Retrofitting and Rehabilitation of Vernacular housing in Flood Prone Areas in Sri Lanka

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Abstract

This paper presents findings from an investigation into applications to improve the structural resilience and safety of low-rise vernacular masonry homes when subject to extreme flooding. In 2016 and 2017 flooding brought devastation throughout many areas in Sri Lanka. Findings from field investigations to evaluate, characterize, and quantify the extent and nature of structural damage to low rise vernacular masonry houses from these flood events are presented. Low cost solutions were developed to enhance the flexural capacity of masonry walls using reinforced plasters. Single storey homes in rural areas are particularly at risk from rapid flood events, and limited evacuation opportunities require a means of in-situ refuge. Focusing on these risks, a unique retrofitting project, including an elevated refuge area for occupants to escape and shelter during flood events, is also presented. This research will directly improve the welfare of vulnerable communities living in flood risk areas, minimizing the risk of flood induced structural failure, while enabling people to safely remain in their homes.

Keywords:

Cement Block; Fired Clay Brick; Masonry; Refuge; Resilience

1. Introduction

Extreme natural weather events, causing flooding, have increasingly become risks to people's lives and livelihoods. It is often the most vulnerable members of society who are most impacted. Unless infrastructure, building techniques, and institutional support systems are improved the impact of such weather events are expected to escalate with pressures from increasing urbanization and environmental change.

Unreinforced masonry (URM) construction is one of the oldest forms of construction. Developed as vernacular responses to a wide variety of environmental, geological and cultural factors, URM requires relatively low skill levels, can be constructed with a range of locally available materials, whilst offering comparatively good durability and at relatively low cost. Approximately, three-quarters of URM structures around the world can be classified as non-engineered or vernacular [Mendis et al., 2014]. In the face of climate change there is growing need to retrofit many such masonry structures to improve their resilience to loading from extreme weather events [Papanicolaou, et al., 2011].

URM materials can be broadly categorized into: unfired clay (adobe); fired clay brickwork; concrete brick or blockwork; and, natural stone masonry. The availability and use of these materials is dependent on geographic location, vernacular knowledge and experience. In rural areas of low-income countries in particular, where the populations may have limited access to engineering practices, URM structures remain a dominant form of construction [Bhattacharya 2014].

Structural URM walls must withstand vertical (self-weight and transient gravity loads) and horizontal (lateral) forces including wind, impact, seismic, and hydrostatic and hydrodynamic loads due to flooding [Seron & Suhoothi, 2017]. Differential hydrostatic and hydrodynamic forces, a function of floodwater velocity and building geometry, can cause damage and collapse of URM walls.

There is considerable variability in the quality of vernacular URM materials and the quality of construction [Abdellatef, 2011]. Investigations into the retrofit strengthening of masonry construction, including Drysdale & Khattab (1995), Luccioni & Rougier (2011), and Bhattacharya et al. (2014), have been mostly limited to in-plane forces, with a particular focus on seismic loading. Bernat et al., (2013) investigated textile-reinforced masonry walls under eccentric compressive loading. Blondet et al. (2006) applied two types of polymer mesh (industrial geo-grid, and a weaker mesh normally used as a 'soft' barricade on construction sites) to seismically reinforce weak unfired clay (adobe) masonry walls.

The performance of URM during flood events has been specifically studied by Ingargiola & Moline (2013), in which flood damage-resistant materials were evaluated with FEMA (Federal Emergency Management Agency) in developing the guidance for determining the flood damage resistance for materials and assemblies. Ghiassi et al., (2013), further investigated bond issues relating to Fibre Reinforced Plastics (FRP) strengthened masonry when saturated. Herbert et al., (2012) used a centrifuge to model full scale behaviour using 1/6th scale masonry panels, with the test conducted with water levels representative of flood stages.

In response to flood events, retrofitted buildings are thought of as either *flood resilient* or *flood resistant* [Platt et al., 2020]. Flood resilience permits intrusion or contact with the flood water during events, but without permanent structural damage, although normal building occupancy may be affected. Post-flood cosmetic repair include cleaning, sanitizing, and resurfacing materials, where the cost is less than the cost of replacement, is required. This differs from resistance, in which contact with flood water is prevented or minimized with occupancy remaining largely unaffected during the flood event.

The Global Climate Risk Index (2019), which assess direct impacts related to extreme weather events, ranked Sri Lanka as the second most flood affected country in the world [Eckstein, Künzel, & Schäfer, 2019], with 135,000 people displaced due to natural hazards. In 2018, flooding and landslides affected a further 49,364 families and 188,328 individuals [National Disaster Relief Service Centre, 2018]. In response to increasing events, and the extent of human risk and property damage, relocation programmes have been used to protect vulnerable communities. However, these have unintended side effects relating to coordination, management, planning, and finances [Cernea, 2004]. The present study is motivated by the objective of mitigating these impacts and keeping families in their original homes. In preparing this research project the authors have found no other similar flood related retrofit or reconstruction studies or applications specific to low-rise masonry structures in use throughout Sri Lanka or similar at-risk countries.

The research work presented in this paper aimed to maximise the impact of structural strengthening and disaster resilient measures applied to URM buildings subject to flooding in Sri Lanka. To meet this aim the research had the following objectives:

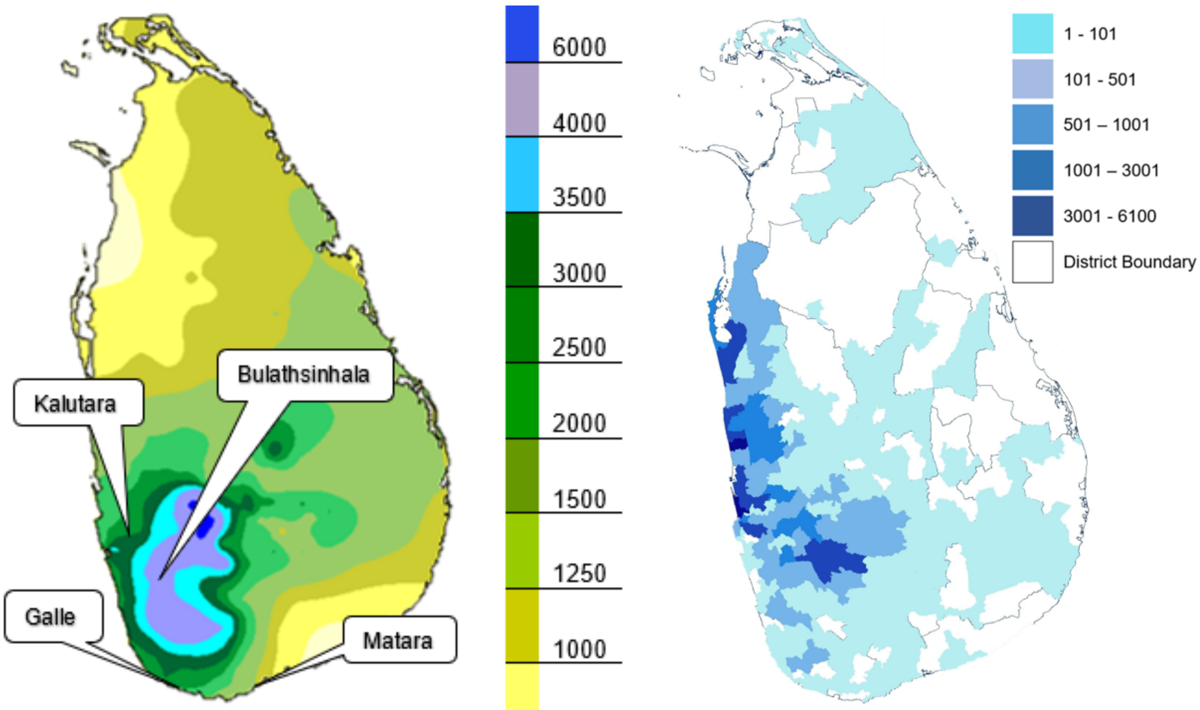
1. Test proposed measures under flood simulated loading conditions, to increase the structural resilience to withstand flood damage of low-rise masonry walls;
2. Deploy flood resilience measures on a demonstration building in Sri Lanka;
3. Develop and present design guidance of proposals for implementation in Sri Lanka and present at public engagement event;

2. Background

URM is the dominate form of construction for low rise housing in Sri Lanka. These buildings can be roughly categorized into adobe, fired clay brickwork, concrete blockwork, and stone masonry, with materials dependent on geographic location and the level of construction knowledge or experience. Rural communities in Sri Lanka rely heavily on locally made masonry units, which typically have poor dimensional regularity and consequently variable quality masonry construction. Masonry walls are normally built upon reinforced concrete slab foundations, strengthened at locations of load bearing walls. Foundations are typically 450-600 mm deep, varying with building typology and ground conditions [Nawagamuwa & Perera, 2015]. Foundation failure, such as under scour in flood, has not been observed in the study areas. URM structures are usually plastered and rendered single leaf construction; with the coatings improving resistance to moisture ingress as well as aesthetics. In Sri Lanka, plaster and renders are commonly 1:5 cement: sand mixtures applied in one or two coats totalling 15-20 mm [Platt et al., 2020]. Although reinforcing plaster and render coatings is currently not common in Sri Lankan practice, there is scope for inclusion of reinforcement into the plaster, with potential to greatly improving the flexural capacity of walls.

2.1 Field surveys of flood affected regions in Sri Lanka

In 2018, field surveys of flood damaged regions were carried out by the University of Moratuwa (UoM) and the Sri Lankan Government National Building Research Organisation (NBRO) [Platt et al., 2020]. The southwestern Kalutara, Matara, and Galle regions, having a combined total population of 3.1 million (2012 census), was selected to provide context to the need for intervention. The mean annual rainfall and areas of interest receiving upwards of 4000 to 6000 mm annually is shown in Figure 1(a); and the distribution of the approximately 80,000 persons affected by flooding 6 October 2018 shown in Figure 1(b).



a) annual rainfall patterns in Sri Lanka (mm) ["Climate of Sri Lanka", 2019]

b) affected families in the 6 October 2018 floods [Maps of Incidents, 2018]

Figure 1. Study region

Field surveys of flood damaged buildings were used to evaluate, characterise, and quantify the extent and nature of structural damage stemming from the 2016 and 2017 flood events. In the Kalutara, Matara, and Galle regions,104, 65, and 83 households, respectively, were surveyed. Among those surveyed, 60% had been exposed to flood levels greater than 2 metres. Examples of observed structural damage to masonry buildings are presented in Figure 2. The surveys also collected data on the social and economic impacts of the flood events by interviewing building occupants. In collaboration with local stakeholders, initial proposals were developed for flood protection, including proposals for a “safe” or refuge space structural addition.

Based on the surveys, 57% of reported damage was to structural walls (24% to floors and 19% to roofs). Single leaf load bearing wall panels using either Fired Clay Bricks (FCB) or Cement Sand Blocks (CSB), a form of concrete block, dominate residential construction in the flood effected regions; together accounting for 95% of reported wall construction. Both types of masonry units are produced through a decentralized and largely unregulated cottage industry. The flood damaged homes display many external walls cracked due to flexural failure parallel to the bed joint, as shown in Figures 2c and d.

a) complete collapse of load bearing URM

b) complete collapse of single leaf infill walls

c) flexural failure parallel to bed joint (note the elevated window height)

d) failed external walls and flexural cracks

Figure 2. Observed damage to URM.

3. Experimental Programme

Methods of strengthening URM walls have been investigated, initially with a study characterising the capacity of existing construction forms. Simple methods of reinforcing such walls using geogrid reinforced plaster coats were developed and the potential improvement in wall capacity quantified. The study presented in this paper expands on this previous research [Platt et al., 2020], utilizing wire mesh and including the characterisation of constituent materials and single leaf panels (approximately 390 - 500 mm x 500 - 550 mm (W x H)).

3.1 Masonry Units

Based on the field survey, two common masonry unit types were chosen for the experimental study: CSB and FCB. Samples were obtained from a single supplier on the outskirts of Moratuwa, 17 km south of the capital city, Colombo.

The variation in quality of the FCBs was investigated by testing two separate batches (A and B). The solid fired clay bricks were supplied with nominal dimensions of 220 mm (length) x 105 mm (width) x 65 mm (height). However, the actual dimensions varied, reflecting the small-scale cottage industry; these averaged 188 mm x 93 mm x 54 mm (with a Coefficient of Variation (COV) of 1.4%, 1.5%, and 4.2%, respectively). The CSB were frogged (recessed) on one bed face, and on both vertical edges, and were supplied with nominal dimensions of 400 mm x 100 mm x 200 mm. The average dimensions were 337 mm x 92 mm x 166 mm (COV of 0.5%, 2.0%, and 3.1%, respectively). Representative samples of CSB and FCB are shown in Figure 3.

Cement sand block (CSB) Fired clay brick (FCB)

Figure 3. Masonry units used in study.

Both CSBs and FCBs were characterised to determine their density, porosity, initial water absorption, total water absorption, unit compressive and flexural strengths (under both dry and saturated conditions), as presented in Table 1.

Randomly selected samples of the CSB and FCB were oven dried at 105°C until a stable weight was achieved. After drying, the unit bulk densities were determined from dry mass and unit volumes. Water absorption characteristics were measured in accordance with BS EN 772-11 (2011). Initial Rate of Absorption (IRA) tests were carried out on half-brick specimens and specimens from blocks cut into thirds. Each specimen was placed bed-face down into 3 - 5 mm deep water for 1 minute and the resulting change in mass measured. The masonry unit specimens were then immersed in water for 24 hours to determine their Total Water Absorption (TWA). Density, TWA, and IRA for all masonry units used in this study are given in Table 1.

Compressive and flexural strength of dry and saturated samples were established in accordance with BS EN 772-1 (2015). In preparation for testing, the frog on the bed-face of the CSB was filled with 1:3 (cement: sand) mortar.

Table 1. Masonry unit properties

Property		Cement sand block[b] (CSB)		Fired clay brick (FCB)			
				Batch A[b]		Batch B	
		Average n = 6	COV	Average n = 6	COV	Average n = 6	COV
Dry bulk density (kg/m^3)		1587	2.2%	2031	0.6%	1575	3.0%
Compressive strength (N/mm^2)	Dry, f_u (f_b [a])	2.26 (*2.29*)	25.8%	4.38 (*2.74*)	21.0%	7.69 (4.81)	4.7%
	Saturated, f_u (f_b [a])	1.55 (*2.35*)	23.7%	4.14 (*3.84*)	12.9%	6.71 (6.31)	19.6%
Flexural strength (N/mm^2)	Dry	0.404	42.7%	0.514	27.7%	0.498	8.8%
	Saturated	0.262	39.4%	0.415	29.2%	0.314	12.3%
Total water absorption (%)		10.0	20.6%	18.6	12.8%	18.1	2.7%
Initial Rate of Absorption (kg/m^2.min)		4.31	15.2%	4.71	44.3%	3.70	11.5%

[a] Normalised unit strength in accordance with BS EN 772-1.
[b] Adapted from Platt et al. (2020)

The relatively poor quality of the masonry is reflected in the high initial rate of water absorption and variation in properties reported in Table 1. The normalized compressive strengths (BS EN 772-1) for the CSB and both batches of FCB comply with Sri Lankan building regulation requirements for single storey construction: $f_b \geq 1.2$ N/mm^2 for CSB and $f_b \geq 2.8$ N/mm^2 for FCB [Nawagamuwa & Perera, 2015]. However, neither CSB or FCB Batch A are suitable for two storey load-bearing masonry, where requirements increase to 2.5 N/mm^2 and 4.8 N/mm^2 for CSB and FSB, respectively.

Batch B FCB presented greater strength but lower density than Batch A, although both batches exhibited similar water absorption values. Figure 4 shows the cross sections of bricks from batches A and B. Batch A maintains a finer texture near the surface with greater variations near the centre of the brick, while Batch B has a fairly uniform texture and colour throughout. This is due to differences in raw soil grading and processing, and manufacturing including inconsistent firing [Maskell et al, 2013].

Batch A Batch B

Figure 4. Cross sections of fired clay bricks.

3.2 Mortar and plaster

Ordinary Portland Cement and river sand containing fine aggregate, both representative of materials widely used in Sri Lankan masonry construction, were used to mix, by volume, a 1:6 cement: sand mortar and 1:5 plaster. In keeping with local methods, the mortar was mixed manually by experienced bricklayers with water content controlled for workability. Flow table tests (BS EN 1015-3: 1999) were conducted at each mixing to assess consistency. The average flow for the fresh mortars was 125 mm (COV = 11.7%).

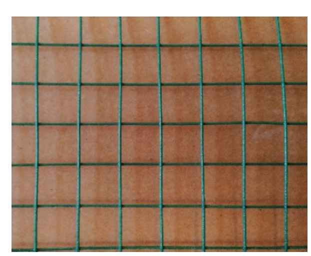
Characterization tests of the mortar mix used for both construction and plastering of the masonry prisms included: flexural and compressive strength, measured in accordance with BS EN 1015-11: 1999. Triplicate samples of mortar prisms measuring 40 mm x 40 mm x 160 mm were prepared from each series of wallettes constructed and plaster applications. These were first tested in flexure; with the two broken sections then used to determine compressive strength resistance. Tests were conducted in both dry and saturated conditions.

Mortar specimens were mostly tested at ages between 28 and 35 days, but always on the same day as testing the wallets for which the mortar was used. The average dry compressive strength was 6.93 N/mm^2 (COV 31.8%) over all batches. Mortar properties are reported in Table 4 with their respective wallette properties.

3.3 Wire mesh reinforcement

A PVC coated steel wire mesh, (widely available from local building supply stores) was previously investigated in a pilot study by Platt et al. (2020) and is presented here for comparison. The square mesh, normally used as a lightweight material for a variety of domestic uses, was selected for its low cost and availability. Samples of both warp and weft bars were tested in uniaxial tension and results are summarized in Table 2.

Table 2. Summary of geogrid geometry and material properties [Platt et al., 2020]

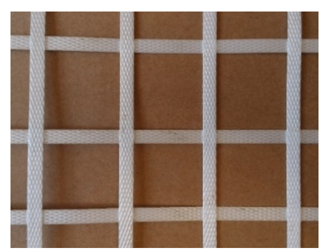
	warp	weft	
Diameter of wire – mm (COV)	0.574 (1.9%)	0.575 (2.5%)	
Thickness of coating - mm (COV)	0.074 (16.9%)	0.076 (7.0%)	
Aperture size – mm	12.0	12.0	
Tensile capacity per rib - N (COV)	243 (5.5%)	210 (3.2%)	
Tensile capacity per meter width – kN/m (COV)	19.3 (4.5%)	16.5 (3.2%)	

3.4 Polypropylene geogrid reinforcement

The application of geogrid reinforced plaster applied to low strength vernacular masonry has been investigated as a method of improving the lateral load resilience. Geogrids are open meshes of geosynthetic materials typically used for load distribution in soils or pavements and slope stabilization. The mesh aperture typically ranges from 25 mm to 150 mm. Geogrids differ from geotextiles in that their apertures are larger and load distribution is expected to occur at the intersection of longitudinal (warp) and transverse (weft) elements.

In this study, a readily available geogrid composed of extruded flat polypropylene (PP) bars with welded junctions (Table 3) was used. The bars are approximately 6.2 mm x 0.17 mm and the aperture dimension is 33.1 mm square. Samples of both warp and weft bars were tested in uniaxial tension and results are summarized in Table 3.

Table 3. Summary of geogrid geometry and material properties

	warp	weft	
Width of rib – mm (COV)	6.32 (7.6%)	6.13 (0.5%)	
Thickness of rib - mm (COV)	0.173 (6.8%)	0.173 (6.85%)	
Aperture size – mm (COV)	33.1 (3.5%)	33.1 (3.5%)	
Tensile capacity per rib - N (COV)	910 (10.6%)	990 (9.0%)	
Tensile capacity per meter width – kN/m (COV)	23.2 (13.2%)	25.2 (10.3%)	

3.5 Wallette construction

Four series of masonry wallettes over four different categories (a total of 80 wallettes) were similarly constructed using local skilled masons and labour. Each CSB wallette was 1.5 units long and 3 courses high (505 mm x 549 mm). The FCB wallettes were 2 units long and 7 courses high (393 mm x 497 mm). The wallettes were constructed with 17.5 mm bed joints. The bed joint thickness was determined based on a previous study which corelated the impact of the mortar thickness and strength (Platt et al., 2020). Prior to laying, the FCB units were immersed in water for about 5 minutes, thereby reducing the dewatering effects of the masonry unit on the mortar. Immersion resulted in an average moisture content of 14% for FCB. The CSBs were used without wetting and had an average moisture content of 2% at the time of laying.

One series of wallettes was tested as-built without plaster. The second series received approximately 17 mm to 20 mm plaster, applied in two lifts, on the interior side of the wallette. This series represents the current state-of-practice for plastered walls. The third retrofitted series included one layer of either the PVC coated welded wire mesh or PP geogrid pressed into the plaster between lifts. A vertical precompression load approximately equal to 2.5×10^{-3} N/mm^2 was applied to the top of each wallette upon completion of construction and remained in place for at least 14 days until the application of plaster.

4. Flexural Strength Tests

Parallel to the bed joint flexural strength of the masonry wallettes was evaluated under four-point lateral loading in accordance with BS EN 1052-2:2016, as shown in Figures 5 and 6a. In every case, the plaster or reinforced plaster was located on the tension face of the wallette. The ultimate load, $F_{i.max}$, applied on the wall panel just before the flexural failure was recorded and the flexural strength, f_{xi}, was calculated according to BS EN 1052-2:2016. Each series of 20 wallettes was divided into half tested under dry and half under saturated conditions. The saturated panels were immersed for 24 hours prior to testing as shown in Figure 6b. Test results are reported in Table 4 along with the mortar and plaster properties coinciding with each series of wallettes. It is noted that for the FCB, all Batch A samples were tested in the dry condition while Batch B was saturated.

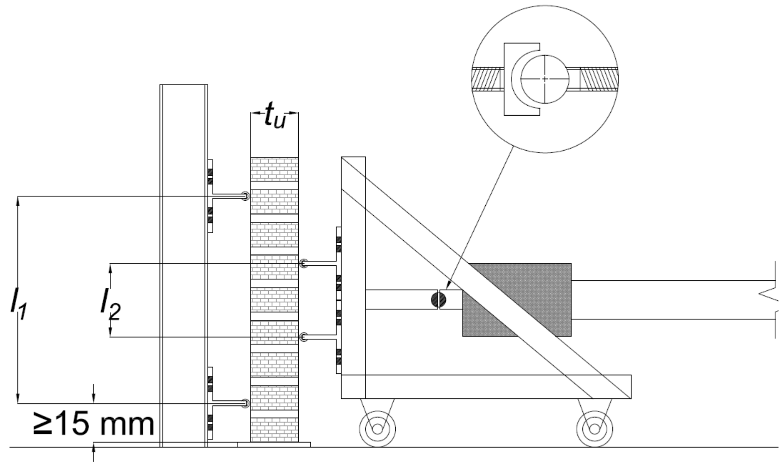


Figure 5. Schematic of parallel joint test (BS EN 1052-2:2016)

a) Parallel to bed joint flexural test (BE EN 1052-2:2016)

b) 24-hour immersion of panels prior to saturation tests

Figure 6. Wallette flexural tests

Figure 7a shows a typical flexural failure occurring in the constant moment region of the test with bond fracture occurring at the interface between the mortar and the masonry unit. BS EN 1052-2:2016 is intended to assess flexural strength of wallettes. However, with the addition of geogrid reinforced mortar, flexural failure is mitigated and the wallettes fail in a shear mode as seen in Figure 7b. For this reason, wallette capacity is reported in terms of maximum applied lateral force rather than flexural strength in Table 4 regardless of failure mode.

a) parallel bed joint flexural test failure of saturated unreinforced plastered wallette

b) typical failure in shear zone of geogrid-reinforced wallette

Figure 7 Representative failure modes of flexural tests.

Table 4. Parallel to bed joint flexural test results

Series		Cement sand block (CSB)								Fired clay brick (FCB)						
		Plaster properties			Mortar properties			Failure load of wall panels	batch	Plaster properties			Mortar properties			Failure load
		f_{mt}	f_m	$f_{m.sat}$	f_{mt}	f_m	$f_{m.sat}$	kN		f_{mt}	f_m	$f_{m.sat}$	f_{mt}	f_m	$f_{m.sat}$	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	N/mm^2	N/mm^2	N/mm^2	N/mm^2	
Plain masonry	Dry	-	-	-	2.59	5.92	6.63	1.74	A	-	-	-	2.35	5.69	6.16	2.67
	CoV (%)	-	-	-	13.7	9.3	3.7	37.9		-	-	-	15.7	13.0	8.4	29.8
	Saturated	-	-	-	1.71	8.37	6.66	1.48	B	-	-	-	1.71	8.37	6.66	0.74
	CoV (%)	-	-	-	8.5	13.4	18.7	36.6		-	-	-	8.5	13.4	18.7	30.3
Unreinforced plaster	Dry	1.80	4.34	3.92	1.55	5.05	5.09	9.21	A	1.80	4.34	3.92	2.93	9.46	7.85	8.38
	CoV (%)	4.3	30.7	16.9	12.4	38.8	25.2	9.21		4.3	30.7	16.9	12.4	38.8	25.2	6.52
	Saturated	1.80	4.34	3.92	1.55	5.05	5.09	9.52	B	1.80	4.34	3.92	2.93	9.46	7.85	6.38
	CoV (%)	4.3	30.7	16.9	12.4	38.8	25.2	23.1		4.3	30.7	16.9	12.4	38.8	25.2	14.7
Plaster with wire mesh	Dry	2.32	4.44	2.95	2.22	4.54	3.01	14.3	A	2.32	4.44	2.95	2.22	4.54	3.01	10.5
	CoV (%)	4.1	14.2	14.7	4.1	22.3	4.3	12.2		4.1	14.2	14.7	4.1	22.3	4.3	8.11
	Saturated	1.19	5.09	4.50	1.55	5.05	5.09	16.7	B	1.40	4.36	4.50	2.93	9.46	7.48	8.56
	CoV (%)	7.1	24.6	18.2	12.4	38.8	25.2	10.5		11.8	22.7	6.9	5.6	15.0	4.0	24.8
Plaster with Geogrid	Dry	1.32	5.89	4.64	2.02	7.28	5.70	23.8	A	1.18	4.97	3.36	2.08	9.63	7.98	13.8
	CoV (%)	39.8	8.6	19.5	10.5	13.0	38.2	3.92		11.1	16.4	29.7	6.9	25.3	22.6	7.61
	Saturated	1.74	5.43	3.59	2.02	7.28	5.70	15.3	B	1.18	3.53	2.82	2.08	9.63	7.98	11.2
	CoV (%)	17.5	10.8	13.7	10.5	13.0	38.2	28.0		9.3	4.9	14.6	6.9	25.3	22.6	25.1

Note: Flexural strength (f_{mt}), compressive strength (f_m), saturated Compressive strength ($f_{m,\,sat}$). Some values have been adapted from Platt et al. (2020).

Figure 8 shows the applied load capacity and calculated flexural strength of the wallettes at failure. The ultimate load, $F_{i.max}$, applied on the wall panel was recorded and subsequently, the flexural strength, f_{xi}, was calculated according to BS EN 1052-2 using Equation 1.

$$f_{xi} = \frac{3F_{i,max} \cdot (L1 - L2)}{2 \cdot b \cdot t_u^2} \ (N/mm^2) \qquad \text{Equation (1)}$$

Where, L_1 and L_2 are the outer and inner bearing spans, respectively. The width and depth (thickness) of the masonry specimen is represented by b and t_u respectively. For the geogrid-reinforced wallettes, the flexural strength calculated at the point of shear failure. This is therefore a lower-bound indication of the flexural strength of these wallettes. Also shown in Figures 8b and 8d is the relative characteristic flexural strengths (f_{xk1}) which the UK National Annex for BS EN 1996:2012 specifies as a function of total water absorption and mortar grade for clay brickwork; and as a function of unit type, unit compressive strength and mortar grade for concrete block masonry. For the experimental materials, the values for f_{xk1} are 0.25 N/mm^2 for the CSB and 0.30 N/mm^2 for the FCB. Neither the un-plastered CSB or FCB meet the prescribed strengths and only obtaining 0.15 N/mm^2 (COV 38%) and 0.197 N/mm^2 respectively. However, with the addition of mortar or reinforced mortar, the wallette capacities (and presumed lower bound capacities) are significantly greater than these limits for both dry and saturated conditions by as much as 252% and 209% respectively (for CSB). In each case there is a reduction in capacity for the saturated wallettes compared to their dry counterparts. The failure plane of the dry wallettes was typically along the interface of mortar and masonry unit at the bed joint. Since the block strength is reduced when in the saturated condition (Table 1), some the failures shifted to occurring within the block itself when the wallette is saturated.

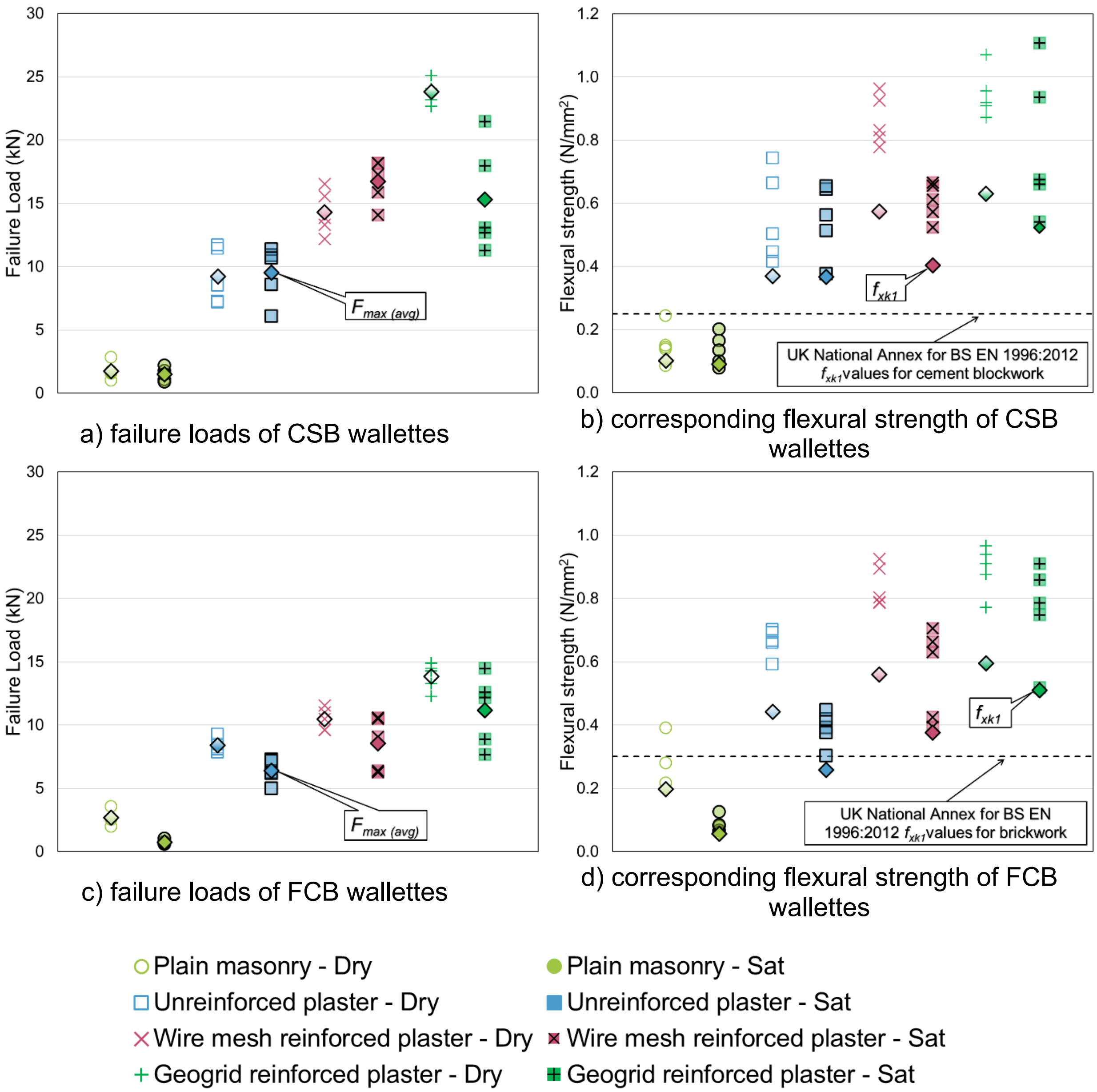


Figure 8. Summary of wallette capacities

The addition of plaster to the masonry wallettes increased their flexural capacity relative to the plain masonry tests. Additional inclusion of geogrid reinforced plaster further enhanced flexural capacity by 159% and 65% for the dry CSB and FCB dry panels, respectively. The focus of this study, however, is on improving the saturated flexural strength of masonry walls during flood events.

The addition of the geogrid provides an additional flexural strength increase of the previously studied wire mesh with gains of 67% and 32% for dry CSB and FCB wallettes respectively. As previously mentioned, the main focus of this study is finding a cost-effective method for flood damage mitigation. The wire mesh is both lower cost and currently more available than the geogrid. The geogrid, having a higher material cost benefits from ease of installation and does have an increasing market due to landslide mitigation and may see the cost and availability become more attractive in the near future. This combined with the added flexural strength gains over wire mesh reinforced plaster of 67% and 32%for CSB and FCB respectively when dry and while near equal for saturated CSB a 30% gain over saturated FCB is realized, provides a realizable benefit from the retrofitting with geogrid.

At a flood depth of 1 m (water on one side only), the total pressure acting on the wall is 9.78 kN/m^2 as calculated using Equation 2 and illustrated in Figure 9 below. This is equivalent to a force (*F*) of approximately 1.92 kN and 2.89 kN at 0.33 m above the floor (the pressure centroid) which is already greater than the observed load capacities of the plain dry or saturated CSB and FCB wallettes tested in this study, respectively using Equation 3. The application of geogrid reinforced plaster was observed to provide the greatest overall improved flexural capacity as shown in Table 4.

$$\Delta P = \rho_w g\left(f_{diff} - y\right) = \Delta P_{y=0} - \rho_y g y \; for \; 0 < y \leq H \qquad \text{Equation (2)}$$

$$F_{f_{diff}/3} = \left[\frac{\left(\rho_w g\left(f_{diff}\right)^2\right)}{2}\right] L \qquad \text{Equation (3)}$$

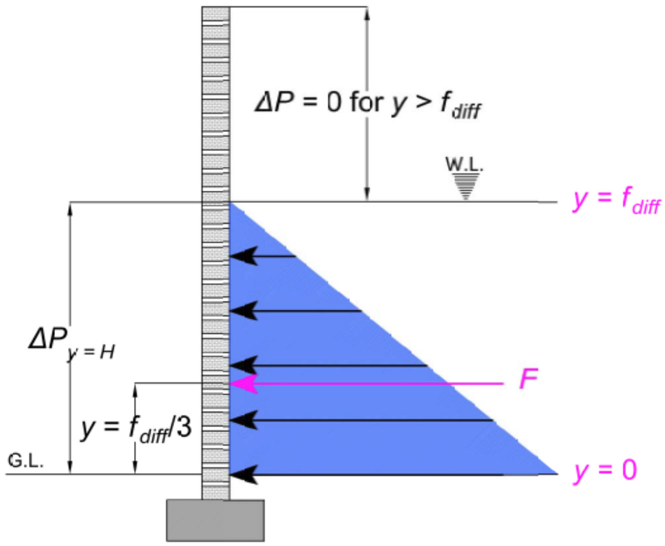


Figure 9. Pressure function on a wall

Where ΔP is the pressure difference (Pa), ρ_w is the density of water (997 kg*m^{-3}), g is the acceleration due to gravity (9.81 m*s^{-2}), f_{diff} is the flood depth differential, and y is the distance up from the base of the wall while L is the length of the wall. For a structure with no interior flood water, the centre of hydrostatic pressure is 1/3 the depth of the flood water.

5. Prototype Demonstration House

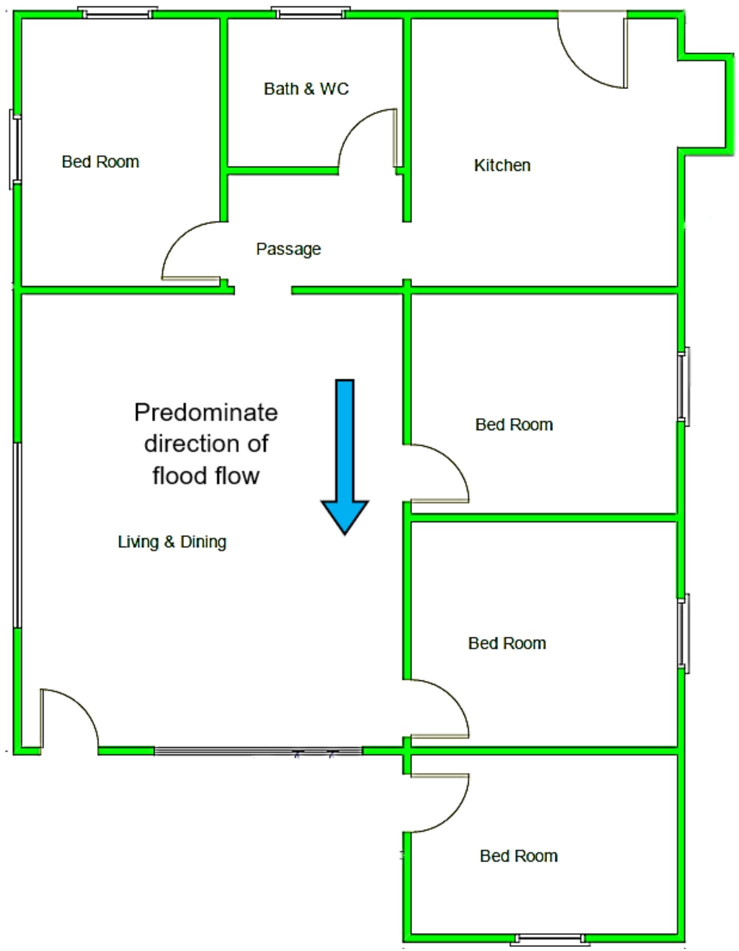
The need for retrofitting is in response to elevated flooding hazards. The architectural vernacular in many Sri Lankan homes includes low-silled windows (Figure 2c). As a result, the resultant force from hydrostatic pressure will rarely be higher than 0.33 m above the base of an exterior wall. Most homes are built with locally made materials, primarily FCB and CSB that vary greatly throughout the country. As seen in Table 1 and Table 3, the sample units tested exhibited poor compressive and flexural strengths even when dry.

The objective in retrofitting these at-risk homes is to ensure that the structure remains sound during flood events and enables the residents to reoccupy their homes in as short as time as possible with minimal structural repair. Previous construction recommendations for flood prone locations [Nawagamuwa & Perera, 2015] have included orienting the structure such that the smallest exterior surface is in line with prevailing flow of the potential flood and the incorporation of multiple opposing openings. These design elements combine to minimise exposure to hydrostatic forces.

In order to evaluate the field performance of proposed retrofitting methods a demonstration site was selected. An overall evaluation of flood safety measures, retrofit methodology, construction practice, and public acceptance was carried out. The study region, Bulathsinhala, located in the Kalutara district of Sri Lanka (Figure 1b) has a population of 64,600 and was selected based on selection criterion developed by NBRO to identify a prototypical home for research activities based on accessibility, amount of previous compensation received, year of construction, flood frequency, ownership of the property, and finally number of family members in the home. The final selection was made by NBRO and reflected the need of the occupants as well as construction considerations.

The four-bedroom 142 m^2 (1532 $ft.^2$) house selected, shown in Figure 10, was constructed in year 2000 for a family of six resettled in 1995 due to landslide threat in Heenpadura (Bulathsinghala). The load-bearing masonry walls are rendered mixed masonry construction, with exterior walls made from FCB and inner walls of CSB. The structure is built on a rubble foundation, with no columns, and the single unit gable roof is sheeted in corrugated cement fibre sheeting. The layout of the building is such that there is increased resistance during a flood with respect to the dominant direction of expected flow from the rear to the front of the building (Figure 8a).

The structure was exposed to flood water depths of 1.2, 1.2, 2.7, and 4.8 metres in 2003, 2007, 2013 and 2017 respectively; 4.8m corresponds to a 1000-year flood event. The occupants reported no flooding prior to the construction (begun in 1999 and completed in 2005) of the nearby Kukuleganga reservoir, apart from the annual flooding of the nearby paddy fields. The slight elevation of the structure and the nearby paddy fields provides adequate drainage and ponding for water during heavy rains and as flood waters recede. However, there is a slight rise to the road in the front of the property which could cause some ponding and increased runoff in the direction of the house.



a) plan

b) exterior view from “bottom” of plan

Figure 10. Prototypical home selected for demonstration

5.1 Retrofitting demonstration house

Retrofitting of the interior face of the exterior walls was conducted to improve the lateral load carrying capacity of exterior FCB walls in the event of a flood. Additional rehabilitation works provided an elevated refuge space in which the occupants could shelter in the event of an extreme sudden rise in water depth which prevents escape.

The application of geogrid-reinforced plastering was selected as the appropriate retrofit measure based on the enhancement observed during the flexural testing, Table 4. The retrofit process is outlined in Figure 11. Initially, the existing plaster was removed to a height of approximately 1 metre above the floor level (Figure 11a). A narrow channel, 15 mm wide and 50 mm deep was created in the floor by cutting a groove with an angle grinder approximately 15 mm away from the bare wall and removing the concrete between this and the wall. The geogrid was placed in the groove folding the bottom aperture along the longitudinal rib so that the vertically aligned ribs were captured. A two-part structural epoxy was used to secure the geogrid in place (Figure 11b). The geogrid was held upright during epoxy cure using tape. Following epoxy cure, the geogrid was laid back and an initial 7 - 10 mm scratch coat of 1:5 cement:sand plaster was applied (Figure 11c). The geogrid was pressed into the scratch coat before applying a similar 10 mm topcoat, embedding the geogrid reinforcement (Figure 11d). The reinforced plaster retrofit was applied to the interior face of all exterior walls and wrapped 300 mm along internal partition walls to strengthen the corners (seen in Figures 11c and d).

a) removal of existing plaster

b) epoxy the geogrid in place

c) application of scratch coat and geogrid

d) final retrofit wall; note that the retrofit looks no different than the existing plastered wall shown in part a)

Figure 11. Application of geogrid reinforced plaster.

5.2 Refuge Space

The addition of a refuge space to at-risk homes provides an elevated secure space for occupants to take shelter in the event of a flash flood event, or that the rise of water occurs too quickly for the residence to escape. In the event of extended flooding, the elevated structure also serves to aid in rescue. The design of the refuge space is such that it does not rely solely on the existing structure for support. This is achieved through the addition of separate load bearing walls added to the existing ground floor for support of the first-floor refuge space. These new walls are placed adjacent ("sistered") to existing walls with brick ties (6 mm reinforcing bar) and grouting any voids between them.

Following site investigations, the existing foundation was considered of sufficient size and depth and therefore, the addition of the secondary interior 100 mm CSB wall required no additional ground support. A new 75 mm reinforced concrete slab with a reinforced concrete grade beam provided further support for the existing walls as well as a stable foundation for the new walls.

The refuge space was located to minimize overall impact on the existing structure. The upper floor of the refuge space extended through the existing roof and was fitted to reduce chances of water infiltration.

For the ground floor, 100 mm concrete blockwork was used (doubling the existing wall of rendered 100 mm brick). For the first-floor walls, 150 mm blocks were used. The floor consisted of precast inverted-T reinforced concrete beams (so called ICC SBS precast system) with a 50 mm cast-in-place concrete topping. The roof, fabricated in the same manner, received a waterproof layer on top of the concrete before applying clay tiles. The existing roof is fitted to the new first floor extension for a watertight seal. Both the elevated floor and roof weigh more than 1000 kg/m^2 thereby mitigating the threat of buoyancy and uplift in a severe flood event. An overview of the procedure is shown in Figure 12 and a summary of the retrofit and shelter rehabilitation is shown in Figure 13.

Currently there are two financial instruments for disaster recovery in Sri Lanka: The National Insurance Scheme (NIS); and the Catastrophe Deferred Drawdown Option (CAT-DDO). The NIS is operated by the Ministry of Finance. The NIS covers life and property insurance, specifically all households and small business establishments, for losses to buildings and contents due to Cyclones, Storm, Tempest, Flood, Land slide, Hurricane, Earthquake, Tsunami and any other similar natural events. The CAT-DDO provides access to loans up to $102 million (US) from the World Bank for a total available budget of $168.6 million (US).

The cost of the retrofit and rehabilitation was Rs. 1.1 million ($5930 USD) as compared to the maximum property damage coverage provided by the NIS of Rs. 2.5 million ($13,470 USD) per event ["NITF-National Natural Disasters", 2019].

As a point of comparison, the Ministry of Disaster management reports compensation of almost 1 trillion Rs ($5.4 million USD) to cover 80,000 damaged or collapsed homes resulting from a single regional flooding event in May 2017. It is worth noting that the entire amount available from the World Bank was withdrawn in 2016 [Ministry of Disaster Management, 2017]. There has traditionally been a low uptake of available private insurance programs in Sri Lanka, with limited communication in local languages cited as a major reason for this situation [Fernando & Jayasekera, 2018].

Near the conclusion of the demonstration house construction, a community engagement event was held in which the project site was opened to the public. During the event, research members and construction workers were on hand to present the objectives of the program, demonstrate the techniques used, and provide guidance on retrofitting methods. At the conclusion of the event, participants were asked to take a short survey. Participants almost universally recognized the need for repair and rehabilitation measures and expressed support for the approaches presented. The retrofitting methods were further presented for inclusion in an updated Hazard Resilient Construction Manual to be published by National Building Research Organization of Sri Lanka.

a) existing wall and floor plastering removed

b) construction of interior wall

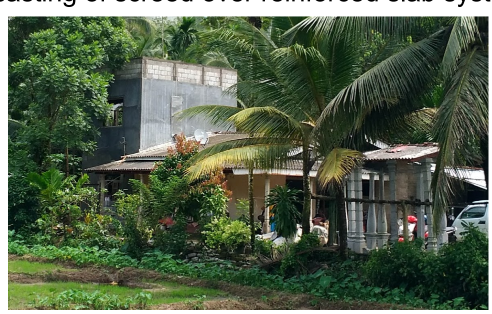
c) ground floor walls with lintel beams added

d) walls capped with reinforced ring beam

e) installation of inverted-T beams and infill

f) casting of screed over reinforced slab system

g) completed first floor with temporary roof



h) view with refuge space

Figure 12. Construction of Refuge Space

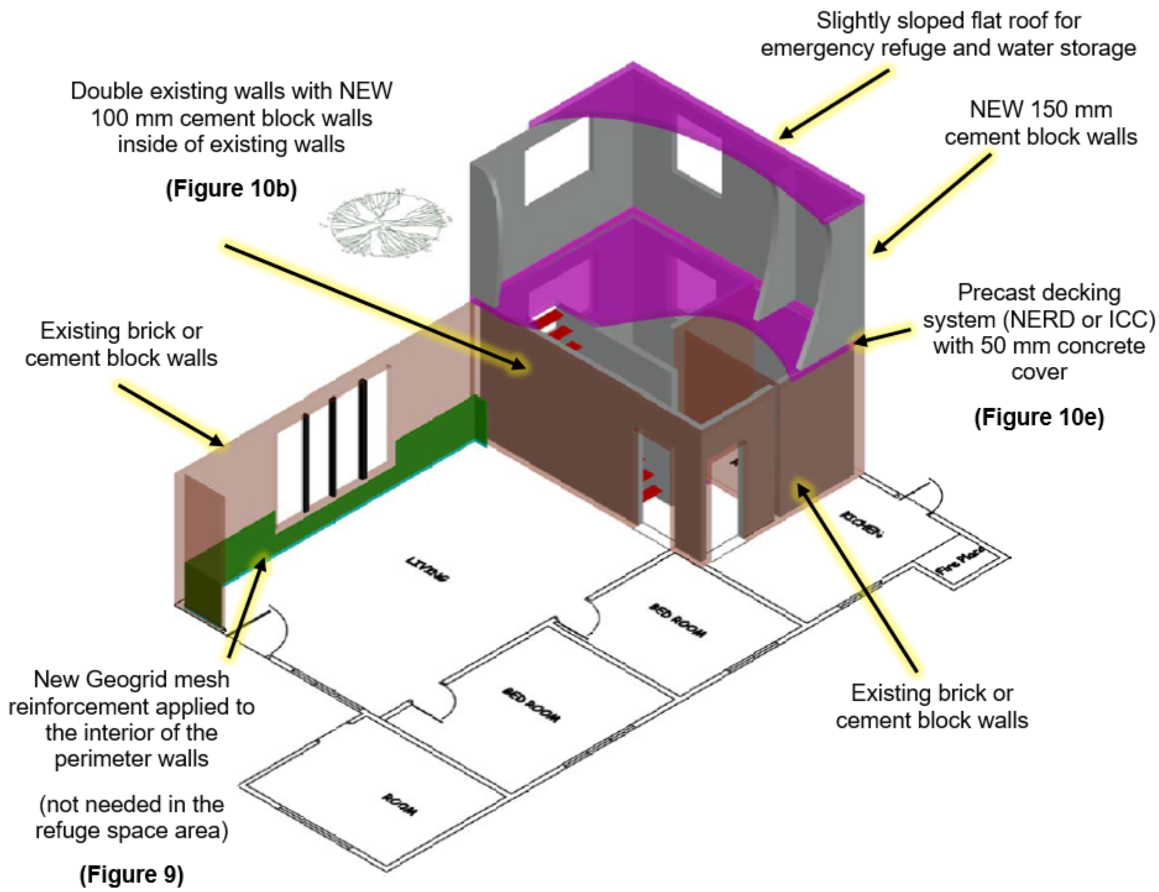


Figure 13. Schematic summary of retrofitting and rehabilitation deployed.

6. Conclusions

This paper has presented an experimental study on flexural capacity of low strength masonry panels strengthened to resist lateral flood loadings, using plain and two different methods for reinforced plaster coatings. Field surveys and investigations along with in-depth laboratory testing was utilized to characterize structural damage and potential retrofitting methods with respect to extreme flooding. This investigation reported the overall flexural capacity of vernacular masonry structures by implementing geogrid as a reinforcement embedded within the plaster.

Furthermore, a prototype Safe Space was presented. This concept provides for retrofitting of a structure within the existing footprint of the home and thereby providing an elevated space from which occupants may find shelter during a rapidly occurring event.

The research and development work long-term will have direct welfare benefit for Sri Lanka as well many other nations living within increasing flood risk areas. The high risk of death and injury from extreme flood events can be largely eliminated by implementing the developed mitigation measures that will increase resilience of masonry walls by preventing collapse under flood loads together with provision of affordable flood resistant refuge spaces. As well as reducing the risk of death and injury, preventing building damage will allow families to rebuild their lives more quickly following flood events. The measures proposed, developed in collaboration with NBRO, have been specifically developed to minimise costs, and disruption, to families.

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