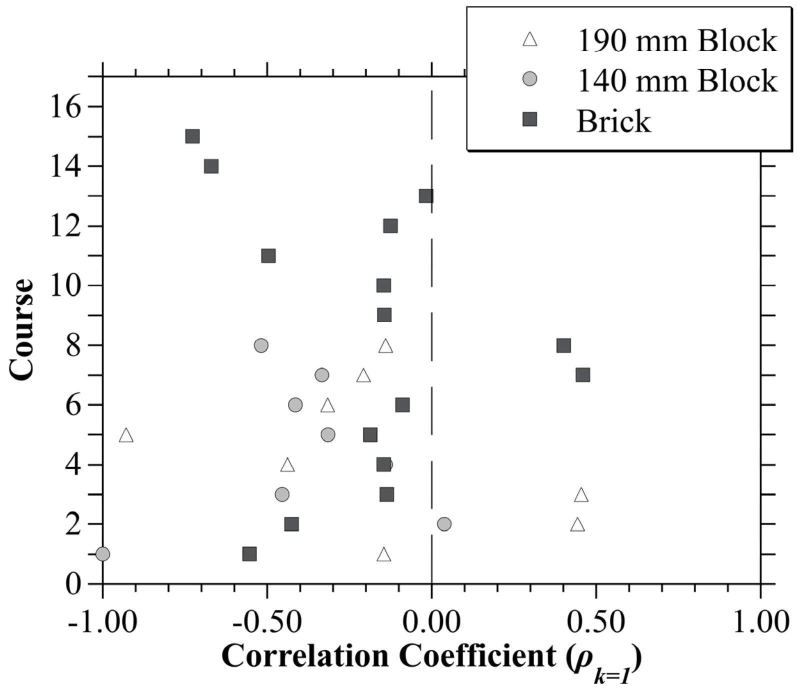


Figure 6: Correlation coefficients for adjacent (*k* = *1*) mortar joint thicknesses.

Correlation of Joint Strength and Thickness

Finally, the correlation between flexural tensile bond strength and mortar joint thickness has been investigated. The correlation between masonry strength and mortar joint thickness has been investigated in a number of previous studies of both clay and concrete masonry. The study by [16] suggests that there is no significant correlation between the masonry compression strength and mortar joint thickness for prisms constructed of typical concrete masonry blocks. However, a strong negative correlation is observed for high-strength concrete blocks. Similarly, [6] suggests that the compression strength of clay brick masonry is inversely proportional to the thickness of mortar. Furthermore, the study by [17] (as cited in [18]) presents a strong negative correlation between joint thickness and flexural tensile bond strength.

These findings suggest that the strength of masonry may be correlated to the stiffness of the mortar, or of the unit-mortar interface. For the flexural tensile bond strength of masonry, the unit-mortar interface stiffness is of greater relevance than the stiffness of the mortar itself as failure at this interface, and not within the mortar or unit itself, defines the bond strength. As discussed by [19], this interface stiffness is inversely proportional to the thickness of the mortar joint (t_j). As such, the coefficients presented in Figure 7 represent the course-wise correlation between the flexural tensile bond strength (f_{tb}) and the inverse of the mortar joint thickness (t_j^{-1}).

The determined values of $\rho_{k=0}$ range from -0.82 to 0.84, with median values between 0.10 and 0.20. This value of ρ is representative of a significantly weaker correlation than those presented by [6, 16, 17], and, based on the limit sample size, would be considered as statistically insignificant by the limiting value of

$2\sqrt{1/n}$ proposed by [20, 21] (as cited in [1]). However, these results, and the findings of others, indicate that some correlation may be present between mortar joint thickness and unit-mortar bond strength. Further testing is recommended to very this conclusion.

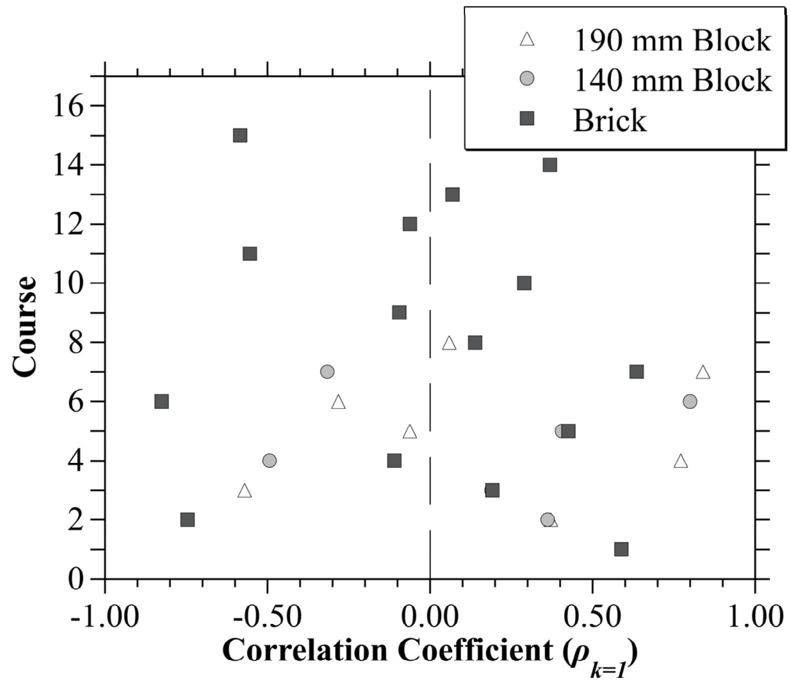


Figure 7: Correlation coefficients between flexural tensile bond strength (f_{tb}) and the inverse of mortar joint thickness (t_j^{-1}) for a given mortar joint ($k = 0$).

CONCLUSIONS

This paper presents the results of an experimental assessment of the correlation between the concrete brick and block masonry material properties of three full-scale wall specimens. These results indicate that the correlation between flexural tensile bond strengths of adjacent mortar bed joints is statistically insignificant in concrete brick and block masonry. Similarly, the thickness of adjacent mortar joints showed no statistically significant correlation for the range of joint thicknesses tested. These findings are largely consistent with those for conventional clay brick masonry structures.

Further to the assessments of correlations between adjacent mortar joints, the correlation between the flexural tensile bond strength and joint thickness of each individual mortar joint was examined. Previous investigations correlating mortar joint thickness with masonry compression or tensile bond strengths indicate that a relatively strong correlation may be present. While the findings of this study suggest that the statistical relationship between the thickness and bond strength of a given joint may be more significant than those between adjacent joints, course-wise correlation coefficients relating these properties ranged from -0.82 to 0.84, with median values ranging from 0.10 to 0.20 for brick and block masonry walls, indicative of a statistically insignificant correlation.

These findings comprise an initial study into the spatial variability of concrete masonry material properties. The testing of additional full-scale wall specimens is underway to develop the conclusions presented in this study. Furthermore, a key limitation to the findings of the current study is the limited data available for a course-wise assessment of material correlations. As such, future studies that consider longer wall specimens (more bed joints per course) may produce more consistent and accurate estimations of the correlation between the properties of unreinforced and ungrouted concrete masonry.

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