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MASONRY PANEL TESTING IN MALAWI

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Abstract

A holistic seismic risk management framework for East Africa, with particular focus on Malawi, is under development as part of the EPSRC-sponsored Global Challenges (GCRF) grant PREPARE. The project aims to co-produce practical tools and guidelines for enhanced disaster preparedness in close partnerships with local governmental and academic institutions. For the seismic vulnerability assessment of masonry buildings in Malawi, a series of tests were conducted in the field and in the Civil Engineering laboratory of the Malawi Polytechnic in Blantyre. The specimens and applied loads are of three main types: (a) single bricks subjected to uniaxial compression and three-point bending; (b) masonry prisms subjected to compression, direct tension and interface shearing; and (c) masonry panels of different brick configurations and reinforcement subjected to in-plane compression/shearing and out-of-plane bending in two planes. The specimens were built by local artisans using locally produced materials to simulate actual field conditions and indigenous construction methods. The different kinds of reinforcement tested were inspired by the recommendations of the Safer House Construction Guidelines of Malawi. Focusing on the masonry panel tests in (c) above, the main results from the experimental program are presented herein. The results help quantify the effect of simple, available types of retrofitting/reinforcing of masonry houses in Malawi.

Keywords: Masonry panel testing; laboratory testing; Malawi; Seismic vulnerability assessment

1. Introduction

Malawi is located along the East African Rift System where large earthquakes in excess of M_w7 are anticipated [1, 2]. As one of the least developed countries around the world, Malawi is coping with high poverty levels including poor infrastructure which increases the risk of major disasters to the local communities due to natural hazards. The Salima (1989) and Karonga (2009) earthquakes severely affected large populations, causing economic losses in the order of tens of millions US$ [3].

Post-earthquake investigations following these events demonstrated that the majority of damage was caused by poor construction, including methods, materials and inspection [4]. Unreinforced masonry is the prevailing construction type in both formal and informal settlements [5, 6]. The vast majority of the houses are built using inadequate materials like sun-dried or fired bricks and mud mortar. Production methods for the bricks lack quality control and are based on traditional skills of local artisans. In poor rural areas, unburned bricks are often the norm. Fired bricks are also used throughout the country, but burning is often inadequate and results in great variability in quality among bricks of the same batch. Mortar quality also varies from simple mud to low strength cement mortar incommensurate with the level of income and affordability. These poor materials combined with the lack of technical expertise and design codes lead to highly vulnerable masonry construction [7].

The experience acquired from previous disasters, together with the pressing need to provide housing in support of the rapidly increasing population in Malawi and the expansion of informal settlements, led to the recent release of the Safer House Construction Guidelines [8], as a joint effort of the Government and international aid organisation experts, to deal with the unregulated masonry construction in the country [9]. These guidelines mainly consist of qualitative instructions based on international experience and practice [10], which can improve the performance of housing structures built with poor quality materials, with local construction practices. Meanwhile, there is a need for proper quantitative assessment of the structural vulnerability based on local data to inform more effective disaster risk reduction actions for the current building stock and for the improved construction methods proposed in the guidelines. This ultimately provides an avenue to establish proper disaster preparedness strategies by stakeholders, such as government and non-governmental organisations.

The experimental work reported in this paper is an intermediate and critical stage in the process of developing an integrated risk assessment framework for East African countries, based on enhanced local data for hazard, exposure and vulnerability [11]. Previous studies by the authors [9, 12] presented results on the testing carried out in 2018 that focused mainly on obtaining realistic properties of local construction materials to inform numerical structural models for seismic vulnerability/loss assessment. In the following sections, the 2019 experimental campaign, performed in Malawi Polytechnic, is presented with a focus on the masonry panel testing to explore the effect of different types of reinforcement to the overall masonry behaviour. The reinforcement solutions tested were inspired by the recommendations of the Safer House Construction Guidelines [8] and are simple and inexpensive to implement using materials readily available in Malawi.

2. Seismicity in Malawi

Malawi is a landlocked country in Sub-Saharan Africa and is one of the least developed countries around the world. In Malawi, the seismic risk is considerable for three main reasons. Firstly, Malawi is located within the western branch of the East African Rift System (Fig. 1), where large earthquakes in excess of M_w7 have occurred including the 1910 Rukwa, Tanzania, earthquake [2]. In recent times, Malawi has experienced several M_w6+ events, including the 1989 Salima [13] and the 2009 Karonga earthquakes [14] which caused significant damage and loss. Secondly, local masonry structures are unreinforced and seismically vulnerable [15], and adequate seismic design provisions and construction practices are currently not in place. Thirdly, Malawi has been experiencing rapid population growth (annual growth rate of about 3%), and more people migrate into informal settlements surrounding major cities, such as Lilongwe and Blantyre [6, 16].

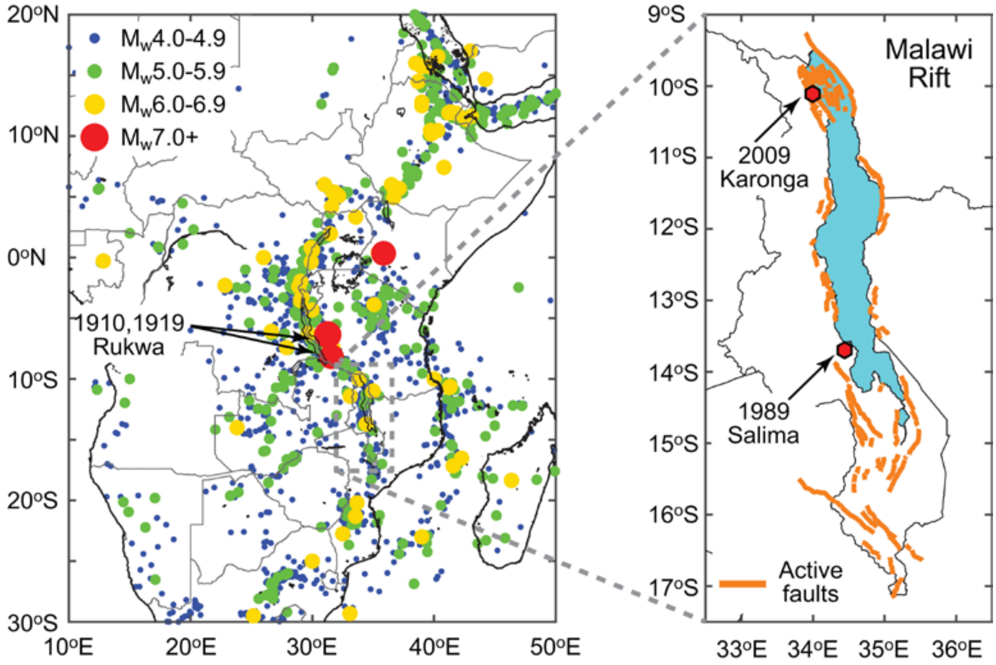


Fig. 1 – EARS: East African Rift System and Malawi Rift.

3. Typical Houses in Malawi

Fig. 2 shows typical houses in Malawi that are, almost exclusively, one-storey buildings made of locally moulded, sun-dried or fired clay bricks and mud or low-strength cement mortar. Walls are often single-skin, against the local guidelines. Double-skin walls are built in the case of higher-income households; however, they are not always adequately constructed. Roofs are typically pitched, constructed by wooden beams and covered using iron corrugated sheets, or thatched (Fig. 2(b)). Quality of materials is low; compressive strengths of bricks vary between 1 and 10 MPa (typically lower than 5 MPa), even within the same batch. The mortar used to bond the bricks varies from plain mud to cement-sand mixtures. The latter typically have a cement-to-sand ratio significantly lower than the either 1:4, suggested for structural masonry (or 1:3 for foundations and special applications) according to MS791-1 [17] or the minimum ratio of 1:6 recommended in the Safer House Construction Guidelines [8]. In local construction practice, the ratio typically depends on the income level of the household and it is generally lower than 1:6 (often 1:8 or even lower) [9].

(a) unfired bricks / mud mortar

(b) fired bricks / mud mortar

(c) fired bricks / cement mortar

Fig. 2 – Typical houses in rural and urban areas of Malawi made of unreinforced bricks and mortar. [7]

In addition to the lack of proper construction materials, the overall quality of the masonry construction is further affected by the climate and the housing construction in Malawi taking place almost invariably during the dry season. The hot, dry weather combined with high water absorption by the clay bricks and low-quality surfaces (mainly dusty surfaces with loose particles), often results in weak bonding that renders the structures vulnerable. In the testing program presented in the next section, these effects have been considered to obtain realistic data.

4. Testing Program

The testing program was conducted both in the field and at the Civil Engineering laboratories of the Malawi Polytechnic and intended to capture the actual field conditions and traditional construction methods of the country. The campaign spanned over three years and encompassed two major activities: (1) material testing and (2) near full-scale masonry panel testing.

The material testing, described in detail in [9], included field and lab testing of:

(i) Bricks: tested under uniaxial compression and 3-point bending [18, 19].

(ii) Mortar: mortar cubes under compression and mortar prisms under flexure [20].

(iii) Brick/mortar interfaces: direct tension on crossed brick couplets [21] and interface shear on brick triplets [22].

4.1. Panel Tests

The panel testing investigates the performance of masonry wall panels, constructed in the Malawi Polytechnic Civil Engineering Laboratory, under pseudo-static lateral loading and aimed to (1) derive constitutive properties of the local masonry and (2) examine the effect of different types of reinforcement on the overall masonry behaviour. To this end, 112 panels were tested (36 in 2018 and 76 in 2019) both in-plane and out-of-plane, which required designing and constructing specimens as well as bespoke testing equipment for the following three types of tests:

(A) *In-plane tests*: Thirty-six (36: 12 in 2018 and 24 in 2019) panels compressed diagonally to measure the shear strength of the masonry panel (according to [24])

(B) *Out-of-plane flexural tests*: Forty-seven (47: 12 in 2018 and 35 in 2019) panels bent parallel to the bed joints (according to [22, 23])

(C) *Out-of-plane flexural tests*: Twenty-nine (29: 12 in 2018 and 17 in 2019) panels bent perpendicular to the bed joints to measure the flexural strength of the panels in that direction (according to [22, 23])

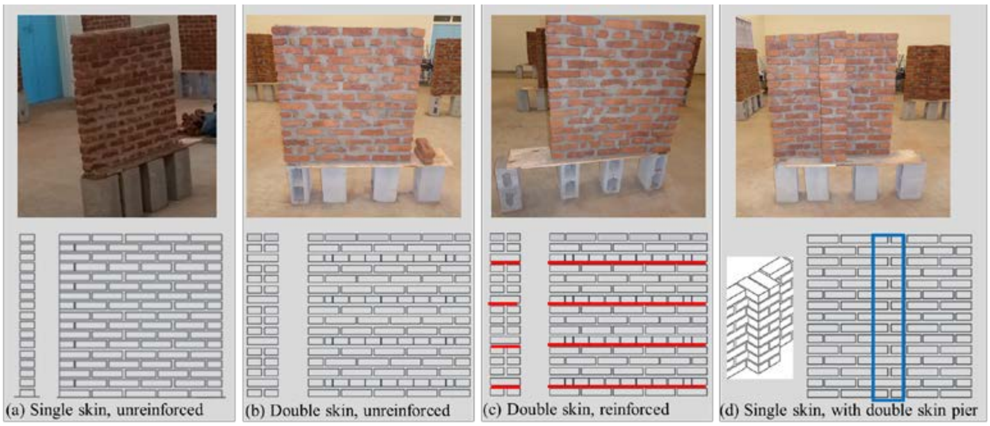


Fig. 3 – Types of panels and reinforcement tested in-plane.

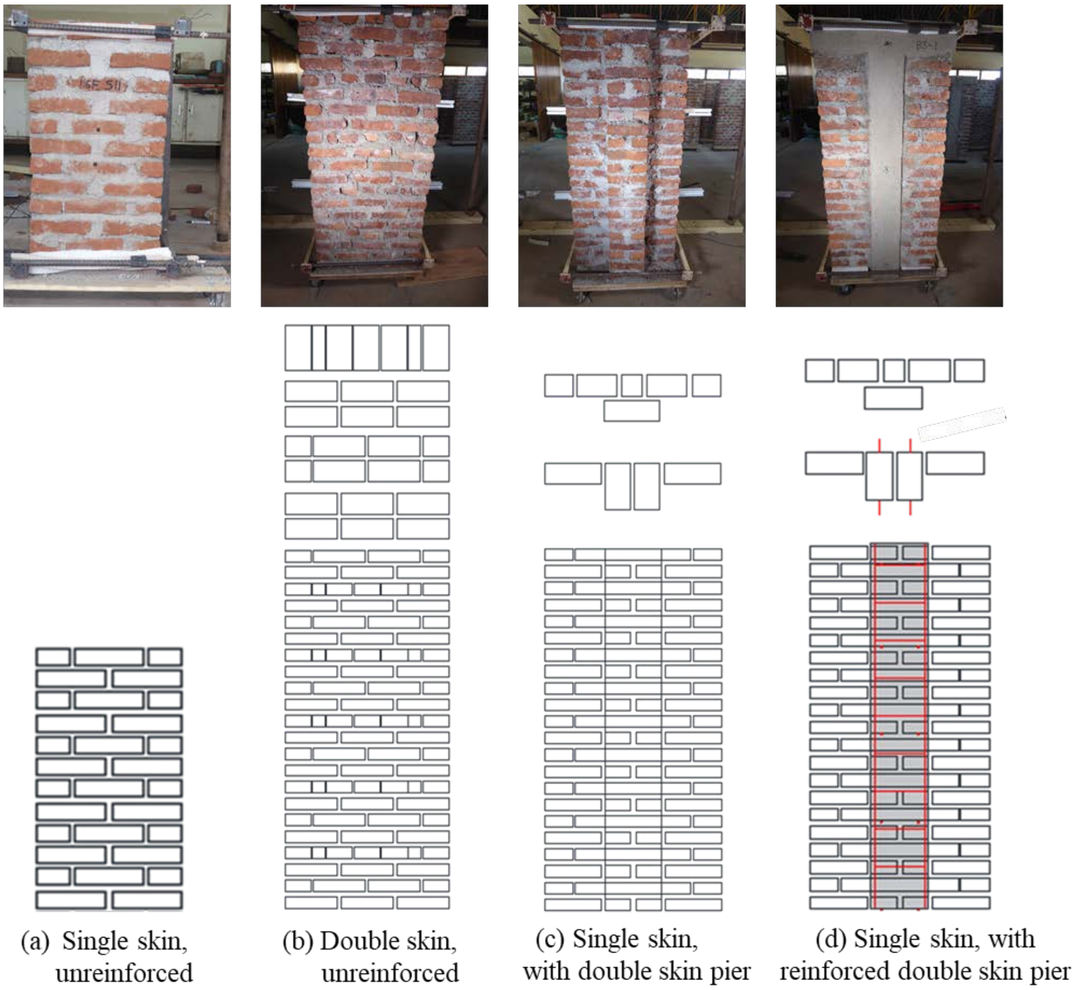

(a) Single skin, unreinforced
(b) Double skin, unreinforced
(c) Single skin, with double skin pier
(d) Single skin, with reinforced double skin pier

Fig. 4 – Types of panels and reinforcement tested out-of-plane/parallel.

The types of masonry tested varied from unreinforced single-skin to double-skin panels, to different types of reinforcement. The reinforcement solutions considered were based on the Safer House Guidelines [8]; They are simple and easy to implement using materials and methods available in Malawi. More specifically, the following types of panels were tested:

(A) *In-plane (36 specimens in total)*:

- Single-skin wall, unreinforced (12 in 2018; 6 in 2019)
- Double-skin wall, unreinforced (6 in 2019)
- Double-skin wall, reinforced with brick force wire embedded in the brick layering mortar (6 in 2019)
- Single-skin wall, with a central double-skin pier, unreinforced (6 in 2019)

(B) *Out-of-plane / parallel (47 specimens in total)*:

- Single-skin wall, unreinforced (12 in 2018; 5 in 2019)
- Double-skin wall, unreinforced (6 in 2019)
- Single-skin wall, with a central double-skin pier, no reinforcement (12 in 2019: 6 tested with pier

under tension and 6 with pier under compression)

- Single-skin wall, with a central double-skin pier, reinforced externally with force wire running along the pier, on both sides (12 in 2019: 6 tested with pier under tension and 6 with pier under compression)

(C) *Out-of-plane / perpendicular (29 specimens in total)*:

- Single-skin wall, unreinforced (12 in 2018 and 5 in 2019)
- Double-skin wall, unreinforced (6 in 2019)
- Double-skin wall, reinforced with brick force wire embedded in the brick layering mortar (6 in 2019)

Figs 3 - 5 show the different typologies of panels and reinforcement mentioned above. As shown in Fig. 3(b) for the double skin panels, the bricks are laid with headers every four layers positioned symmetrically. The reinforcement with horizontal brick force wire (Fig. 3(c)) is a practice recommended by [8] and is installed every four layers of bricks, symmetrically along with the height of the panel. The flexural tests parallel to the bed joints that involve reinforcement with double skin pier are tested considering both bending possibilities: pier under compression and pier under tension.

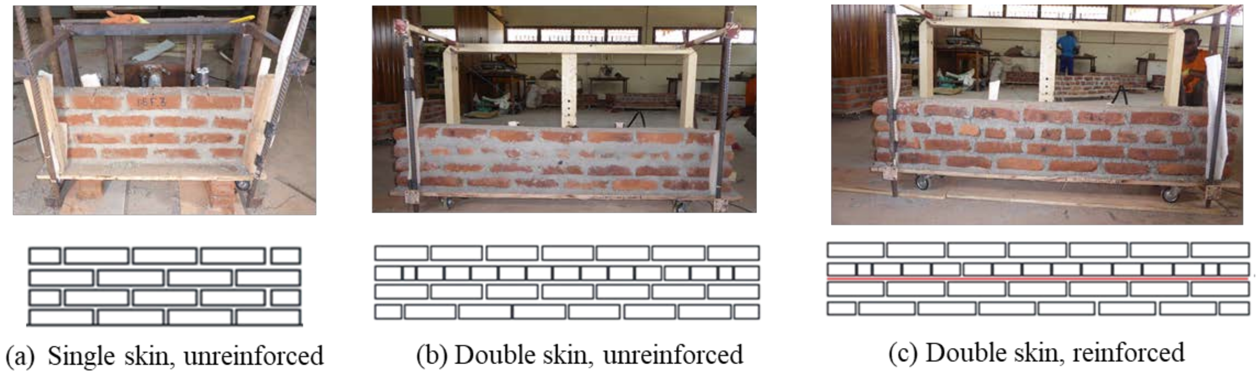

(a) Single skin, unreinforced (b) Double skin, unreinforced (c) Double skin, reinforced

Fig. 5 – Types of panels and reinforcement tested out-of-plane/perpendicular.

4.1.1. Specimen Preparation

The testing programme employed established international methods and standards, with the exception of the specimen preparation and curing, which were specifically designed to replicate the actual field conditions. Firstly, bricks used for the construction of specimens were sourced from ordinary commercial local production batches that exhibited the same range of strength values and variability. Then, the panels were built at the Civil Engineering Laboratory of the Malawi Polytechnic using materials prepared by local artisans, by means of traditional, representative, techniques to replicate the actual field conditions as realistically as possible. The nominal brick dimensions were 200 *mm* × 90 *mm* × 50 *mm* exhibiting some deviation from approximately 190*mm* × 80 *mm* × 40 *mm* for the smallest, to 210 *mm* × 100 *mm* × 60 *mm* for the largest. The specimen geometry was selected to produce panels, depending on the brick size, of approximately 1.1*m* × 1.1*m*, for the diagonal compression test, and 1.40*m* long for the flexural test.

For the first round of panel testing conducted in 2018 on single-skin panels, four different mortar types were employed: three cement-to-sand mix ratios of 1:4, 1:6, and 1:8, plus mud mortar. For the cement mortars, two different conditions were considered: a) “unfavourable” with mortar applied on dry and dusty bricks and b) “favourable” with bricks soaked in water prior to masonry construction [9].

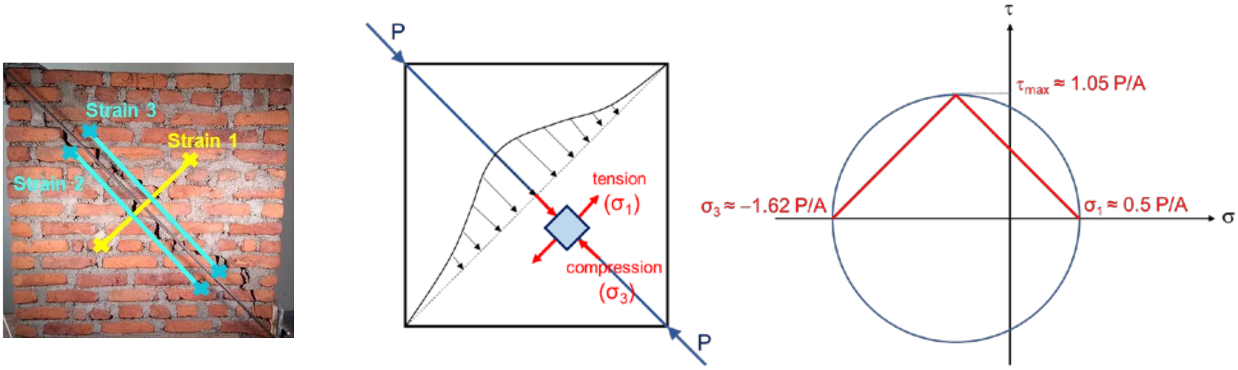
In 2019, the objective was to examine the effect of reinforcement, therefore one type of mortar material was selected as representative of an average condition. The mortar joints were prepared using a 1:6 cement/sand mixture with constant water/cement ratio of approximately 0.5, and favourable bonding conditions (i.e. clean bricks with no surface dust, bricks wetted before use, panels kept moist during curing). The joints were between approximately 10 and 25 *mm* thick.

4.1.2. Testing Equipment

The laboratory testing equipment (Fig. 6) consisted of a combination of (1) conventional testing devices with a number of portable testing rigs mountable on the specimens directly and on the strong floor, and (2) a high-precision video tracking system to measure displacements (Imetrum Video Gauge, [25]), with synchronised analogue load cell signals connected to it.

(a) (b)

Fig. 6 – The (a) in-plane and (b) out-of-plane testing apparatus and Imetrum Vision System.



(a) (b)

Fig. 7 – Test measurements and interpretation (Fig. 7b modified after [26])

The diagonal compression test was performed according to the in-situ variant of the test with the wall panel upright [26]. Test measurements were: (i) analogue, taken through two synchronised load cells (Fig. 6) attached to the loading shoe in the upper left corner of the specimens; and (ii) digital, monitored by the vision system, in the case of the specific test as strain gauges along the two diagonals of the specimen. In interpreting the above measurements into shear strength, RILEM standards were chosen [26, 27] shown in Fig. 7.

5. Results

5.1. Material Testing

Representative samples from the batch of bricks, mortar cubes, and brick force wire were tested to infer the material properties of the individual elements of the masonry panel. Fig. 8 shows results from the three-point bending tests on 82 bricks, in total, tested in three different occasions, in both lab and field as follows:

(a) 44 bricks were tested in the field, in 2018, from selected areas of interest across Malawi (Salima, Mangochi, Balaka, Golomoti-Mua and Blantyre) [12]

(b) 12 sample bricks from the batch used to build the 2018 wall panels were tested in the lab, and

(c) 26 sample bricks from the batch used to build the 2019 wall panels were tested in the lab.

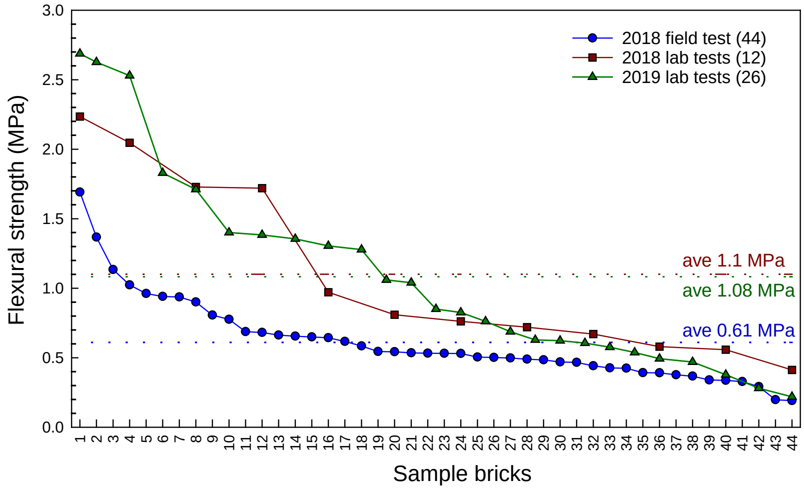


Fig. 8 – Results from 3-point bending tests on 82 bricks during 2018, 2019 laboratory tests and the 2018 fieldwork. (Number in brackets refers to sample size.)

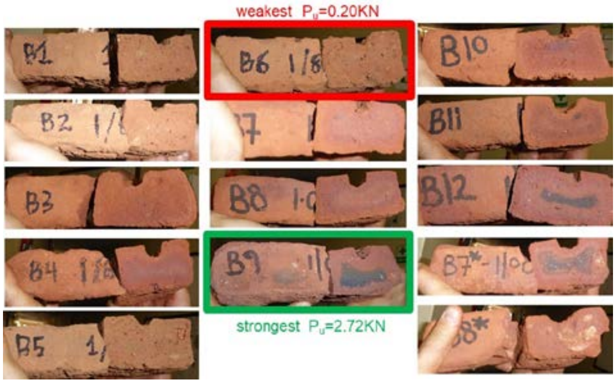


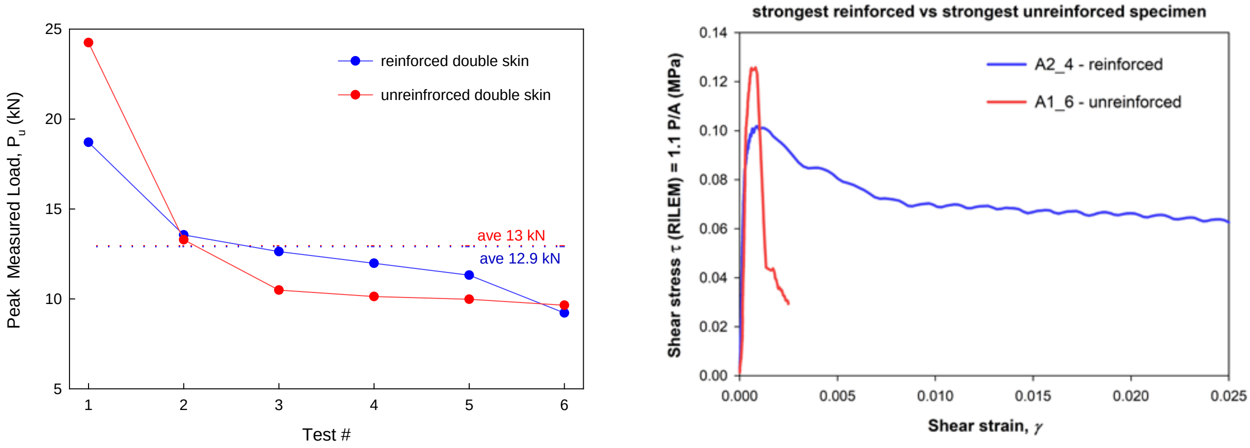
Fig. 9 – Fired clay bricks tested in flexure(/shear) (3-point bending test) from the 2019 batch.

Although all bricks tested during the 2018 lab work and all bricks tested in 2019 were selected from batches with almost the same average sizes, variability in strength was significant, ranging from 0.28 to 2.6 MPa. Coefficient of Variation (CV) is 58% for the 2018 lab tests and 65% for the 2019 lab tests. Interestingly, the mean values of the two batches are almost identical (~1.0 MPa average flexural strength). Bricks found in rural areas and tested in the field exhibited, again, significant variability in strength (CV 49%), and lower average strengths (~0.6 MPa average flexural strength), as expected.

5.2. Masonry Panel Tests

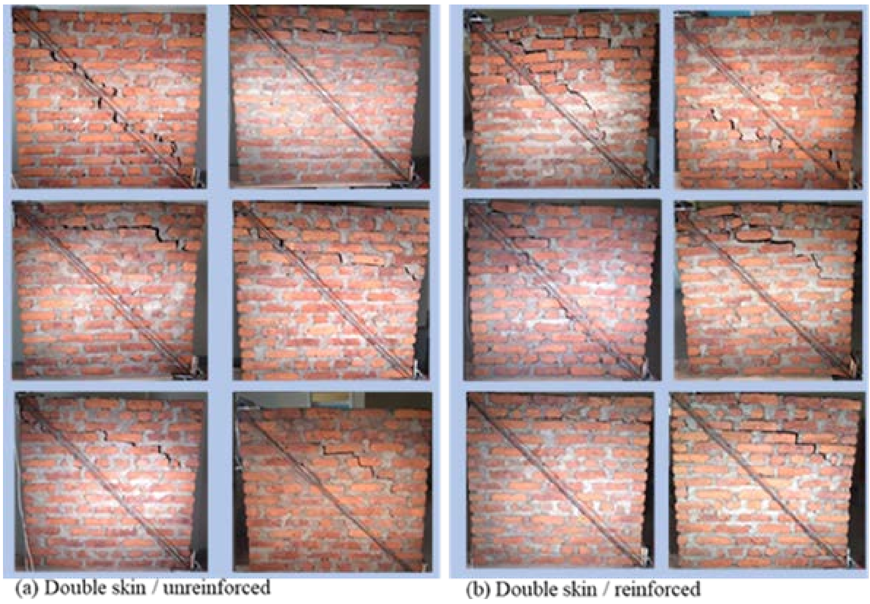
5.2.1 In-plane tests

Results from the in-plane shear tests are shown in Fig. 10(a) in the form of peak measured load P_u. Two types of panels are shown here for comparison: (1) unreinforced double-skin walls and (2) double-skin walls of the same geometry and material, reinforced using horizontal layers of brick force wire. The results indicate that both panel types have almost identical average shear strengths (average peak measured loads in both types of tests were 13kN.) with reinforced panels exhibiting, naturally, a smaller scatter. The failure mechanisms, however, are different as shown in Figs. 10(b) and 11: failure mode in unreinforced panels is brittle, along the mortar interfaces. On the other hand, reinforced panels exhibit a more uniform distribution of cracks – concentrated mostly along the diagonal.



(a) (b)

Fig. 10 – (a) Peak measured loads from in-plane tests on double-skin unreinforced panels and panels reinforced using brick force wire; (b) Comparison of strongest unreinforced double-skin panel to strongest reinforced with force brick wire, from in-plane tests. Measured shear strain; shear stress interpretation after RILEM [27] standards.



(a) Double skin / unreinforced (b) Double skin / reinforced

Fig. 11 – Failure mechanisms for in-plane tests on different types of panels: (a) unreinforced and (b) reinforced double-skin walls.

By comparing the strongest of each type (Fig. 10(b)), the unreinforced panel carried a larger load. The initial ("elastic") stiffness is identical – as both panels are of the same material and geometry – but the unreinforced one has a brittle failure mode while the reinforced one carries loads up to a nominal shear strain of 2.5%. Evidently, the reinforcement increases ductility, not strength.

5.2.2. Out-of-plane tests

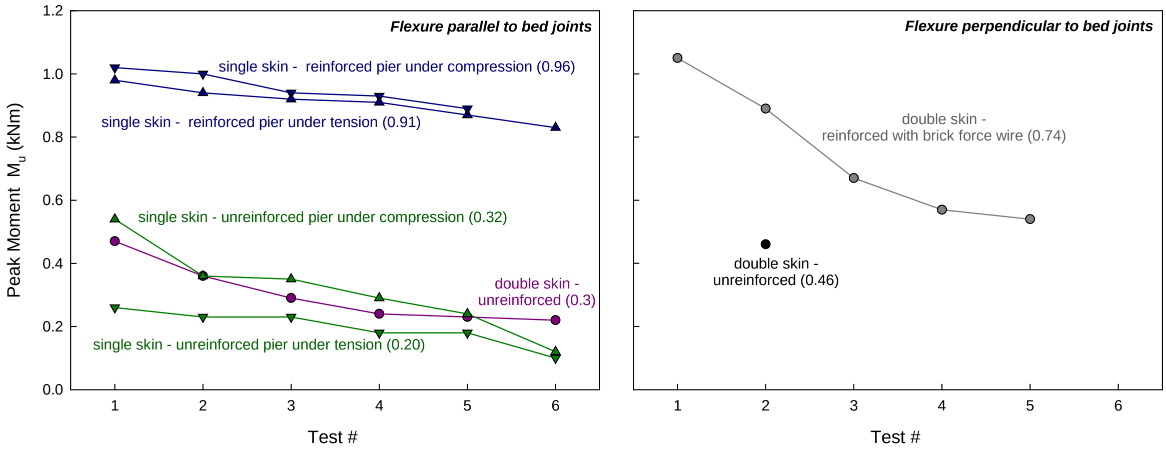


Fig. 12 – Peak measured moments from out-of-plane flexural tests on different types of reinforced panels, parallel and perpendicular to the bed joints.

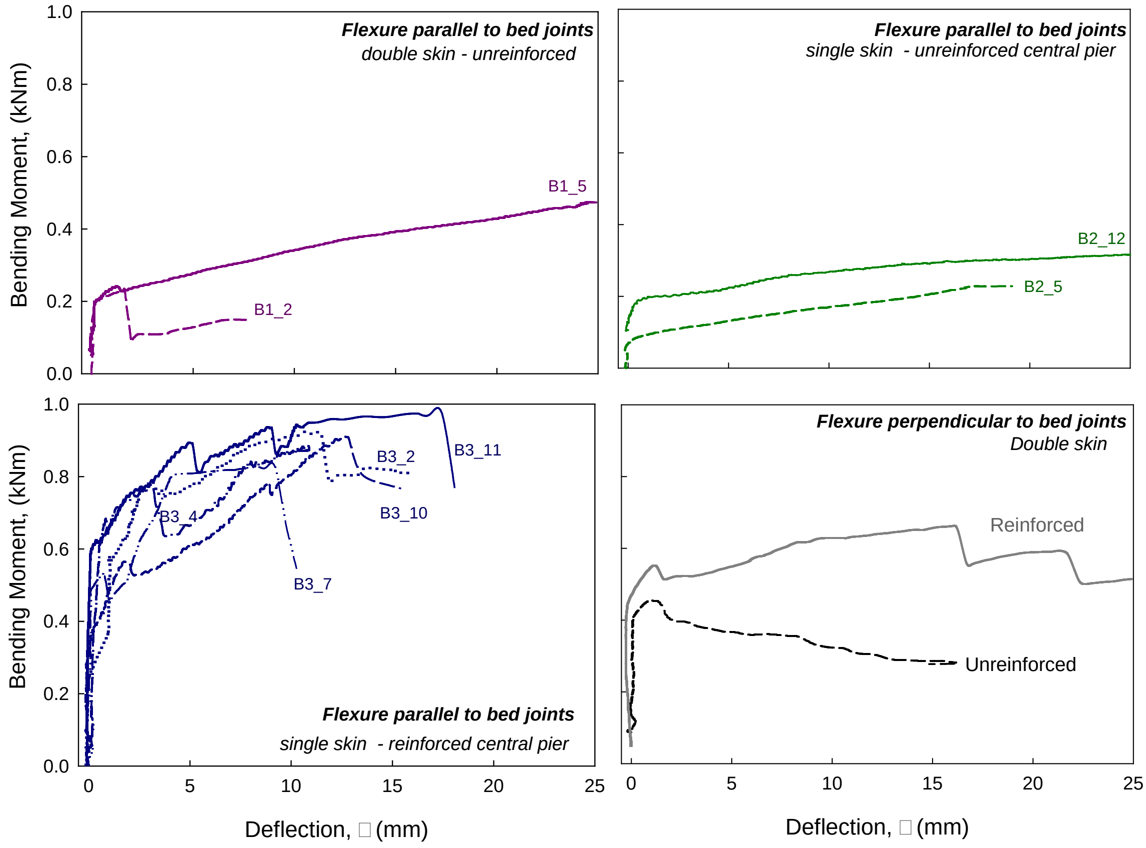


Fig. 13 – Selected moment-deflection curves from the out-of-plane flexural tests on different types of reinforced panels, parallel and perpendicular to the bed joints.

The out-of-plane flexural behaviour is among the most critical parameters influencing the performance of masonry structures under seismic loading. Figs. 12 and 13 present results in terms of measured (derived from test data) peak moments (Fig. 12) and moment-deflection curves (Fig. 13). As evident from both figures, the reinforcement with external brick force wire along the two sides of the pier has significantly improved the out-of-plane response parallel to the brick courses which is the weaker of the two modes of failure.

In Fig. 13 one may observe similar behaviour in low loads, under 0.3 kNm, in all specimens. This is expected, given that all specimens are of the same material and geometry. At higher loads, however, the reinforcement provides extra strength and ductility. In the case of flexure loads perpendicular to the brick courses (Fig. 13(d)), the layers of brick force wire do not significantly improve the response.

6. Conclusions

This work reports on an experimental study on the strength of Malawi masonry construction. The results help quantify the effect of simple retrofitting/reinforcing methods of masonry houses in Malawi and can be used to validate/calibrate finite-element and discrete-element numerical models to be employed in assessing earthquake risk and losses in the area. The main conclusions from this study highlight:

1) Significant variations of material properties and local construction conditions lead to a large scatter of strength results for low-quality masonry in Malawi.

2) Although all bricks tested during the 2018 lab work and all bricks tested in 2019 were selected from batches with almost the same average sizes variability in strength is high, ranging from 0.28 to 2.6 MPa. Interestingly, the mean values of the two batches are almost identical (~1.0 MPa average flexural strength). Bricks found in rural areas and tested in the field showed lower average strengths (~0.6MPa average flexural strength).

3) Reinforcement does not increase shear strength but significantly improves the overall behaviour of the masonry panel by providing ductility to the system which allows reinforced panels to carry loads up to a nominal shear strain of 2.5%.

4) A simple, low-cost reinforcement technique of a simple single-skin wall panel, using brick force wire along the two sides of a central double-skin pier significantly improves the out-of-plane flexural behaviour in terms of both strength and post yielding stiffness/ductility.

Further analyses and post-processing of the results are required to obtain representative/characteristic values of the different masonry retrofitting types.

7. Acknowledgements

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8. Data Availability Statement

This publication is in compliance with EPSRC Open Access framework. All underlying data are available to download from [28].

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