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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).

24

25

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

27

28 To date a variety of approaches have been developed to retrofit and strengthen

29 unreinforced masonry structures [Ingargiola and Moline 2013; Herbert et al. 2012].

30 Surface treatments are used to increase flexural strength and water ingress and

31 typically involves rendering the wall, some incorporating a mesh. The render is often

32 based on cementitious mixes, while the meshes are either metallic or textile. Fibre

33 Reinforced Polymers are an alternative approach that are increasing being considered,

34 but the cost and availability within ODA recipient countries remains questionable

35 [Triantafillou, 1998]. Alternatively, prestressing ties can be added either internally or

36 externally that help to prevent the masonry failing through flexural induced tension,

37 however there are concerns over the cost of the retrofit within the given context.

38   Retrofitting approaches have mainly considered strength enhancement under dry

39   conditions with only a few studies investigating the combination of out-of-plane loading

40   with the material in saturated conditions [Herbert et al 2018].

41

42   Factors that influence performance of masonry walls in flood events have been

43   summarised by Bowker & Wallingford (2005) including: hydrostatic effects;

44   hydrodynamic effects; erosion; buoyancy; damage from debris; non-physical effects

45   (e.g. chemical changes; biological growth); and effects from direct water contact.

46   However, Kelman and Spence (2004) suggest that the most important effects in flood

47   damage are the lateral hydrostatic forces, lateral hydrodynamic forces, and the effects

48   of direct water contact.

49

50   The overall aim of the study presented in this paper has been to explore affordable

51   strategies to improve the resilience of low-rise masonry structures, and communities, to

52   extreme flooding events in Sri Lanka. To meet this aim the work had the following four

53   objectives:

54   1. Survey the flood affected areas to evaluate, characterise and quantify the extent

55   and nature of structural damage to low rise masonry houses.

56   2. Characterise the mechanical properties of the Sri Lankan vernacular masonry

57   materials.

58   3. Investigate the influence of variable mortar thickness on the properties of

59   masonry built using low strength units.

60   4. Propose and evaluate potential retrofitting measures to improve lateral load

61   capacity of vernacular masonry.

62

63   **2   Surveys on flood damaged houses**

64   From February to April 2018 a survey of the affected regions from the 2017 Sri Lankan

65   floods was conducted. Three districts in the Western and Southern provinces were

66   particularly affected by these floods: Kalutara (flooded area 223 km^2); Galle (62 km^2);

67   and, Matara (122 km^2). Householder surveys were undertaken to record various

68   structural impacts of the flooding, including: location; age and building typology;

69   materials; nature of structure. In this paper the survey findings concerning materials use

70   and flood damage are briefly summarised. The survey was carried out jointly by

71   researchers from the University of Moratuwa and the National Building Research

72   Organization (NBRO) of Sri Lanka.

73

74   In total, 154 households were surveyed, with, 94% of the residential buildings having

75   been built using loadbearing masonry walls, with the remainder primarily constructed

76   from reinforced concrete frame with masonry in-fill construction. The masonry materials

77   were split equally between fired clay brick masonry (a locally produced cottage industry

78   style brick commonly found in Sri Lanka) and cement sand block masonry (a relatively

79   low strength solid cement block, with no large aggregate, commonly found throughout

80   Sri Lanka). The walls in the single storey houses were typically less than 100 mm thick

81   masonry units (both fired clay bricks and cement blocks) typically with cement-sand

82   mortars of thicknesses varying between 10-25 mm thick. The walls were usually

83   plastered or rendered inside and out with a cement-sand mortar mix around 15-20 mm

84   thick, and subsequently painted. The typical total wall thickness therefore rarely

85   exceeds 135 mm, which is less than the 200 mm minimum thickness recommended by

86   Sri Lankan building standards for masonry units in external walls [Nawagamuwa &

87   Perera 2015]. This general lack of compliance enhances the need for retrofitting and

88   strengthening.

89

90   In 83% of buildings surveyed in the flood affected regions, the flood waters reached at

91   least 2 metres high. Damage to masonry walls and buildings from the flooding

92   characterised during the field survey included: cracking/failure between adjoining walls

93   (Figure 2); cracking along solid walls (Figure 3); cracking/failure around openings

94   (Figure 4); and total wall collapse (Figure 5).

95

96

97   Figure 2. Cracking between adjoining walls

98

99

100   Figure 3. Cracking in solid wall

101

102   Figure 4. Cracking around opening

103

104

105   Figure 5. Total wall collapse

106

107   Many walls also showed moisture ingress, leading to subsequent mould growth, as well

108   as cracking of plaster and masonry. Cracking, and failure, of walls was likely caused by

109   many interconnected factors unique to each site. However the majority of the damage

110   can be attributed to an out-of-plane flexural failure due to the presence of horizontal

111   flexural cracks commonly observed in the field survey. This is most likely due to the

112   hydrostatic lateral pressures from the water inducing flexural failure parallel to the bed

113   joint as well as a reduction in material strength due to the ingress of moisture into the

114   masonry. Addressing this is the focus of the experimental programme.

115

116

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

139   the constituents generally comprise cement, sand, and quarry dust. The nominal

140   dimensions of the cement blocks were 400 mm (length) 100 mm (width) x 200 mm

141   (height). The fired clay brick and cement blocks used are shown in Figure 6.

142

143

144   Figure 6. Masonry units

145

146

147   *3.1.2 Mortar*

148   Masonry wall panels were built to determine the flexural and compressive strength of

149   the cement block and fired clay brick masonry using representative materials. The wall

150   panels were built using the same mortar mix commonly used in Sri Lankan practice, a

151   1:6 cement: sand mortar using Ordinary Portland Cement and a river sand fine

152   aggregate. The sieve analysis results for the sand are shown in Figure 7.

153
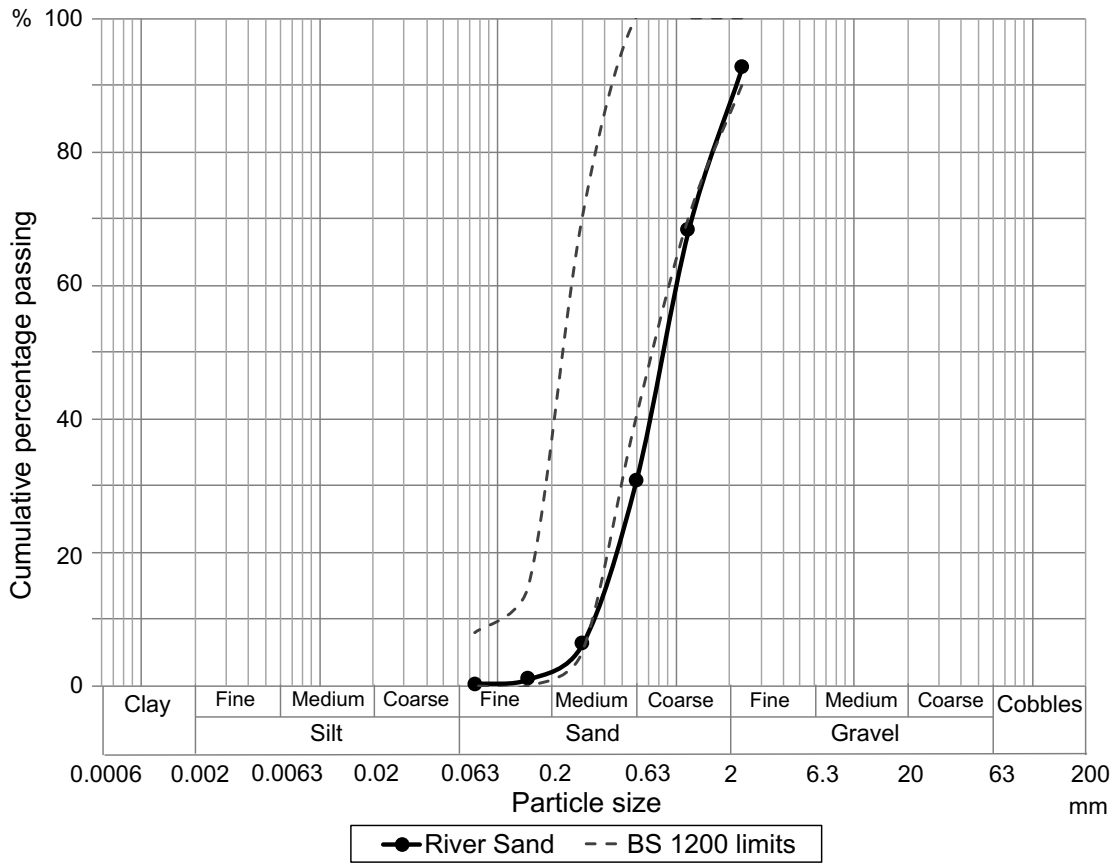
Figure 7. Sand composition related to BS1200 requirements

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%).

12

163   *3.1.3 Masonry wall panels*

164   The field survey identified a wide variation in mortar bed joint thickness, reflecting the

165   poor dimensional regularity of the units and the variable quality of the works. To

166   investigate the influence of mortar joint thickness compressive strength panels were

167   built in three series for both the fired clay bricks and cement blocks, each having bed

168   joints nominally 10 mm, 17.5 mm and 25 mm (± 3mm) thick.

169

170   In keeping with common Sri Lankan practice, the clay bricks were immersed in water for

171   5 minutes prior to laying to account for their high water absorption, whereas the cement

172   blocks only wetted just before laying, thereby reducing the dewatering effects of the

173   masonry unit on the mortar. Immersion resulted in average moisture contents at laying

174   of the units of 2% for cement blocks and 14% for fired clay bricks.

175

176   *3.1.4 Materials used for Retrofitting*

177   In Sri Lanka, and many other areas with tropical climates, single leaf masonry panels

178   are typically plastered (internal application) or rendered (external application) to improve

179   resistance to moisture ingress as well as their aesthetics. In Sri Lanka masonry wall

180   surface coatings, such as internal plasters and external renders, are both commonly

181   formed using a 1:5 cement to sand ratio mix. This mix, slightly richer than that used for

182   the mortar joints, is commonly applied in one or two coats up to 15-20 mm total

183   thickness. These surface coatings will likely increase the flexural capacity of the walls

184   which, together with the inclusion of reinforcement, could sufficiently improve capacity to

185   resist flood loads. Using reinforced surface coats with unreinforced masonry walls is not

186   included in current practices in Sri Lanka. The application of the unreinforced and

187   reinforced surface coating to low strength vernacular masonry, with consideration of the

188   socio-techno-economic climate, has been investigated as a method of improving the

189   lateral load resilience.

190

191   A PVC coated galvanised mild steel wire mesh, (widely available from local hardware

192   stores and building merchants) was selected (Figure 8). The square mesh,

193   manufactured in Sri Lanka, is comprised of 0.81 mm diameter wires spaced at 12.5 mm

194   openings. Normally used as a lightweight material for a variety of domestic uses, it was

195   selected for its low cast, ease of handling, and readily availability throughout Sri Lanka.

196   Welded wire mesh products tend to be orthotropic due to their production process

197   where the longitudinal wires (machine direction - *md*) are under tension as the cross

198   wires (cross machine direction - *cmd*) are welded in place.

199
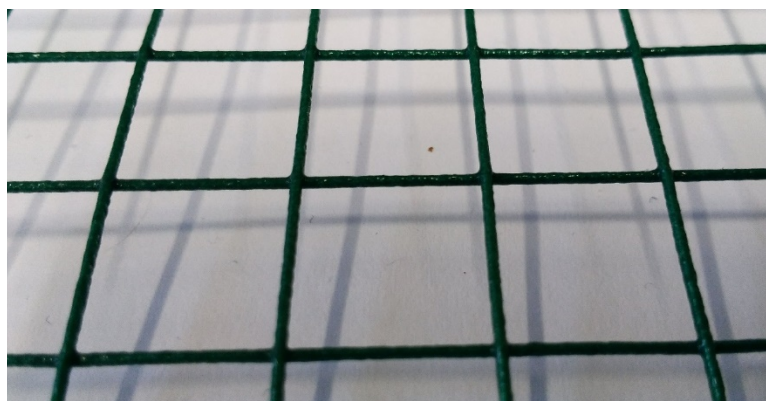
200

201   Figure 8. PVC coated welded wire mesh

202

203 The selected mesh was tested in uniaxial tension. For each direction, 10 wires 140 mm

204 in length were cut from a single roll of PVC coated welded wire mesh (PWWM) from

205 edge and central regions of the roll. The strain was determined by using a clip gauge

206 placed in-between the welds and on top of the PVC coating. The experimental

207 properties of the mesh are reported in Table 1.

208

209 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%)

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

211

212 A 17 mm thick 1:5 cement:sand plaster coating was applied in two coats: an initial

213 scratch coat of 10-12 mm thickness followed by a 5-7 mm thick topcoat. The surface

214 coating was applied only to one face of the panels; the face subjected to tension during

215 testing. The surface coating was the same material as that used for the mortar. The

216 PVC coated mesh was applied to the selected panels by pressing the mesh into the

217 scratch coat prior to the addition of the topcoat after an initial 14 days of curing and then

218 allowed to cure an additional 28 days before testing.

219

220

221 3.2 Test Methods

222 *3.2.1 Masonry Units*

223 The following material characterisation tests were conducted: density, initial moisture

224 absorption; total water absorption; unit compressive and flexural strength (under dry and

225 saturated conditions). Following unit tests, a series of masonry tests were completed to

226 determine flexural and shear strength.

227

228 Prior to characterisation samples of the cement blocks and fired clay bricks were oven

229 dried at 105°C until stable mass was achieved prior to establishing their density. Initial

230 Rate of Absorption (IRA) was also conducted in accordance with BS EN 772-11 (2000);

231 a sample of ten units were each individually placed bed face down into 3 - 5 mm deep

232 water for 1 minute. The change in mass of each unit was measured following removal

233 from the water tank and removing any excess surface moisture. Following the IRA test

234 the units were then immersed in water for 24 hours to establish their Total Water

235 Absorption (TWA) with the change in mass measured again. Dry and saturated samples

236 of both units were also subjected to compressive strength characterisation tests in

237 accordance with BS EN 772-1 (2015). In preparation for testing, the frog in the cement

238 blocks was filled with 1:3 (cement: sand) mortar.

239

240 *3.2.2 Mortar*

241 Characterisation testing of the mortars prepared for the prism tests included: flexural

242 and compressive strength, measured in accordance with BS EN 1015-11: 1999.

243 Specimens measuring 40 x 40 x 160 mm were prepared in triplicate. These were first

244 tested in flexure, with the two broken sections used for compressive strength resistance.

245

246 *3.2.3 Masonry Panels*

247 Plain (un-retrofitted) masonry panels were tested under compression and flexure

248 independently. The retrofitted samples were tested under flexure only. All tests were

249 undertaken with the two different masonry units, with five repeat tests completed for

250 each type. All panel types were tested under laboratory air dry conditions, with some

251 selected samples all tested saturated, following 24 hours submersion in water. The plain

252 masonry panels were constructed with the three mortar thicknesses, whereas the

253 retrofitted panels were constructed using only a single joint thickness of 17.5 mm. In

254 total 30 panels were constructed for compressive strength testing and 60 panels for the

255 flexural strength tests. These are summarised in Table 2. An additional five panels for

256 each masonry unit were constructed with 17.5 mm bed joints for testing under saturated

257 conditions. The masonry panels were cured in the laboratory and tested from 28 days

258 after construction. The masonry panels were constructed at different times and while a

259 standard mortar mix was used, samples of mortar was taken for each experimental

260 variation.

261

262   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

263

264   Two unit wide stack bonded wall panels were built to establish the compressive strength

265   of the cement block and fired clay brick masonry (Figure 9). The fired clay brick panels

266   were five courses high, whilst the cement blocks were three units high.

267

268

269   Figure 9. Masonry prism construction

270   The vertical compression testing was undertaken in accordance with

271   BS EN 1052- 1- 1999. The walls were loaded at a rate of 0.09 N/mm^2/min with all

272   failures occurring within 15 minutes.

273

274   Flexural strength was determined in accordance with BS EN 1053-2:1999 for both

275   parallel and perpendicular to the bed joint. For parallel flexure the panels of burnt clay

276   bricks were of length equivalent to two units and the height equivalent to seven courses.

277   For the cement blocks, the length was equivalent to 1.5 units long and the height was

278   equivalent to three courses. After the completion of each panel, further units were

279   stacked on top to provide a precompression load approximately equal to

280   2.5×10^{-3} N/mm^2. The panels were tested under four-point loading laterally, as shown

281   in Figure 10, in accordance with BS EN 1052-2:1999. Lateral loading was applied at a

282   steady rate equivalent to 0.03 N/mm^2/min.

283

284

285   Figure 10. Parallel to bed joint flexural test

286   Investigating the flexure perpendicular to the bed joint required different panel sizes.

287   The fired clay brick panels were four units wide and four courses high. The cement

288   blocks were 2½ units long by three courses high. After the completion of each panel,

289   further units were stacked on top to provide a precompression load approximately equal

290   to 2.5×10^{-3} N/mm^2. The panels were tested under four-point loading laterally in

291   accordance with BS EN 1052-2:1999. Lateral loading was also applied at a steady rate

292   equivalent to 0.03 N/mm^2/min.

293

294

295   **4. Results and analysis**

296   4.1 Masonry units

297   The water absorption characteristics and compressive strength properties for the

298   cement blocks and fired clay bricks are summarised in Table 3. The initial rate of water

299   absorption for both units is very high and likely to be detrimental to bond strength

300   between the units and mortar. The relatively poor quality of the units is also reflected in

301   their variability in performance, with Coefficients of Variation (CoV) in excess of 20%

302   (Table 3). Both masonry units present low compressive strength and when normalised

303   to account for the shape factor are not statistically different based on a 't test'. Similarly

304   the normalised performance, which accounts for their state of saturation, shows there is

305   no statistical difference between the dry and saturated cement blocks, but there is

306   statistically difference to the performance of the fired clay bricks. The normalised

307   compressive strengths (BS EN 772-1) are both less than 4.0 N/mm^2, but both comply

308   with local building regulation requirements for single storey construction of 1.2 N/mm^2

309   for the cement blocks and 2.8 N/mm^2 for fired clay bricks. However, neither would be

310   deemed suitable for two storey load-bearing masonry, where requirements increase to

311   2.5 N/mm^2 and 4.8 N/mm^2 for the block and brick respectively, according to the national

312   regulations in Sri Lanka. The moisture contents for the air-dry cement block and fired

313   clay brick samples were 1.5% and 3.3% respectively.

314

315   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%

316   [1] Average six test specimens

317   [2] Normalised unit strength in accordance with BS EN 772-1.

318

319   4.2 Mortar

320   Due to the range of mechanical testing undertaken, the flexural and compressive

321   strength properties of the 1:6 cement:sand mortar were measured for each test and are

322   presented together with masonry test results below. This resulted in 60 specimens

323   across 20 sample series with three specimens cast for each sample series. The mortar

324   strengths are presented alongside the masonry test results below. Specimens were

325   mostly tested between 28 and 35 days old, always coincident with testing of the

326   masonry panels. The average 28-35 day dry compressive strength was 5.97 N/mm^2

327 (Coefficient of Variation 15.9%), which is significantly stronger than the masonry units.

328 General practice in masonry recommends that mortar is weaker than the units. This

329 assists in reuse of the masonry units but also ensures cracking will generally occur

330 within the joints, rather than through the units, easing any necessary repairs. However,

331 with weaker masonry units, there could be a tendency to rely on stronger mortar since

332 the thickness of the mortar bed is also generally greater than the usually recommended

333 10 mm.

334

335 4.3 Masonry Panels

336 *4.3.1 Compressive strength*

337 The compressive strength properties of the cement blockwork and fired clay brickwork

338 prisms are presented in Table 4. The average mortar compressive (f_m) and flexural (f_{mt})

339 strengths are also included. Tests were only completed under air-dry conditions. The

340 characteristic compressive strength has been calculated in accordance with

341 BS EN 1052-1:1999. Failure of the wall panels in compression was preceded by vertical

342 cracking of masonry units prior crushing of the materials (Figure 11).

343

344 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

345

346

347   Figure 11. Brickwork prism failure in compression tests

348

349   The experimentally derived characteristic masonry compressive strength can be

350   compared with that predicted by EuroCode 6 (BS EN 1996: 2005). Taking the mortar

351   compressive strengths in Table 4 and f_b values from Table 3, the predicted

352   characteristic compressive strengths f_k are 1.7 N/mm^2 and 2.2 N/mm^2 for the cement

353   block masonry and fired clay brickwork respectively. The predicted values for both

354   masonry types compare quite favourably with the experimental values.

355

356   *4.3.2 Flexural strength*

357   The results for flexural strength parallel to bed joints are summarised in Table 5. The

358   average mortar compressive (f_m) and flexural (f_{mt}) strengths are also included. A

359   representative failure mode in testing is shown in Figure 12 with failures most commonly

360   at the interface between the mortar and unit. Therefore, it is expected that the bond

361   strengths are consistently lower than the flexural strengths of the mortar (Table 4). In

362 accordance with the testing standard, any panels where failure was observed outside of

363 the constant moment region have been excluded from the results.

364

365 After testing the panel series under dry conditions, a separate series of panels were

366 constructed under similar conditions but only with 17.5 mm bed joints. These panels

367 were fully submerged in water for 24 hours before testing, but after their initial 28 day

368 curing period, to represent static flooding conditions.

369

370 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

371

372

373 Figure 12. Parallel bed joint flexural test failure

374   The UK National Annex for BS EN 1996:2012 specifies characteristic flexural strengths

375   (f_{xk1}) as a function of unit total water absorption and mortar grade for clay brickwork, and

376   a function of unit type, unit compressive strength and mortar grade for concrete block

377   masonry. For the experimental materials the code values for f_{xk1} are 0.25 N/mm^2 for the

378   cement blockwork and 0.3 N/mm^2 for the brickwork; both are significantly higher than

379   the measured values.

380

381   The parallel to bed joint saturated flexural strengths for the cement block masonry and

382   fired clay brick decreased by 10% and 72% respectively. As parallel flexure was

383   determined to be the critical failure mode, both experimentally from dry results and

384   observations from the field study, no saturated tests were carried out for flexural

385   strength perpendicular to the bed joint.

386

387   The results for flexural strength perpendicular to bed joints are summarised in Table 6.

388   The average mortar compressive (f_m) and flexural (f_{mt}) strengths are also included.

389   Typical failure in testing is shown in Figure 13, with cracking observed at joint interfaces

390   but also through the masonry units. The measured values for the brickwork were

391   significantly lower than the value (0.9 N/mm^2) predicted by NA BS EN 1996:2012.

392

393   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			0.47	28.1%	0.32			0.52	27.8%	0.35
17.5 mm	6.92	2.66	0.60	12.5%	0.40	4.56	1.98	0.68	33.2%	0.46
25 mm			0.48	18.6%	0.32			0.64	23.4%	0.42

394

395

396 Figure 13. Perpendicular to bed joint flexural test failure

397

398 *4.3.4 Flexural tests on retrofitted masonry*

399 The results of the retrofitted panel tests, average of five repeat tests, are presented in

400 Table 7. The average mortar and plaster compressive (f_m) and flexural (f_{mt}) strengths

401 are also included in Table 7. Rather than flexural strength, the failure load resistance of

402 each specimen is presented. The panels failed in flexure, with horizontal cracking

403 observed at the masonry unit-mortar joint interfaces but also through the masonry units

404 (Figure 13).

405

406

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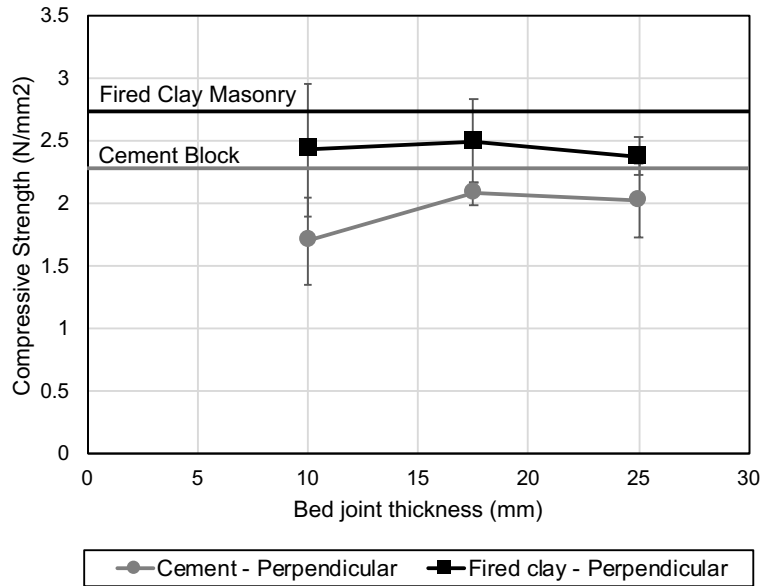
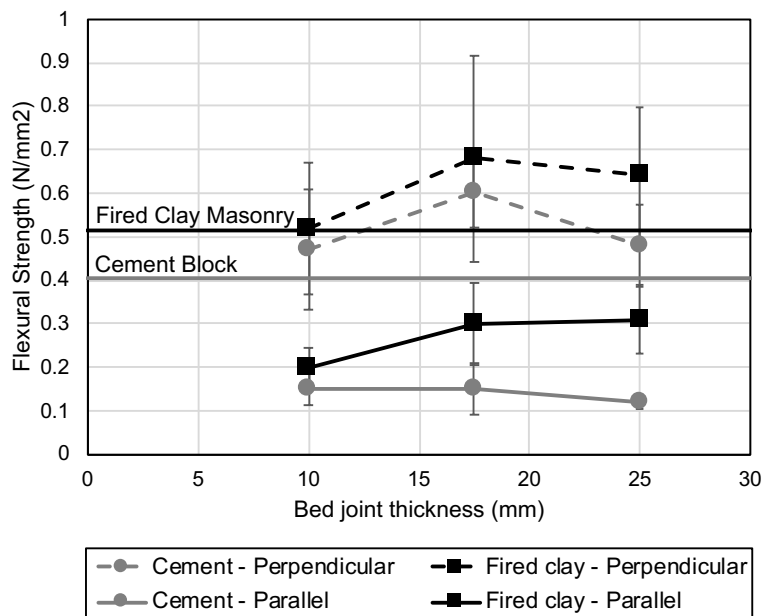Figure 14. Influence of mortar thinkness of compressive strength of masonry panels.

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.
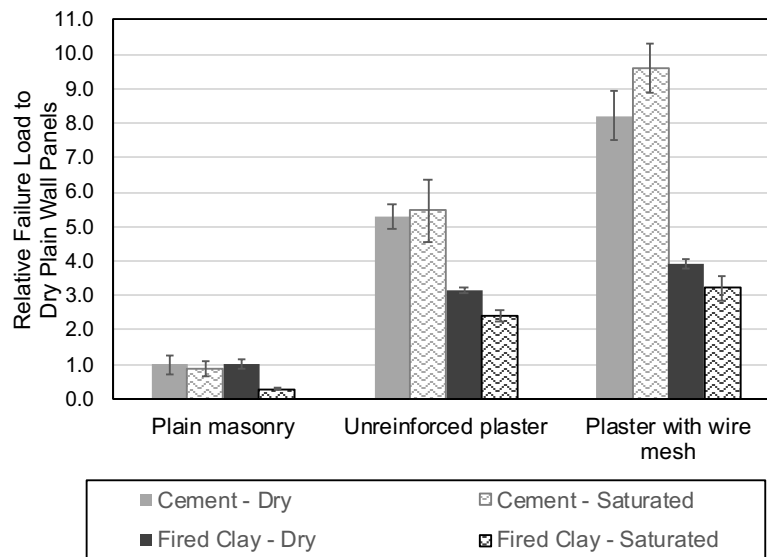

Figure 16. Relative Failure Loads of the wall panels compared to the Dry Plain Walls

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

31

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.

Acknowledgements

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