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SEISMIC VULNERABILITY ASSESSMENT OF NON-ENGINEERED MASONRY BUILDINGS IN MALAWI

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Abstract

Malawi is located within the southern branch of the active East African Rift System, where earthquakes of Mw 7.0 (or greater) can occur along major faults. In Malawi, the majority of dwellings in both formal and informal settlements are non-engineered unreinforced masonry constructions, built by local artisans with little input from engineers. These constructions are highly vulnerable to seismic events due to poor materials and lack of construction detailing. This study develops analytical vulnerability functions that enable the assessment of seismic capacity of typical buildings in Malawi. Since the seismic vulnerability greatly depends on building characteristics, geometrical and structural data are collected by conducting semi-rapid surveys of 300 houses located in urban and rural areas of Central and Southern regions of Malawi. Mechanical properties of the local materials are also obtained from an experimental campaign. In this work, a mechanical method FaMIVE (Failure Mechanism Identification and Vulnerability Evaluation) is adopted and the effects of both in-plane and out-of-plane behaviour of the masonry structures are taken into consideration to derive capacity curves for seismic vulnerability assessment. Special attention is given to 1) the Malawian building typologies as described in the Word Housing Encyclopedia and 2) failure mode classes for the Malawian constructions as calculated by FaMIVE. Hence, the derived vulnerability functions can serve as a benchmark for typical buildings in Malawi. The results and conclusions are also relevant for other East African countries, where similar construction techniques are adopted.

Keywords: non-engineered masonry constructions, mechanical approach, seismic vulnerability, capacity curves, East African Rift System

1. INTRODUCTION

Malawi is located in Sub-Saharan Africa and shares borders with Mozambique, Zambia, and Tanzania. The country is ranked as the third poorest country in the world [1, 2]; where the main economic sector is agriculture, which is often negatively affected by adverse environmental disturbances and hazards (e.g. drought, poor health, heavy rains, windstorms, and floods).

Malawi is also a seismic-prone country within the southern branch of the active East African Rift System, where M_w 7.0 (or greater) earthquakes can occur near major geological faults [3, 4]. In recent years, the most significant earthquake in the country occurred in 1989 with Mw 5.7 in Central Malawi, making 50,000 people homeless [5].

In Malawi, residential buildings are made of unreinforced masonry and are regarded as non-engineered constructions, since they are built by local artisans with little input from qualified engineers. These dwellings are built informally, using poor-quality materials and inadequate structural detailing. Issues related to seismic vulnerability of non-engineered masonry structures need to be investigated through methods for building performance assessment by taking into account geometry and strengths/weakness of local structures. In fact, such an undesirable situation is prevalent across many countries in East Africa and most developing countries around the world.

During the first preliminary investigation carried out in Malawi by the authors to identify the prevalent building features and understand local construction practice, information was gathered from the Malawi Housing and Population Census [6] and World Housing Encyclopedia [7], and the Malawian Safer Housing Construction Guidelines [8]. As discussed in [9], collected data underlined high inconsistencies between datasets, highlighted by different criteria adopted to identify building typologies and distributions and non-compliance with design standards and guidelines.

To overcome discrepancies identified in the available data, in this work on-site investigations on local constructions are carried out with the aim at investigating the real distribution of the local buildings and identify parameters affecting the seismic vulnerability of the selected regions. Based on the collected data, seismic performance of the inspected houses is estimated by using a viable mechanical approach FaMIVE (Failure Mechanism Identification and Vulnerability Evaluation; [10, 11]), which evaluates failure modes and capacity curves by taking into account geometrical/structural features observed on site and mechanical parameters derived experimentally. Results will provide useful data for the development of structural vulnerability evaluation tools for masonry structures in Malawi, and for the implementation of risk assessment frameworks for East African countries [12].

2. METHODOLOGY

In order to enhance the data on building features of the Malawian buildings available from local/global datasets and guidelines [6, 7, 8], on-site structural surveys were carried out on 300 buildings. Data collected during the on-site inspections characterize urban and rural settlements of the Central-Southern Malawi, selected as a representative country in the East African Rift region, where rapid expansion of informal settlements is occurring. Recorded information includes geometry in plan and elevation, structural condition related to connections between walls, roof structures, masonry type and fabric quality, as discussed in Section 3. With reference to the collected data, in Section 4 inspected buildings are classified in building typologies. The adopted classification for the Malawian constructions was proposed by the authors in a World Housing Encyclopedia report [13], where three typologies were identified to classify buildings according to their expected seismic vulnerability.

Seismic performance and actual vulnerability of the three identified building typologies are evaluated in Section 5 using the mechanical approach FaMIVE [10, 11]. The proposed approach was adopted to capture failure modes and derive capacity curves as a function of the geometrical/structural data collected on site. Furthermore, since the major factors influencing the building performance are correlated the strength properties of masonry materials commonly used for housing construction in Malawi, these are also defined following an experimental campaign, carried out on local materials [14]. Results obtained from the laboratory testing and their correlation with different types of materials observed on site are discussed in Section 5.1.

The building performances derived from the urban settlements of Balaka and in the rural settlements in Lifidzi are focused upon. The seismic vulnerability of these buildings is discussed in Section 5.2 where failure mode distributions are illustrated and in Section 5.3, where capacity curves are presented. The results for the two different sites highlight how buildings with the same material types and roof structures, within the same (broad) building class, behave differently and have, consequently, dissimilar vulnerability. This is due to a high variety of construction details (e.g. different fabric quality and connection levels between walls observed for each identified typology) between rural and urban settlements which is extremely dependent on material and resource availability of a specific area.

3. ON-SITE STRUCTURAL SURVEYS

On-site structural surveys were carried out on 300 non-engineered buildings located in formal and informal settlements in the urban areas of Salima and Balaka and in the informal settlements of the rural villages Lifidzi and Golomoti (see Figure 1(a) and 1(b)). For each building, data were collected only for two orthogonal façades, since parallel walls of the inspected buildings had similar opening layouts. Data collection consisted of taking a few geometrical measurements as the ones illustrated in Figure 1 (c) (i.e. plan geometry, building/gable height, and opening dimensions and layout). Information related to structural features, such as masonry and mortar types, roof structure, connection levels between walls, and between walls and roof, were also collected.

Furthermore, since the inspected houses were constructed using locally-sourced materials with poor quality control, and construction materials differ considerably in shape, homogeneity, consistency, density, and brittleness, the fabric quality of the observed construction materials was recorded and defined as:

(1) good fabric quality: bricks have regular shapes and regular mortar layers. The clay has a homogeneous texture. Overlapping of bricks is regular. The bricks might have hairline cracks or cracks are apparently absent.
(2) medium fabric quality: bricks have uneven shapes and partially regular mortar layers. The clay has a medium porosity. Overlapping of bricks is partially regular. The bricks might have light cracks or small holes.
(3) poor fabric quality: bricks have irregular shapes and mortar layers. The clay has high porosity. Overlapping of bricks is irregular. The bricks have deep cracks or are partially lost.

Deficiencies derived from poor structural detailing, presence of damage, material loss and lack of maintenance were also investigated during the structural survey to take into account how existing structural weakness impacts on the performance of the investigated buildings.

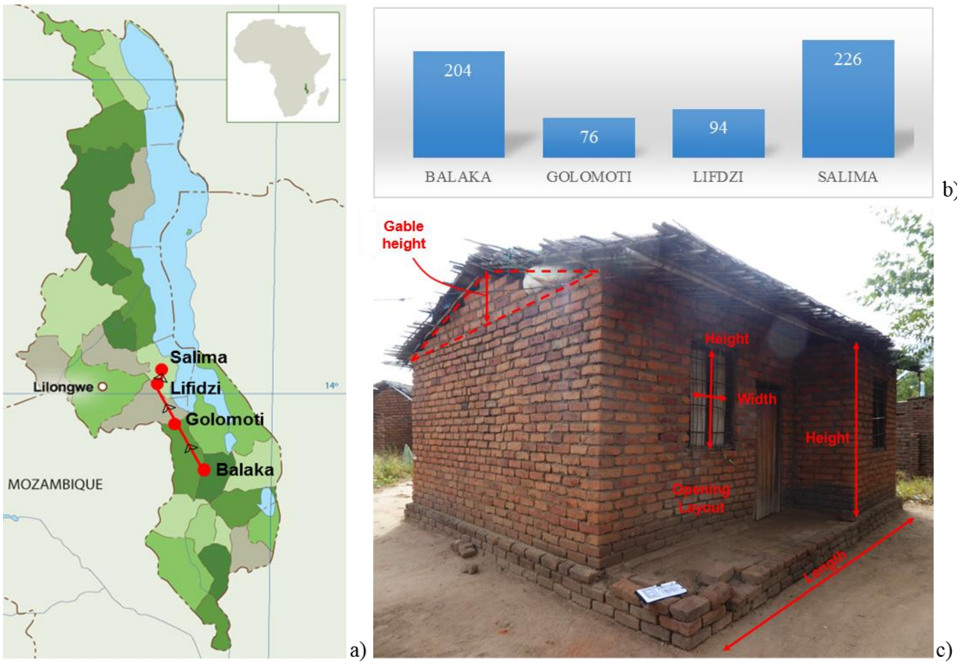


Figure 1: a) Building survey locations, Balaka, Golomoti, Lifidzi, and Salima; b) number of façades collected for each site c) geometrical measurments collected for each inspected façade

4. BUILDIGN CLASSIFICATION DERIVED FROM DATA

Data collected on site were used to classify the inspected buildings in typologies, which are adopted in Section 5 to derive the vulnerability of the Malawian constructions. In Table 1, the inspected buildings are classified according to material type (a: unfired bricks, b: unfired bricks), fabric quality (1: good, 2: medium; 3: poor), and roof type (thatched/metallic sheet roof). Main features of the inspected constructions are reported in Figure 2.

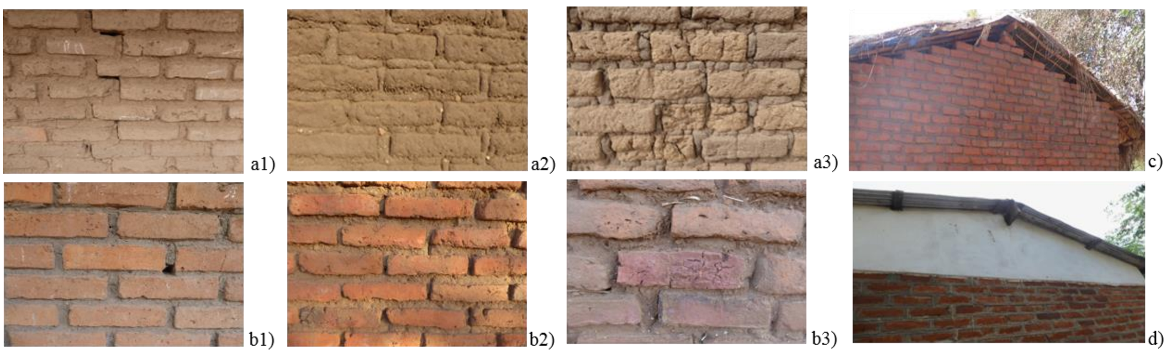


Figure 2: a1) and b1) good; a2) and b2) medium and a3) and b3) poor fabric quality of unfired and fired bricks, respectively c) thrached roof and d) metallic sheet roof

Most of the observed buildings (82%) were made of fired bricks, since these are affordable materials to be sourced on-site, and they do not require high construction skills. Mud mortar was identified for 76% of the inspected buildings, while cement mortar, observed for the remaining inspected houses, is gradually being adopted. Fabric quality varies considerably from poor to good and underlines the need of assessing the building performance by defining mechanical properties which reflect the actual masonry strength according to the different fabric quality identified on site (see Section 5.1).

The majority of the inspected houses (55%) were built with single-skin walls with thickness varying from 100 mm to 160 mm. For these constructions, the connections between adjacent walls were assumed poor, while for the remaining inspected houses with double-skin walls and thickness varying from 210 mm to 260 mm, the connections between walls were assumed stronger only if cement mortar was employed. Regarding building roofs, these were made of timber rafters supporting thatch for 21% of the inspected buildings or light metallic corrugated sheets for the remaining ones. Both roof types were inspected on site and classified as light systems, as they are not rigid along the entire plane do not act as rigid diaphragm.

According to the collected data described above, inspected buildings, as illustrated in Table 1, are classified in three typologies: A, B, and C (shown in Figure 3) introduced in the World Housing Encyclopedia by the authors [9, 13] Typology A is representative for 20% of the inspected buildings, characterized by low seismic vulnerability (Figure 3 (a)). These buildings were made of mud mortar combined with fired bricks of poor fabric quality (see Figure 2(b3)) and unfired bricks from poor to high fabric quality (see Figure 2(a1), (a2), and (a3)). Generally, these houses have smaller building footprints than the typical floor plan of 8 m × 6 m. Most of these houses (17%) have thatch supported by light timber elements, while the remaining are made with metallic sheet roof. Roof structures are characterized by a poor structural detailing (e.g. lack of connection between walls and between the walls and roof).

	Thatched roof				
	Unfired bricks + mud mortar			Fired bricks +mud mortar	
	a1	a2	a3	b2	b3
	1.2%	11.3%	1.8%	4.6%	2.5%
typology	A			B	A

	Metallic sheet roof							
	Unfired bricks + cement mortar			Fired bricks +mud mortar			Fired bricks + cement mortar	
	a1	a2	a3	b1	b2	b3	b1	b2
	0.3%	2.5%	0.6%	3.7%	41.4%	6.4%	11.7%	12.0%
typology	A			B			C	

Table 1: Building distribution with reference to material type (a: unfired brick, b: fired brick), fabric quality (1: good; 2: medium and 3: poor), and roof type (thatched or metallic sheet roof).

The most common typology observed in Malawi, B, representing 52 % of the buildings, is rated as medium seismic vulnerability (see Figure 3(b)). These buildings were made of fired bricks characterized from poor to a good quality fabric (Figure 2(b1), (b2), and (b3)). Due to the presence of mud mortar in these houses, the bonding between bricks is considered poor, therefore connections between walls were assumed weak. The construction details varied significantly, as well as maintenance levels.

Typology C covers 28% of the inspected houses (see Figure 3(c)). These were made of fired bricks from poor to good quality fabric (Figure 2(b1), (b2), and (b3)) and cement mortar. Generally, these houses had a larger floor plan than the typical plan. Due to the extended plan size, irregularities were likely to occur (e.g. portico and re-entrant corner). Most of these houses had corrugated metallic sheets supported by timber elements or truss, and good structural detailing (e.g. adjacent walls and walls/roof are connected). The good structural quality of these houses can be also attributed to the presence of strengthening elements (e.g. ring beams).

Figure 3: Typical one-story masonry building in Malawi. a) typology A; b) typology B; c) typology C

5. DERIVATION OF SEISMIC PERFORMANCE FOR BUILDING TYPOLOGIES

In this work, results are shown for two locations: Lifidzi and Balaka, classified as a rural and an urban area, respectively. These sites are adopted in this study with the scope of illustrating that buildings with the same construction material types and roof structures, classified in the same typologies (i.e. A, B and C), they may have a different seismic response. This is stated because, during the on-site survey, it was observed that buildings of the same typology are often characterized by a different geometry (i.e. plan size, height, and opening layouts) or a different fabric quality (dimensions of the bricks, bonding between brick-mortar in terms of friction and cohesion) or a different level of structural conditions (connections between orthogonal walls, and between the walls and roof). Therefore, there is a high possibility that the different observed parameters could impact on the behaviour of the individual building and consequently, on the vulnerability of the specific typology.

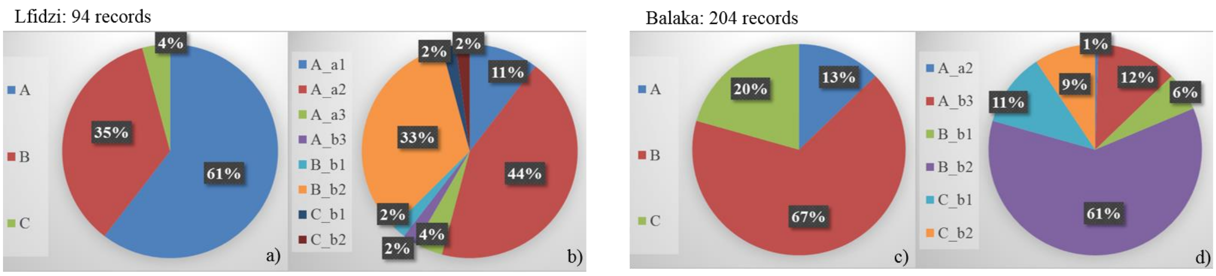


Figure 4: a) and c) Building typology distribution (A, B and C) identified in Lifidzi and Balaka; b) and c) each identified building typology is associated to inspected material type and fabric quality, where a1 and b1 is good; a2 and b2 is medium and a3 and b3 poor fabric quality for unfired and fired bricks.

Before discussing the results obtained for the two different sites, Figure 4(a) and 4(c) are presented to illustrate the building distributions identified for building typologies A, B and C for Lifidzi and Balaka, respectively. As expected, the weakest typologies A, built with unfired bricks and low low-quality of fired bricks, has a higher concentration in Lifidzi, where houses are constructed in rural communities by local builders/artisans in absence of technical guidance. Building typologies B and C are more concentrated in Balaka, where houses are built using materials with better mechanical properties than the ones in rural areas. Figure 4(b) and 4(d) present the fabric quality observed in the three typologies, underlining, as expected, that materials adopted in Balaka have better fabric quality than the ones observed in Lifidzi. This can be underlined by typology A, where 79% of the houses belonging to this class for Lifidzi are made of unfired bricks of medium/poor fabric quality against the 4% in Balaka, where houses are mainly made of fired bricks of poor fabric quality. For typology B, 16% of the houses in Balaka are made with bricks of high fabric quality compared to 6% identified in Lifidzi, while the remaining houses for both sites are made of bricks with medium fabric quality. For typology C, houses belonging to this class, cover only 4% of the inspected houses in

Lifidzi, whereas 20% observed in Balaka. Mechanical properties defined for the different material types are indicated in Section 5.1. As discussed in Section 4, roofs are made in thatch or metallic corrugated sheets supported by timber elements, therefore in both cases it is assumed that the roof structures behave as flexible horizontal systems. Furthermore, for the classes A and B, it is assumed that the roof structure is completely detached from the walls, in order to be consistent with the observations on site. As for the connections between walls, they are assumed absent for houses constructed with single-skin walls, features belonging to 63% of the inspected houses in Lifidzi and Balaka.

5.1 Strength of local masonry in Malawi

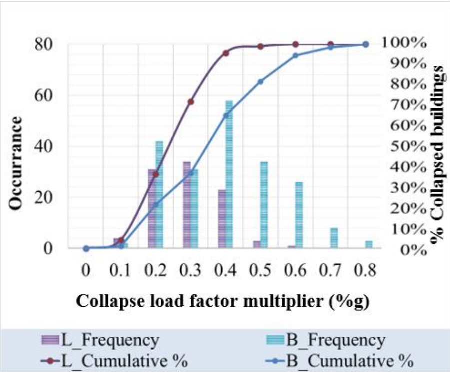
Strength properties of masonry materials commonly used for housing construction in formal and informal settlements in Malawi, were investigated by means of laboratory testing, conducted on masonry prisms and panels [14]. The tests were conducted with the scope at reproducing actual field conditions and construction practices in the country. Based on the observations from the on-site structural surveys, specimens were prepared by local artisans using local commercial production of brick batch and mortar types in mud and cement, which were cured in uncontrolled conditions. The results revealed that the behaviour of the masonry in compression is governed by the low compressive strength of the brick units. It was also found that the quality of the brick-mortar bonding governs the in-plane shear and out-of-plane flexural behaviour, which are the critical parameters of the resistance to horizontal loading, such as earthquake action. These are directly related to the quality of the brick-mortar interface bonding and the thickness of the walls. Values for interface cohesion, measured by means of standard triplet shear testing, vary between 0.01-0.02 MPa for mud mortar and between 0.2-0.25 MPa for cement mortar configurations. Friction angles were measured at around 32 degrees.

With reference to these measured values, they are used to define the mechanical properties of the observed fired bricks with mud and cement mortar with a good fabric quality. In evaluating seismic vulnerability of the houses based on FaMIVE, typologies with poor/medium structural features are penalized by considering that their fabric quality and brick-mortar bonding are inferior compared to the ones derived from the tested materials [11].

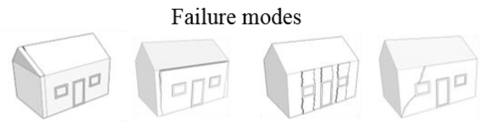
5.2 Estimation of load factor multipliers and failure mode distribution

The seismic performance of the buildings inspected in Lifidzi and Balaka is assessed using FaMIVE [10, 11, 15, 16]. The approach is based on a mechanical procedure, relying on the assumption that buildings behave as an assemblage of macro elements, held together by compressive forces. Analyses are performed using equilibrium equations, where earthquake actions are simulated as a horizontal static force, proportional to the mass of the single inspected façade. The analysis is static equivalent and aims to predict the horizontal static actions, quantified by means of collapse load factor multipliers (λ), corresponding to a percentage of gravity acceleration, g [10, 11]. The factor λ is calculated for each of the failure modes, which are defined as all possible collapse mechanisms that can occur for a masonry building subjected to earthquake shaking. The estimated values of λ indicate the lower bounds of the level of shaking which trigger the identified failure modes. Among the computed collapse load factor multipliers, the failure mode with the smallest multiplier is considered to occur on a façade (as the weak link). In implementing the FaMIVE method, geometrical/structural features described in Sections 3 and 4 for the inspected houses in Malawi are used as input of the proposed approach. Furthermore, since masonry type, fabric quality, and connection level between walls have a considerable impact on the building responses, both angle of friction and cohesion taken from Section 5.1, and relative dimensions of bricks and walls taken from the survey carried on site were adopted to assess the capacity of the inspected buildings.

The occurrence of λ, evaluated for the selected building stocks in Lifidzi and Balaka are illustrated in Figure 5(a). The median of λ, being 0.24g and 0.38g for Lifidzi and Balaka respectively, underlines that the buildings inspected in Lifidzi are weaker than the ones inspected in Balaka, as they fail for lower values of λ. This is also highlighted by the slope of the cumulative curve: the one derived for Lifidzi has a higher slope than the one derived for Balaka (i.e. for λ = 0.35g, 72% and 35% of the inspected buildings fail in Lifidzi and Balaka, respectively).

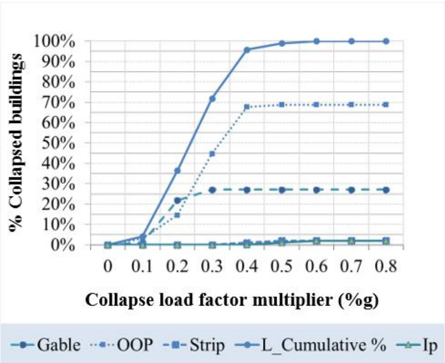


a)

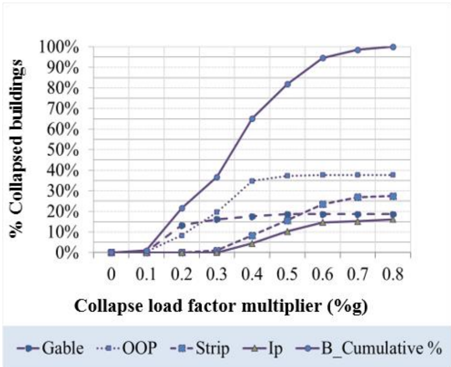


Location	Gable	Oop	Strip	Ip
LIFIDZI	27%	69%	2%	2%
BALAKA	19%	38%	27%	16%

b)



c)



d)

Figure 5: a) Collapse load factor multiplier distribution in the selected building stocks in Lifidzi (L) and Balaka (B); b) failure modes distribution; c) collapse load factor multiplier distribution for the failure modes identified in Lifidzi (L) and d) collapse load factor multiplier distribution for failure modes identified in Balaka (B)

The failure modes associated with the identified collapse load factor multipliers are illustrated in Figure 5(b). These are classified into four categories: 1) *Gable*: predominantly occurs on walls with gables which are not connected to roofs, and therefore fail in overturning; 2) *Oop*: Out of plane, predominantly occurs on single-skin walls with a low-quality material and poor connection with orthogonal walls and roof, causing overturning of a single façade; 3) *Strip*: predominantly occurs on single-/double-skin walls with a medium-quality material and a good connection with orthogonal walls and roof; causing overturning of a strip of piers and spandrels; and 4) *Ip*: In-plane, predominantly occurs on single/double-skin walls with a medium-quality material and a good-quality connection with orthogonal walls and roof; causing shear failure of a single façade.

As expected from the on-site surveys, since a lack of connections between the walls and roof and low-quality construction materials were frequently observed in the inspected buildings in Lifidzi, *Oop* is the most likely failure mode with a percentage of 69%. By contrast in Balaka, there is a smaller percentage of buildings failing in *Oop* (38%), and a higher percentage of buildings failing for *Strip* (27%), where the latest occurs on buildings with stronger connections, belonging to typologies B or C. Only a small percentage of the inspected buildings fail for *Ip* (16%), emphasizing that even buildings of typology C, built with double-skin walls, fired bricks of better quality and cement mortar, mostly fail due to overturning of gables, walls, and spandrels and piers, due to use of poor construction materials and construction practice details.

Figure 5(c) and 5(d) show the distribution of collapse load factor multipliers for the failure modes identified in Lifidzi and Balaka, respectively. *Gable* failure modes occur for the lowest values of λ (smaller than 0.3g) for inspected buildings with tall gables, resulting in separation of their roofs. Buildings in classes B and C, classified in a medium high-quality class, mostly fail for *Strip* and *Ip* failure modes with the highest values λ, (greater than 0.3g). Regarding *Oop*, λ varies from a minimum value of 0.1, values identified for buildings belonging to typology A, to 0.4, values identified for buildings belonging to typologies B and C.

5.3 Derivation of capacity curves

In this section, capacity curves are derived for the building typologies identified in Lifidzi and Balaka with reference to [10, 11, 16, 17, 18]. Derived capacities strictly correspond to the parameters defining the geometry, structural conditions, connection level between walls, material types and fabric quality of the inspected buildings in the case study. Multiple capacity curves, one for each analysed façade, are derived for a single building. This is because capacity curves are directly developed from the load factor multipliers, which are also calculated for each inspected façade, as illustrated in Section 5.2.

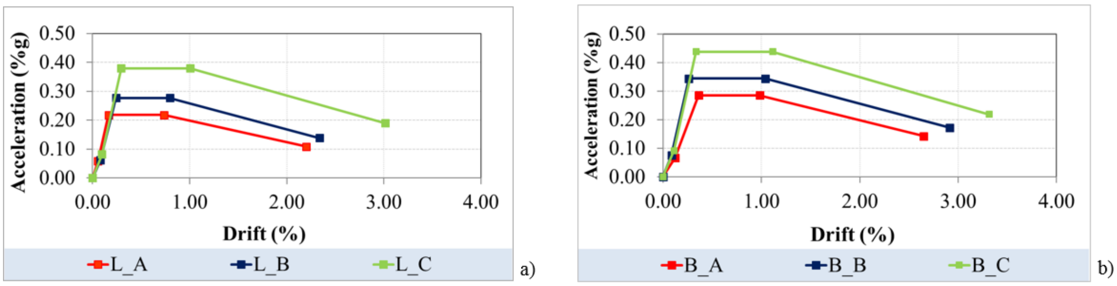


Figure 6: Median capacity curves for a) the building typologies: A, B and C for Lifidzi and Balaka, respectively

The maximum strength or maximum acceleration (g) in a capacity curve is taken equal to the minimum collapse load factor estimated by FaMIVE for each inspected façade. The elastic limit displacement of each façade is calculated as a function of the elastic stiffness and the mass of the façade, involved in the identified failure mode. The ultimate displacement is defined as the displacement identifying the geometrical instability of the façade and hence its collapse. Computed these displacements, these are divided by the height of the single inspected façade to derive the drift.

Figure 6 shows the different capacity curves derived for the building typologies A, B, and C identified in Lifidzi and Balaka, respectively. As expected from the definition of the three typologies, it is noticeable that the building typology A (class of buildings characterized by low-quality materials and construction details) has the lowest values of acceleration and drift compared to B and C. Clearly, the derived capacity curves are capable of capturing the different performances for the single typology. Furthermore, they underline that classifying buildings according to structural conditions and differentiating mechanical properties with respect to the fabric quality improve the reliability of the vulnerability obtained for the single typology. This can be observed from the different values of acceleration obtained for the single typologies (i.e. typology A: maximum acceleration is 0.21g, and 0.29g for Lifidzi and Balaka, respectively), which point out that buildings of the same typology (same construction materials and roof types) located at different sites and subjected to different levels of quality control are likely to behave differently under seismic events.

6. CONCLUSIONS

This paper has shown the results derived from a seismic vulnerability study carried out for representative non-engineered masonry buildings in Central-Southern Malawi. The presented work integrates an effective methodology for collecting data, classifying non-engineered masonry buildings in main typologies, correlating observed masonry types to their strength measured experimentally, and assessing vulnerability. The data collected during the structural investigations and presented in this paper have enhanced the available information related to building distribution and typologies compared with local/global datasets that were previously available for the Malawian constructions (Ngoma & Sassu, 2002; National Statistical Office of Malawi, 2008; Bureau TNM, 2016). Furthermore, this work illustrates the importance of gathering detailed structural information, including masonry type, fabric quality, bonding between masonry and mortar, and connection levels between walls. Moreover, the vulnerability calculated for this work can offer notable advantages to identify failure modes and derive capacity curves for non-engineered masonry buildings which could be further implemented in a risk assessment tool together with enhanced local data.

DATA ACCESS STATEMENT

The underlying data can be obtained by contacting the first author.

ACKNOWLEDGEMENT

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