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Improving the lateral load resistance of vernacular masonry walls subject to flooding

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Abstract

Low rise vernacular masonry buildings are vulnerable to damage from extreme flooding. This paper presents findings from a study based in Sri Lanka assessing the structural resilience of non-engineered single storey houses constructed with either fired clay brickwork and cement block masonry walls. A structural survey of flood damaged houses enabled characterisation of masonry materials, and development of proposals to improve the lateral load capacity of masonry walls. The structural survey revealed that a combination of low-quality masonry units and variable thickness of mortar beds may have contributed to flexural failure due to the hydrostatic pressures during flood events. An experimental programme investigated the impact of differing masonry units and mortar thickness on masonry properties under dry and saturated conditions. A simple retrofit method has been developed, using reinforced renders, enhancing sectional flexural capacity by over 11 times, offering greater resilience to lateral flood loads. The impact of the research will have direct welfare benefits for Sri Lankan's living in flood risk areas, reducing the risk of structural collapse and enabling people to safely remain in their homes during flood events.

Keywords:

Brick; Cement block; Flexural strength; Flooding; Masonry; Mortar.

1 Introduction

In 2016 and 2017 the tropical lowlands of Sri Lanka experienced devastating in-land flooding caused by extreme rainfall events. The high rainfall gave rise to flood waters, landslides and flash floods. These events led to significant loss of life and damage to many single storey houses built using unreinforced loadbearing masonry. Extreme weather events are becoming increasingly common in many countries around the world, and especially those closest to the Equator, often affecting the most vulnerable members of society. In many rural areas of developing countries, unreinforced masonry structures, often using variable quality, but low strength materials, are the dominant form of construction [Bhattacharya et al. 2014]. As a consequence of climate change and urbanisation, the frequency of extreme flooding can be expected to increase in the coming years and infrastructure resilience needs to be improved. There is a need to retrofit existing low-rise vernacular masonry structures to avoid structural failures and fatalities as a result of natural disasters [Papanicolaou et al. 2011].

There are differing approaches to reducing the impact of flooding that broadly involve improving either resistance or resilience. Houses that are flood resistant prevent flooding of the space, and therefore allow operation to continue largely unaffected during and after the event. However, flood resilient buildings allow flood waters to enter the house without causing permanent damage, thus maintaining structural integrity, and allowing normal use to resume once the flood waters have receded. Many of the vernacular low-rise houses in Sri Lanka, and elsewhere, are neither flood resistant nor resilient, as seen from the typical damage in the 2016 and 2017 floods (Figure 1).

Figure 1. Flood damaged masonry house, Sri Lanka, 2017

To date a variety of approaches have been developed to retrofit and strengthen unreinforced masonry structures [Ingargiola and Moline 2013; Herbert et al. 2012]. Surface treatments are used to increase flexural strength and water ingress and typically involves rendering the wall, some incorporating a mesh. The render is often based on cementitious mixes, while the meshes are either metallic or textile. Fibre Reinforced Polymers are an alternative approach that are increasing being considered, but the cost and availability within ODA recipient countries remains questionable [Triantafillou, 1998]. Alternatively, prestressing ties can be added either internally or externally that help to prevent the masonry failing through flexural induced tension, however there are concerns over the cost of the retrofit within the given context.

Retrofitting approaches have mainly considered strength enhancement under dry conditions with only a few studies investigating the combination of out-of-plane loading with the material in saturated conditions [Herbert et al 2018].

Factors that influence performance of masonry walls in flood events have been summarised by Bowker & Wallingford (2005) including: hydrostatic effects; hydrodynamic effects; erosion; buoyancy; damage from debris; non-physical effects (e.g. chemical changes; biological growth); and effects from direct water contact. However, Kelman and Spence (2004) suggest that the most important effects in flood damage are the lateral hydrostatic forces, lateral hydrodynamic forces, and the effects of direct water contact.

The overall aim of the study presented in this paper has been to explore affordable strategies to improve the resilience of low-rise masonry structures, and communities, to extreme flooding events in Sri Lanka. To meet this aim the work had the following four objectives:

1. Survey the flood affected areas to evaluate, characterise and quantify the extent and nature of structural damage to low rise masonry houses.
2. Characterise the mechanical properties of the Sri Lankan vernacular masonry materials.
3. Investigate the influence of variable mortar thickness on the properties of masonry built using low strength units.

4. Propose and evaluate potential retrofitting measures to improve lateral load capacity of vernacular masonry.

2 Surveys on flood damaged houses

From February to April 2018 a survey of the affected regions from the 2017 Sri Lankan floods was conducted. Three districts in the Western and Southern provinces were particularly affected by these floods: Kalutara (flooded area 223 km^2); Galle (62 km^2); and, Matara (122 km^2). Householder surveys were undertaken to record various structural impacts of the flooding, including: location; age and building typology; materials; nature of structure. In this paper the survey findings concerning materials use and flood damage are briefly summarised. The survey was carried out jointly by researchers from the University of Moratuwa and the National Building Research Organization (NBRO) of Sri Lanka.

In total, 154 households were surveyed, with, 94% of the residential buildings having been built using loadbearing masonry walls, with the remainder primarily constructed from reinforced concrete frame with masonry in-fill construction. The masonry materials were split equally between fired clay brick masonry (a locally produced cottage industry style brick commonly found in Sri Lanka) and cement sand block masonry (a relatively low strength solid cement block, with no large aggregate, commonly found throughout Sri Lanka). The walls in the single storey houses were typically less than 100 mm thick masonry units (both fired clay bricks and cement blocks) typically with cement-sand mortars of thicknesses varying between 10-25 mm thick. The walls were usually plastered or rendered inside and out with a cement-sand mortar mix around 15-20 mm thick, and subsequently painted. The typical total wall thickness therefore rarely exceeds 135 mm, which is less than the 200 mm minimum thickness recommended by Sri Lankan building standards for masonry units in external walls [Nawagamuwa & Perera 2015]. This general lack of compliance enhances the need for retrofitting and strengthening.

In 83% of buildings surveyed in the flood affected regions, the flood waters reached at least 2 metres high. Damage to masonry walls and buildings from the flooding characterised during the field survey included: cracking/failure between adjoining walls (Figure 2); cracking along solid walls (Figure 3); cracking/failure around openings (Figure 4); and total wall collapse (Figure 5).

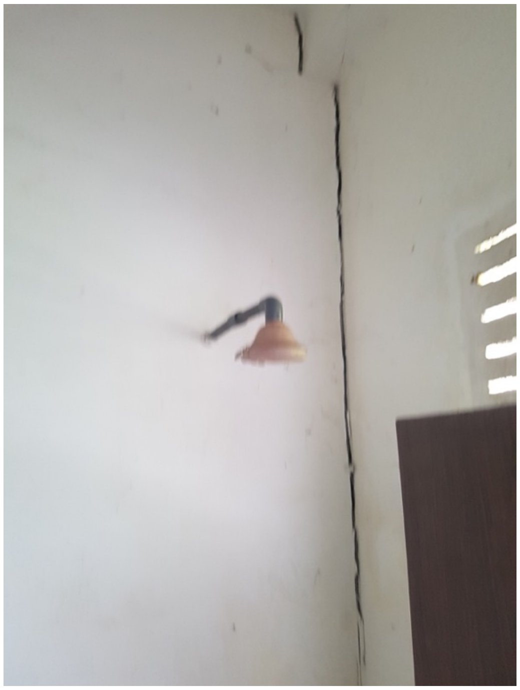

Figure 2. Cracking between adjoining walls

Figure 3. Cracking in solid wall

Figure 4. Cracking around opening

Figure 5. Total wall collapse

Many walls also showed moisture ingress, leading to subsequent mould growth, as well as cracking of plaster and masonry. Cracking, and failure, of walls was likely caused by many interconnected factors unique to each site. However the majority of the damage can be attributed to an out-of-plane flexural failure due to the presence of horizontal flexural cracks commonly observed in the field survey. This is most likely due to the hydrostatic lateral pressures from the water inducing flexural failure parallel to the bed joint as well as a reduction in material strength due to the ingress of moisture into the masonry. Addressing this is the focus of the experimental programme.

3 Experimental Programme

3.1 Materials

Initially the experimental programme reported here comprised characterisation of representative vernacular masonry materials, including unit, mortar and masonry properties. This included an experimental study of the influence of mortar bed joint thickness on masonry flexural and compressive strength. Thereafter, the study considered simple retrofitting measures to improve flexural resistance to hydrostatic loads using plain and reinforced plasters.

3.1.1 Masonry units

Surveys of the affected regions of the Sri Lankan floods confirmed that the majority of masonry construction in housing is primarily single leaf loadbearing wall panels, but that masonry is also used for in-fill panels in reinforced concrete frame structures. The masonry is either fired clay brickwork or cement block masonry, with the manufacture of both masonry unit types a decentralised largely unregulated cottage industry.

Representative samples of both the clay bricks and cement blocks were obtained from a single supplier on the outskirts of Moratuwa, in the western province of Sri Lanka, 17 km south of the capital city Colombo. The fired clay bricks were solid units with nominal dimensions 220 mm (length) x 105 mm (width) x 65 mm (height). The cement blocks were solid but frogged (recessed) on one (bottom) bed face and also on both vertical edges. The cement blocks are manufactured using electrically vibrated machines and the constituents generally comprise cement, sand, and quarry dust. The nominal dimensions of the cement blocks were 400 mm (length) 100 mm (width) x 200 mm (height). The fired clay brick and cement blocks used are shown in Figure 6.

Figure 6. Masonry units

3.1.2 Mortar

Masonry wall panels were built to determine the flexural and compressive strength of the cement block and fired clay brick masonry using representative materials. The wall panels were built using the same mortar mix commonly used in Sri Lankan practice, a 1:6 cement: sand mortar using Ordinary Portland Cement and a river sand fine aggregate. The sieve analysis results for the sand are shown in Figure 7.

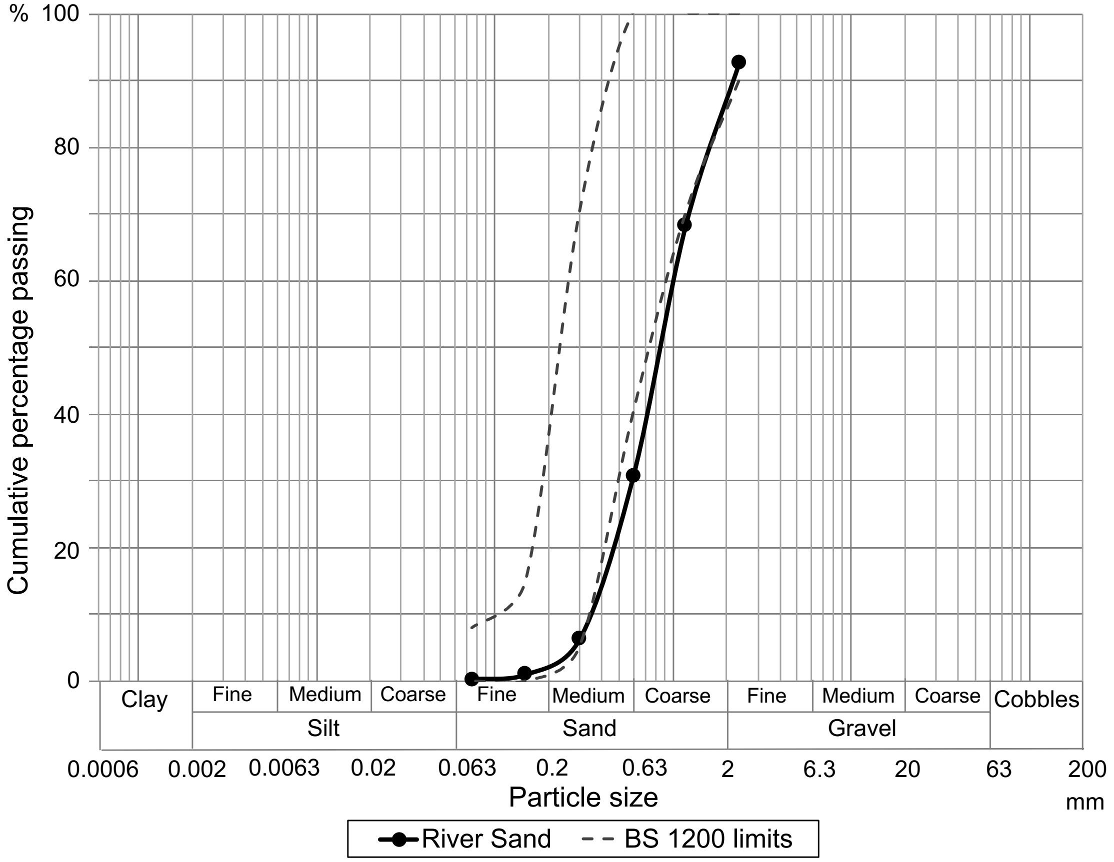

Figure 7. Sand composition related to BS1200 requirements

The mortar was mixed manually by experienced local bricklayers. The water content of the mortar mix was controlled by the masons for workability, but the flow table (BS EN 1015-3: 1999) was used to assess consistency with, the average flow for the fresh mortars was 125 mm (Coefficient Of Variation (CoV) = 11.7%).

3.1.3 Masonry wall panels

The field survey identified a wide variation in mortar bed joint thickness, reflecting the poor dimensional regularity of the units and the variable quality of the works. To investigate the influence of mortar joint thickness compressive strength panels were built in three series for both the fired clay bricks and cement blocks, each having bed joints nominally 10 mm, 17.5 mm and 25 mm (± 3mm) thick.

In keeping with common Sri Lankan practice, the clay bricks were immersed in water for 5 minutes prior to laying to account for their high water absorption, whereas the cement blocks only wetted just before laying, thereby reducing the dewatering effects of the masonry unit on the mortar. Immersion resulted in average moisture contents at laying of the units of 2% for cement blocks and 14% for fired clay bricks.

3.1.4 Materials used for Retrofitting

In Sri Lanka, and many other areas with tropical climates, single leaf masonry panels are typically plastered (internal application) or rendered (external application) to improve resistance to moisture ingress as well as their aesthetics. In Sri Lanka masonry wall surface coatings, such as internal plasters and external renders, are both commonly formed using a 1:5 cement to sand ratio mix. This mix, slightly richer than that used for the mortar joints, is commonly applied in one or two coats up to 15-20 mm total thickness. These surface coatings will likely increase the flexural capacity of the walls which, together with the inclusion of reinforcement, could sufficiently improve capacity to resist flood loads. Using reinforced surface coats with unreinforced masonry walls is not included in current practices in Sri Lanka. The application of the unreinforced and reinforced surface coating to low strength vernacular masonry, with consideration of the socio-techno-economic climate, has been investigated as a method of improving the lateral load resilience.

A PVC coated galvanised mild steel wire mesh, (widely available from local hardware stores and building merchants) was selected (Figure 8). The square mesh, manufactured in Sri Lanka, is comprised of 0.81 mm diameter wires spaced at 12.5 mm openings. Normally used as a lightweight material for a variety of domestic uses, it was selected for its low cast, ease of handling, and readily availability throughout Sri Lanka. Welded wire mesh products tend to be orthotropic due to their production process where the longitudinal wires (machine direction - *md*) are under tension as the cross wires (cross machine direction - *cmd*) are welded in place.

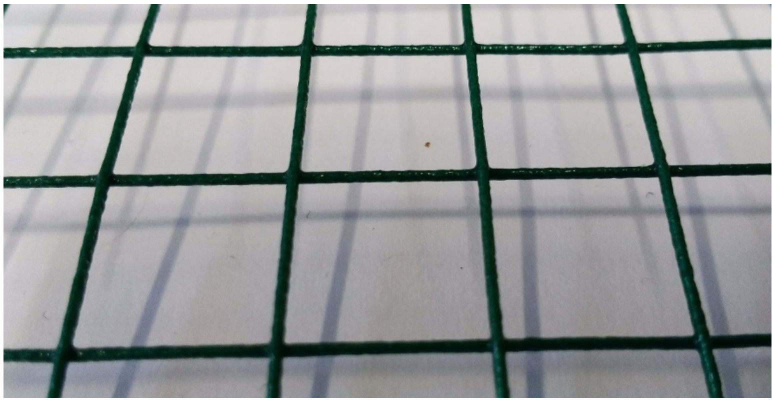

Figure 8. PVC coated welded wire mesh

The selected mesh was tested in uniaxial tension. For each direction, 10 wires 140 mm in length were cut from a single roll of PVC coated welded wire mesh (PWWM) from edge and central regions of the roll. The strain was determined by using a clip gauge placed in-between the welds and on top of the PVC coating. The experimental properties of the mesh are reported in Table 1.

Table 1. PVC coated welded wire mesh properties (n = 6)

Property	*md*	*cmd*
Diameter of wire – mm (CoV)	0.574 (1.9%)	0.575 (2.5%)
Thickness of PVC coating – mm (CoV)	0.074 (16.8%)	0.076 (6.9%)
Tensile capacity per meter length - kN/m (CoV)	19.1 (4.7%)	16.4 (3.2%)

** *md* = machine direction, *cmd* = cross machine direction

A 17 mm thick 1:5 cement:sand plaster coating was applied in two coats: an initial scratch coat of 10-12 mm thickness followed by a 5-7 mm thick topcoat. The surface coating was applied only to one face of the panels; the face subjected to tension during testing. The surface coating was the same material as that used for the mortar. The PVC coated mesh was applied to the selected panels by pressing the mesh into the scratch coat prior to the addition of the topcoat after an initial 14 days of curing and then allowed to cure an additional 28 days before testing.

3.2 Test Methods

3.2.1 Masonry Units

The following material characterisation tests were conducted: density, initial moisture absorption; total water absorption; unit compressive and flexural strength (under dry and saturated conditions). Following unit tests, a series of masonry tests were completed to determine flexural and shear strength.

Prior to characterisation samples of the cement blocks and fired clay bricks were oven dried at 105°C until stable mass was achieved prior to establishing their density. Initial Rate of Absorption (IRA) was also conducted in accordance with BS EN 772-11 (2000); a sample of ten units were each individually placed bed face down into 3 - 5 mm deep water for 1 minute. The change in mass of each unit was measured following removal from the water tank and removing any excess surface moisture. Following the IRA test the units were then immersed in water for 24 hours to establish their Total Water Absorption (TWA) with the change in mass measured again. Dry and saturated samples of both units were also subjected to compressive strength characterisation tests in accordance with BS EN 772-1 (2015). In preparation for testing, the frog in the cement blocks was filled with 1:3 (cement: sand) mortar.

3.2.2 Mortar

Characterisation testing of the mortars prepared for the prism tests included: flexural and compressive strength, measured in accordance with BS EN 1015-11: 1999.

Specimens measuring 40 x 40 x 160 mm were prepared in triplicate. These were first tested in flexure, with the two broken sections used for compressive strength resistance.

3.2.3 Masonry Panels

Plain (un-retrofitted) masonry panels were tested under compression and flexure independently. The retrofitted samples were tested under flexure only. All tests were undertaken with the two different masonry units, with five repeat tests completed for each type. All panel types were tested under laboratory air dry conditions, with some selected samples all tested saturated, following 24 hours submersion in water. The plain masonry panels were constructed with the three mortar thicknesses, whereas the retrofitted panels were constructed using only a single joint thickness of 17.5 mm. In total 30 panels were constructed for compressive strength testing and 60 panels for the flexural strength tests. These are summarised in Table 2. An additional five panels for each masonry unit were constructed with 17.5 mm bed joints for testing under saturated conditions. The masonry panels were cured in the laboratory and tested from 28 days after construction. The masonry panels were constructed at different times and while a standard mortar mix was used, samples of mortar was taken for each experimental variation.

Table 2. Summary of masonry tests

Test	**Cement block masonry**	**Fired clay brick masonry**
Plain masonry tests:		
Air dry compressive strength	15 tests: 5 each with mortar thickness 10 mm, 17.5 mm and 25 mm.	15 tests: 5 each with mortar thickness 10 mm, 17.5 mm and 25 mm.
Air dry flexural strength (parallel to bed joint)	15 tests: 5 each with mortar thickness 10 mm, 17.5 mm and 25 mm.	15 tests: 5 each with mortar thickness 10 mm, 17.5 mm and 25 mm.
Air dry flexural strength (perpendicular to bed joint)	15 tests: 5 each with mortar thickness 10 mm, 17.5 mm and 25 mm..	15 tests: 5 each with mortar thickness 10 mm, 17.5 mm and 25 mm.
Saturated flexural strength (parallel to bed joint)	5 tests with 17.5 mm mortar joint	5 tests with 17.5 mm mortar joint
Strengthened masonry tests		
Air dry unreinforced render coat	5 tests with 17.5 mm mortar joint	5 tests with 17.5 mm mortar joint
Wire mesh reinforced render	5 tests with 17.5 mm mortar joint	5 tests with 17.5 mm mortar joint

Two unit wide stack bonded wall panels were built to establish the compressive strength of the cement block and fired clay brick masonry (Figure 9). The fired clay brick panels were five courses high, whilst the cement blocks were three units high.

Figure 9. Masonry prism construction

The vertical compression testing was undertaken in accordance with BS EN 1052- 1- 1999. The walls were loaded at a rate of 0.09 N/mm^2/min with all failures occurring within 15 minutes.

Flexural strength was determined in accordance with BS EN 1053-2:1999 for both parallel and perpendicular to the bed joint. For parallel flexure the panels of burnt clay bricks were of length equivalent to two units and the height equivalent to seven courses. For the cement blocks, the length was equivalent to 1.5 units long and the height was equivalent to three courses. After the completion of each panel, further units were stacked on top to provide a precompression load approximately equal to 2.5 x 10^{-3} N/mm^2. The panels were tested under four-point loading laterally, as shown in Figure 10, in accordance with BS EN 1052-2:1999. Lateral loading was applied at a steady rate equivalent to 0.03 N/mm^2/min.

Figure 10. Parallel to bed joint flexural test

Investigating the flexure perpendicular to the bed joint required different panel sizes. The fired clay brick panels were four units wide and four courses high. The cement blocks were 2½ units long by three courses high. After the completion of each panel, further units were stacked on top to provide a precompression load approximately equal to 2.5×10^{-3} N/mm^2. The panels were tested under four-point loading laterally in accordance with BS EN 1052-2:1999. Lateral loading was also applied at a steady rate equivalent to 0.03 N/mm^2/min.

4. Results and analysis

4.1 Masonry units

The water absorption characteristics and compressive strength properties for the cement blocks and fired clay bricks are summarised in Table 3. The initial rate of water absorption for both units is very high and likely to be detrimental to bond strength between the units and mortar. The relatively poor quality of the units is also reflected in their variability in performance, with Coefficients of Variation (CoV) in excess of 20% (Table 3). Both masonry units present low compressive strength and when normalised to account for the shape factor are not statistically different based on a ‘t test’. Similarly the normalised performance, which accounts for their state of saturation, shows there is no statistical difference between the dry and saturated cement blocks, but there is statistically difference to the performance of the fired clay bricks. The normalised compressive strengths (BS EN 772-1) are both less than 4.0 N/mm^2, but both comply with local building regulation requirements for single storey construction of 1.2 N/mm^2

for the cement blocks and 2.8 N/mm^2 for fired clay bricks. However, neither would be deemed suitable for two storey load-bearing masonry, where requirements increase to 2.5 N/mm^2 and 4.8 N/mm^2 for the block and brick respectively, according to the national regulations in Sri Lanka. The moisture contents for the air-dry cement block and fired clay brick samples were 1.5% and 3.3% respectively.

Table 3. Masonry unit properties

Property		Cement block		Fired clay brick	
		Average[1]	CoV	Average[1]	CoV
Dry density (kg/m^3)		1587	2.2%	2031	0.6%
Compressive strength (N/mm^2)	Dry, f_u (f_b [2])	2.26 (*2.29*)	25.8%	4.38 (*2.74*)	21.0%
	Saturated, f_u (f_b [2])	1.55 (*2.35*)	23.7%	4.14 (*3.84*)	12.9%
Flexural strength (N/mm^2)	Dry	0.404	42.7%	0.514	27.7%
	Saturated	0.262	39.4%	0.415	29.2%
Total water absorption (%)		10.0	20.6%	18.6	12.8%
Initial Rate of Absorption (kg/m^2.min)		4.31	15.2%	4.71	44.3%

[1] Average six test specimens

[2] Normalised unit strength in accordance with BS EN 772-1.

4.2 Mortar

Due to the range of mechanical testing undertaken, the flexural and compressive strength properties of the 1:6 cement:sand mortar were measured for each test and are presented together with masonry test results below. This resulted in 60 specimens across 20 sample series with three specimens cast for each sample series. The mortar strengths are presented alongside the masonry test results below. Specimens were mostly tested between 28 and 35 days old, always coincident with testing of the masonry panels. The average 28-35 day dry compressive strength was 5.97 N/mm^2

(Coefficient of Variation 15.9%), which is significantly stronger than the masonry units. General practice in masonry recommends that mortar is weaker than the units. This assists in reuse of the masonry units but also ensures cracking will generally occur within the joints, rather than through the units, easing any necessary repairs. However, with weaker masonry units, there could be a tendency to rely on stronger mortar since the thickness of the mortar bed is also generally greater than the usually recommended 10 mm.

4.3 Masonry Panels

4.3.1 Compressive strength

The compressive strength properties of the cement blockwork and fired clay brickwork prisms are presented in Table 4. The average mortar compressive (f_m) and flexural (f_{mt}) strengths are also included. Tests were only completed under air-dry conditions. The characteristic compressive strength has been calculated in accordance with BS EN 1052-1:1999. Failure of the wall panels in compression was preceded by vertical cracking of masonry units prior crushing of the materials (Figure 11).

Table 4. Compressive strength of masonry panels

Bed joint thickness (mm)	Cement block masonry					Fired clay brickwork				
	Mortar properties		Masonry compressive strength			Mortar properties		Masonry compressive strength		
	f_m (N/mm^2)	f_{mt} (N/mm^2)	Average (N/mm^2)	CoV	f_k (N/mm^2)	f_b (N/mm^2)	f_{mt} (N/mm^2)	Average (N/mm^2)	CoV	f_k (N/mm^2)
10 mm	9.08	2.61	1.70	19.6%	1.42	6.01	2.02	2.43	20.8%	2.03
17.5 mm			2.08	4.1%	1.73			2.50	12.6%	2.08
25 mm			2.03	13.8%	1.69			2.38	5.8%	1.98

Figure 11. Brickwork prism failure in compression tests

The experimentally derived characteristic masonry compressive strength can be compared with that predicted by EuroCode 6 (BS EN 1996: 2005). Taking the mortar compressive strengths in Table 4 and f_b values from Table 3, the predicted characteristic compressive strengths f_k are 1.7 N/mm^2 and 2.2 N/mm^2 for the cement block masonry and fired clay brickwork respectively. The predicted values for both masonry types compare quite favourably with the experimental values.

4.3.2 Flexural strength

The results for flexural strength parallel to bed joints are summarised in Table 5. The average mortar compressive (f_m) and flexural (f_{mt}) strengths are also included. A representative failure mode in testing is shown in Figure 12 with failures most commonly at the interface between the mortar and unit. Therefore, it is expected that the bond strengths are consistently lower than the flexural strengths of the mortar (Table 4). In accordance with the testing standard, any panels where failure was observed outside of the constant moment region have been excluded from the results.

After testing the panel series under dry conditions, a separate series of panels were constructed under similar conditions but only with 17.5 mm bed joints. These panels were fully submerged in water for 24 hours before testing, but after their initial 28 day curing period, to represent static flooding conditions.

Table 5. Parallel to bed joint flexural strength test results

Bed joint thickness (mm)	Cement block					Fired clay brickwork				
	Mortar properties		Flexural strength			Mortar properties		Flexural strength		
	f_m (N/mm^2)	f_{mt} (N/mm^2)	Average (N/mm^2)	CoV	f_{xk1} (N/mm^2)	f_m (N/mm^2)	f_{mt} (N/mm^2)	Average (N/mm^2)	CoV	f_{xk1} (N/mm^2)
Dry tests										
10 mm	5.92	2.59	0.15	22.7%	0.10	5.69	2.35	0.20	20.3%	0.13
17.5 mm			0.15	37.9%	0.10			0.30	29.8%	0.20
25 mm			0.12	11.8%	0.08			0.31	24.5%	0.21
Saturated tests										
17.5 mm	8.37	1.71	0.14	36.6%	0.09	8.37	1.71	0.08	30.3%	0.06

Figure 12. Parallel bed joint flexural test failure

The UK National Annex for BS EN 1996:2012 specifies characteristic flexural strengths (f_{xk1}) as a function of unit total water absorption and mortar grade for clay brickwork, and a function of unit type, unit compressive strength and mortar grade for concrete block masonry. For the experimental materials the code values for f_{xk1} are 0.25 N/mm^2 for the cement blockwork and 0.3 N/mm^2 for the brickwork; both are significantly higher than the measured values.

The parallel to bed joint saturated flexural strengths for the cement block masonry and fired clay brick decreased by 10% and 72% respectively. As parallel flexure was determined to be the critical failure mode, both experimentally from dry results and observations from the field study, no saturated tests were carried out for flexural strength perpendicular to the bed joint.

The results for flexural strength perpendicular to bed joints are summarised in Table 6. The average mortar compressive (f_m) and flexural (f_{mt}) strengths are also included. Typical failure in testing is shown in Figure 13, with cracking observed at joint interfaces but also through the masonry units. The measured values for the brickwork were significantly lower than the value (0.9 N/mm^2) predicted by NA BS EN 1996:2012.

Table 6. Perpendicular to flexural strength test results

Bed joint thickness (mm)	Cement block					Fired clay brickwork				
	Mortar properties		Flexural strength			Mortar properties		Flexural strength		
	f_m (N/mm^2)	f_{mt} (N/mm^2)	Average (N/mm^2)	CoV	f_{xk1} (N/mm^2)	f_m (N/mm^2)	f_{mt} (N/mm^2)	Average (N/mm^2)	CoV	f_{xk1} (N/mm^2)
10 mm	6.92	2.66	0.47	28.1%	0.32	4.56	1.98	0.52	27.8%	0.35
17.5 mm			0.60	12.5%	0.40			0.68	33.2%	0.46
25 mm			0.48	18.6%	0.32			0.64	23.4%	0.42

Figure 13. Perpendicular to bed joint flexural test failure

4.3.4 Flexural tests on retrofitted masonry

The results of the retrofitted panel tests, average of five repeat tests, are presented in Table 7. The average mortar and plaster compressive (f_m) and flexural (f_{mt}) strengths are also included in Table 7. Rather than flexural strength, the failure load resistance of each specimen is presented. The panels failed in flexure, with horizontal cracking observed at the masonry unit-mortar joint interfaces but also through the masonry units (Figure 13).

Table 7. Reinforced prism flexure test results

Series		Cement block					Fired clay brick				
		Plaster properties		Mortar properties		Failure load	Plaster properties		Mortar properties		Failure load
		f_{mt}	f_m	f_{mt}	f_m	kN	f_{mt}	f_m	f_{mt}	f_m	kN
		N/mm^2	N/mm^2	N/mm^2	N/mm^2		N/mm^2	N/mm^2	N/mm^2	N/mm^2	
Plain masonry	Dry	-	-	2.59	5.92	1.74	-	-	2.35	5.69	2.67
	CoV	-	-	13.7%	9.3%	37.9	-	-	15.7%	13.0%	29.8
	Saturated	-	-	1.71	8.37	1.48	-	-	1.71	8.37	0.74
	CoV	-	-	8.5%	13.4%	36.6	-	-	8.5%	13.4%	30.3
Unreinforced plaster	Dry	1.80	4.34	1.55	5.05	9.21	1.80	4.34	2.93	9.46	8.38
	CoV	4.3%	30.7%	12.4%	38.8%	9.21	4.3%	30.7%	12.4%	38.8%	6.52
	Saturated	1.80	4.34	1.55	5.05	9.52	1.80	4.34	2.93	9.46	6.38
	CoV	4.3%	30.7%	12.4%	38.8%	23.1	4.3%	30.7%	12.4%	38.8%	14.7
Plaster with wire mesh	Dry	2.32	4.44	2.22	4.54	14.3	2.32	4.44	2.22	4.54	10.5
	CoV	4.1%	14.2%	4.1%	22.3%	12.2	4.1%	14.2%	4.1%	22.3%	8.11
	Saturated	1.19	5.09	1.55	5.05	16.7	1.40	4.36	2.93	9.46	8.56
	CoV	7.1%	24.6%	12.4%	38.8%	10.5	11.8%	22.7%	5.6%	15.0%	24.8

5. Discussion

The survey of flood damaged housing indicated that the vernacular masonry used masonry units of poor and variable quality together with a mortar joints of significantly varied thickness. These factors influence potential retrofitting solutions and ultimately the design suitability for flood resilient structures.

5.1 Influence of Mortar thickness of masonry properties

In general the compressive strength of masonry can be expected to decrease with increasing mortar joint thickness. Figure 14 (the error bars represent 95% confidence interval) shows that this behaviour has not been observed here. While there is an apparent peak in both compressive and flexural strength (Figure 14) at 17.5mm for all masonry units, there is no statistically significant difference, based on the two-sided 't-test' with a p-value of <0.05, between the respective results for a given mortar thickness. The relative high strength of the mortar compared to the unit strengths is the most likely explanation.

Whilst it would appear that the mortar thickness enhances the flexural strength properties of the masonry, similarly to compressive strength there is no statistically significant difference between the units and the flexural strength of the panels. However, the limiting factor, as observed in Figure 15 is the interface between the mortar and the masonry unit under parallel flexure which is the focus of the retrofitting.

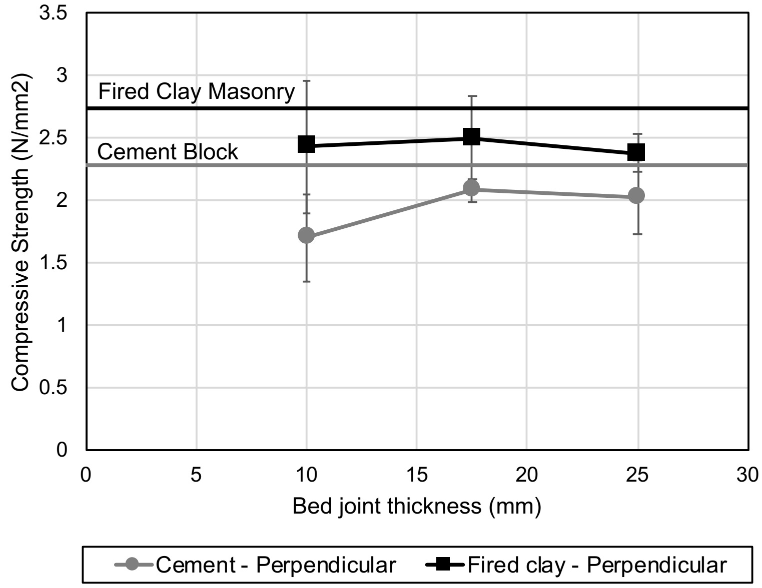

Figure 14. Influence of mortar thinkness of compressive strength of masonry panels.

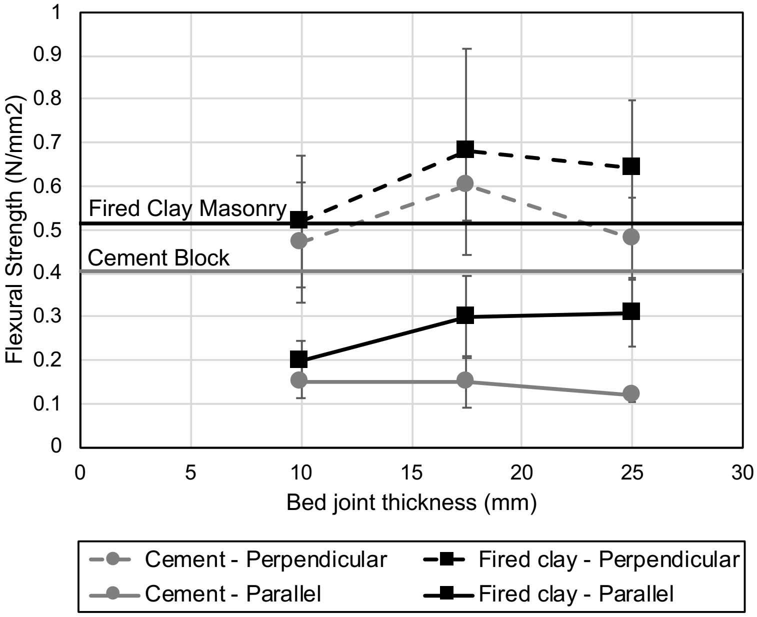

Figure 15. Influence of mortar thinkness of flexural strength of masonry panels.

5.2 Masonry retrofitting

The plaster coatings significantly increased flexural capacity compared to the plain masonry, with further 25% and 55% enhancement from the inclusion of the mesh reinforcement in cement block panels and fired clay masonry, as observed in Figure 16 (with error bars representing normalised confidence intervals) . The unreinforced plaster significantly increased the failure load, which is not solely attributed to the increased thickness of the material. The increase can be attributed to the additional tensile capacity provided by the plaster but also the continuity that the plaster provided over the mortar joints, the point of failure in the unplastered masonry panels. The additional enhancement in the panels with mesh reinforced plaster indicates that the mesh acted as a tensile reinforcement.

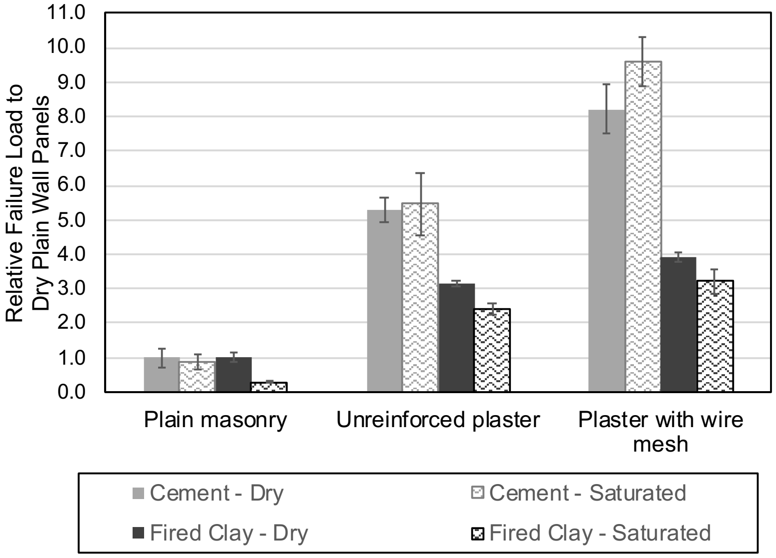

Figure 16. Relative Failure Loads of the wall panels compared to the Dry Plain Walls

5.3 Impact for vernacular masonry design

Based on the characteristic flexural strengths f_{xk1} in Table 7, the depth of flood water required to cause wall failure can be estimated. Assuming the flood water is retained by the wall on only one side, this will induce flexural moments, and resultant stresses, into the masonry. For a single storey (2.5 m high) single unit thick wall panel, that is unrestrained by the roof and surrounding frame or walls (i.e. simply cantilevered from the base), static flood levels between only 200 mm and 240 mm deep will be sufficient to induce failure. Assuming the walls are effectively propped by the surrounding frame or roof structure increases the static flood depths necessary to cause flexural failure to 660 mm for the cement block masonry, and 750 mm for the fired clay brickwork. Increasing the wall thickness to the minimum recommended 140 mm thick, from the Sri Lankan Standards, increases the estimated differential flood levels necessary to induce failure to 790 mm for the cement blockwork, and 900 mm for the brickwork. With the reinforced plaster in place single storey height single leaf fired clay brick walls are capable of sustaining flood water hydrostatic pressures up to 1.25 m without collapse. However, these estimations are based on static flood levels, and the action of the water moving, both during the initial impact of the flood and during the event will result in dynamic forces being applied.

6. Summary and conclusions

This paper has presented findings from a field study investigating the flood damage of vernacular masonry buildings in Sri Lanka. The study identified common failure modes within masonry housing and highlighted the local and global risk to such structures and communities by flooding. The main focus of this paper has been experimental characterisation of vernacular masonry and the development of simple measures to improve lateral load resistance. Though comparatively low compressive strength, tests on locally produced fired clay brick and cement block samples confirmed their compliance with local requirements for single storey masonry construction. The masonry units exhibited high total water absorption and initial rate of absorption properties, which is reflected in the common practice to pre-wet blocks and bricks during construction to limit their dewatering effects.

In comparison to the masonry units, the typical mortar mix used in Sri Lankan vernacular masonry is up to 250% stronger in compression. In conventional masonry, mortar with 10 mm bed joints, the mortar is generally selected to be the weakest element. However, the use of a higher strength mortar in this vernacular masonry facilitates construction with mortar joints up to 25 mm thickness without any statistically significant deterioration in masonry strength in compression or flexure. The characteristic compressive strength of the vernacular masonry walls is sufficient to sustain expected vertical loads in single storey construction. However, measurement of flexural strengths, especially under saturated conditions, confirm the vulnerability of walls to hydrostatic pressures during flood events.

A reinforced plaster retrofit solution has been investigated through further panel tests. The method was successful in enhancing flexural resistance, offering potentially greater flood resilience. The potential impact of this work will result in developing safer housing for communities in Sri Lanka, and elsewhere, through simple and affordable retrofitting measures, which may also be adopted in new and existing constructions. This technical solution will have significant socio-economic impact on communities in flood prone areas.

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