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SEISMIC PERFORMANCE EVALUATION OF THE EXISTING AND RETROFITTED STONE MASONRY HOUSES IN NEPAL

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Abstract

The residential building typology of stone in mud mortar (SMM) masonry, being the most common vernacular construction type in Nepal, contributed significantly to the seismic losses caused by the 2015 Nepalese seismic sequence, also known as the Gorkha earthquake. During the recovery phase, the post-event survey highlighted the need for strengthening of thousands of residential houses of the SMM typology. As part of the ongoing national strengthening campaign, several hundred SMM houses with slight to moderate damage have been retrofitted in rural mountainous districts by different organizations in collaboration with local governments and communities. This paper thus deals with a comparative study of the seismic performance of SMM houses in their existing and retrofitted conditions, in order to assess the increase in seismic resilience due to retrofitting. The results of numerical seismic analyses of both existing and retrofitted index buildings, using validated 3-D element-by-element modelling approach, are first presented and discussed in terms of their capacity curves and failure mechanisms. As per the seismic design code of Nepal (NBC 105:2019), seismic performance assessment is then conducted to understand the performance levels of these constructions. Finally, seismic fragility functions for existing and retrofitted SMM index buildings, considering the uncertainty in ground motions and material quality, are presented and discussed. Considering the seismic hazard in Nepal, the existing SMM typology is found highly vulnerable and the seismic strengthening of these buildings is urgent. The selected retrofit approach i.e. 'reinforced concrete (RC) strong-back approach' confirms the life safety performance requirement as per the NBC 105:2019 code, when quality of construction materials and workmanship of the existing SMM construction is according to the traditional standards.

Keywords: 2015 Nepal earthquake, rubble stone masonry, seismic retrofit, strong-back approach, seismic performance assessment

1. Introduction

Nepal is one of the most earthquake prone countries in the world and has experienced several devastating earthquakes of magnitude exceeding Mw7.5 [1]. The most recent earthquake of Mw7.8, occurred in the central region of Nepal on April 25, 2015 with epicenter located in Barpak village, Gorkha district, approximately 78 km northwest of Kathmandu with a focal depth of 15 km [2]. The mainshock was followed by two significant aftershocks having Mw 6.7 on April 26, 2015, and Mw 7.3 on May 12, 2015 [3]. The seismic sequence resulted in a maximum Modified Mercalli Intensity of IX (Violent) causing 8,790 deaths and nearly 22,300 injuries [4]. About eight million people were left homeless and the resulting economic loss is estimated at about $7 billion [4].

Residential properties were heavily affected by the seismic sequence with about half a million houses destroyed and more than 250,000 houses partially damaged [4]. Extent of damage and typical damage patterns sustained by stone in mud mortar (SMM) masonry houses due to the 2015 earthquake sequence are discussed in more detail in Adhikari and D'Ayala [5]. The houses (of any construction type) suffering damage grade 2 and 3 (EMS-98 scale) were selected as eligible for the government retrofit grant under which each beneficiary receives a sum of $1,000 in two installments as long as the retrofit complies with the standards set out by the National Reconstruction Authority (NRA) [6]. Under the retrofit grant scheme, although about 38,000 households have signed the agreement and received the first installment, as of January 2020, only 36 households have completed the retrofitting of their damaged houses, indicating slow progress of retrofitting in the country [7]. The NRA produced a retrofit manual [6] that provides a catalogue of repair and retrofit options for SMM constructions mainly using the 'RC splint and bandage plus wire meshing (RC-S&B)' approach.

Build Change, a social enterprise with a mission to greatly reduce deaths, injuries and economic losses caused by housing collapse due to earthquakes and typhoons in emerging nations; designs disaster-resistance homes and provides trainings to builders, homeowners, engineers, and government officials in order to promote sustainable resilience. In the years following the 2015 Nepal earthquake, Build Change has devised solutions adapted to the Nepalese context, one of which is a 'type design' retrofit approach for Nepalese SMM construction, known locally as the 'RC strong-back approach (RC-SB)' that was approved by the NRA in 2017 [8]. About two hundred SMM houses affected by the 2015 event have been retrofitted to date employing this approach [9]. A summary of these RC-S&B and RC-SB retrofit approaches in the context of Nepal can be found in HRRP [10]. The RC-SB approach costs on average $4,500 for a typical two story plus an attic SMM house and can be completed in 6 to 10 weeks with about 5 to 6 local masons being trained per house [9]. The design details and structural elements of the RC-SB are presented later in §3. Given the large numbers of both damaged and undamaged SMM houses in rural mountainous districts in needs of retrofitting, it is of great importance to understand the associated improvements in seismic performance provided by the interventions such as the RC-SB, to confirm the potential improvement in seismic resilience.

Experimental studies exploring the strengthening methods for Nepalese SMM buildings are reported in literature [11-13]. These tests, either on single walls or on scaled models of 3-D buildings, have confirmed that the application of simple and low-cost strengthening techniques such as timber/RC bands or steel wire mesh, can significantly improve stiffness, strength, integrity and ductility of SMM constructions. Several low-strength (i.e. mud mortar) masonry school buildings, retrofitted using the RC-S&B approach, performed satisfactorily during the 2015 seismic sequence [14]. However, there is very little experimental evidence on the seismic strengthening with the strong-back (RC-SB) approach, although few single wall level studies performed in New Zealand [15-16] have shown that both out-of-plane and in-plane capacity of solid and cavity brick in cement mortar walls can be significantly improved with the use of timber strong-backs.

This study thus focuses on the comparative evaluation of the seismic performance and fragility behavior of the existing and retrofitted Nepalese SMM buildings, as such are currently lacking in literature. The retrofitting using the RC-SB design approach is selected for the present analysis. The paper is organized as follows: first, the construction characteristics of the existing SMM (PRE-SMM, PRE meaning built previous to the 2015 event) buildings and the elements of the RC-SB retrofit approach are presented. The results of advanced non-linear seismic analyses on index building (IBs) of the SMM typology in its existing and retrofitted condition are then presented in terms of their capacity curves and failure mechanisms. Seismic performance assessment results against the requirements of NBC 105: 2019 [17] are then discussed. Considering the uncertainty in ground motions and the material quality, fragility functions for these IBs are derived and discussed. Finally, some conclusions are drawn in the context of ongoing retrofitting work in Nepal.

2. Construction characteristics of PRE-SMM buildings

Most PRE-SMM buildings, traditionally constructed by local masons, are often built with uncoursed random rubble stone in mud mortar thus displaying poor tensile and shear strength. The range of masonry bond patterns of these constructions is reported in Adhikari and D'Ayala [5]. The SMM walls are usually thick (400 mm – 600 mm) and the wythes are not properly inter-connected using adequate amount of through stones. The number of stories varies from one to three with a typical story height of 2.0 m.

(a) (b) (c) (d)

Fig. 1 – Construction characteristics of a typical PRE- SMM building: (a) 3-D view, (b) view of a corner connection, (c) longitudinal timber frame and floor structure, and (d) timber roof system with timber keys and compression struts

Fig. 1 presents photographs of a typical PRE-SMM house in a rural mountainous (i.e. Sindhupalchowk) district, used as an IB representative of this typology in the present study. This building has no internal cross wall in the short direction and is non-symmetric in the longitudinal direction because of the opening distribution. The wall densities in the longitudinal and transverse directions are about 15% and 9%, respectively, indicating that the building is weaker in the transverse direction. The IB has two-stories plus an attic floor covered in a multi-pitched timber roof structure. The cross-wall connections in these constructions are usually built with fairly rectangular shaped large corner stones which improves the cross-wall connections (Fig. 1(b)). Besides the SMM wall load bearing system, a timber frame (although the timber posts are not continuous at floor levels) centrally placed in the longitudinal direction also supports the floor structure, see Fig. 1(c). The longitudinal girder at each floor level, resting over the through thickness of the short walls, supports several transverse joists resting over the through thickness of the long walls, which in turn hold up the mud-topped timber floor structure. However, the connections of the timber girders and joists to the walls are not anchored. The unique timber roof structure, supported by a system of compression struts locked to the masonry by timber keys as seen in Fig. 1(d), promotes the confining action of all walls at the roof level.

It is worth noting that the selected IB does not necessarily represent the whole portfolio of the Nepalese SMM construction, as there are variations in the construction characteristics (e.g. presence/absence of internal cross-wall) as well as in the workmanship and quality of the vertical and horizontal structures.

3. RC-SB type design approach: retrofit details

The RC-SB retrofit approach consists of an internal system of reinforced concrete (RC) beams and columns fixed to the masonry wall via RC dowels to facilitate the transfer of seismic forces between the wall and strong-back system. The decision on whether a house is eligible to be retrofitted with the RC-SB design is based on several criteria related to the existing construction characteristics and damage levels in the building, which is confirmed by a Go/No Go checklist [18] . Before the installation of any retrofit elements, existing cracks (up to 25 mm width) are first repaired: up to 5 mm wide cracks are repaired with grouting while 5-25 mm cracks are repaired with grouting plus wire mesh stitching as required by the NRA retrofit manual [6]. The RC-SB approach includes several structural/non-structural elements to collectively strengthen the existing SMM buildings. Each of these elements are listed below, in the order of their installation, along with their role in improving the seismic performance of SMM buildings [19]:

- *RC ring beam*: The first major component of the RC-SB retrofit approach involves the addition of an RC ring beam (150 mm deep) on top of all SMM walls at attic level which acts as a belt connecting the longitudinal and transverse walls and provides integrity of the building, promoting box-type action.
- *RC strong-back columns*: Next, RC columns (200 mm x 200 mm) are constructed (from the foundation to the top of ring beam) at each corner and designated mid-span locations (spacing ≤ 2800 mm c/c). These columns, connected to the SMM walls by a number of *RC dowels*, provide stiffness, strength and ductility to the SMM walls under horizontal loading.
- *Timber posts splicing:* Since the existing timber posts are not continuous from the foundation to the top in most of the PRE-SMM houses, these are made continuous by splicing them at each floor level. These timber posts are also connected to the SMM walls by installing *RC dowels* thereby helping towards the improvement of box-type behavior of the building.
- *RC slab strips*: RC slab strips (300 mm x 100 mm) are added at first and attic floor levels, as a mean to improve the connection of the RC strong-backs and SMM walls system thereby improving the diaphragm and box-type action. These members are installed around the building perimeter connecting the RC strong-backs and timber posts and are connected to the SMM walls with a number of *RC dowels* (600 mm c/c). At the attic and first floor levels, a rebar X-bracing is also provided in order to enhance box-type action.
- *RC through elements*: RC through elements (150 mm deep) are inserted at 600 mm intervals in both horizontal and vertical directions in all SMM walls of the building. These elements provide integrity between the wythes of SMM walls and hence control the diagonal shear cracks and delamination of walls.
- *Gable wall replacement*: The vulnerable SMM gables are replaced by light-weight gables.
- *Roof connection improvement:* The structural conditions and connections of the timber roof elements and their connections to the SMM walls are also improved.
- *Wall plastering*: Cement sand (1:5 ratio) plaster is finally applied to the external and internal faces of all SMM walls.

Geometry, reinforcement details, and the procedure on preparation and installation of various retrofit elements of RC-SB approach can be found in Build Change Technical Manual [19]. Few photographs taken during the RC-SB retrofit installation are shown in Fig. 2. 3-D models of these retrofit elements in a SMM building can be viewed online at https://naxa.com.np/vtour/. The RC-SB type design of retrofit is applied to the PRE-SMM IB discussed in §2 and the resulting retrofitted structure (R-SMM) is selected as a representative IB for the comparative seismic performance and fragility analysis.

(a) (b) (c)

Fig. 2 – Photographs of different retrofit elements installed in an SMM house in Sindhupalchowk: (a) RC strong-back column, (b) RC ring beam and slab strip, and (c) RC through elements (Photos: Jeet K. Chaulagain, Build Change)

4. Seismic analysis of PRE-SMM and R-SMM IBs

Due to the complexity of full-scale building level experimental tests to characterize the seismic behavior, and with the advancement of modelling approaches, software tools and computational capabilities; numerical seismic assessment methods are increasingly and widely used within the engineering community [20-21]. This section presents a discussion on the modelling approach, followed by the non-linear pushover analyses results.

4.1 Applied element modelling of SMM masonry

Simplified micro-modelling approach with the applied element method (AEM) commercialized in Extreme Loading for Structures (ELS) software [22] is used in the present study. In the simplified micro-modelling approach, the mortar layer and the two unit-mortar interfaces are lumped into a zero-thickness joint while the units are slightly expanded on all sides to accommodate the mortar thickness. In the AEM, the masonry is discretized into 3D-elements whose surfaces are connected by a number of deformable springs that simulate the interaction among the elements with force-deformation laws representing the elastic and post-elastic behavior of the material as a whole. Two types of springs are used for modelling masonry: the 'unit' or 'element' springs connecting the 3D elements of the units, and the 'interface' springs connecting the individual applied elements to represent the equivalent properties of mortar and mortar-unit interface. A detailed overview of the formulation, constitutive laws, failure criteria etc. for masonry modelling in AEM can be found in ASI [22] and Malomo et al. [23].

To account for the random irregular shape of rubble stone, a triangular 3-D mesh is first created, and then random shaped units are generated by clustering these triangular applied elements by means of the 'unit' springs. In Fig. 13, different colored clusters represent each single stone unit. This modelling technique inherently presents some level of uncertainty as the wall construction itself presents great variability in terms of shape and size of units and the resulting bond pattern [5]. The validation and calibration studies of this modelling strategy against three distinct experimental tests: uniaxial compression behavior, in-plane shear-compression behavior and out-of-plane bending behavior are discussed in Adhikari and D'Ayala [5].

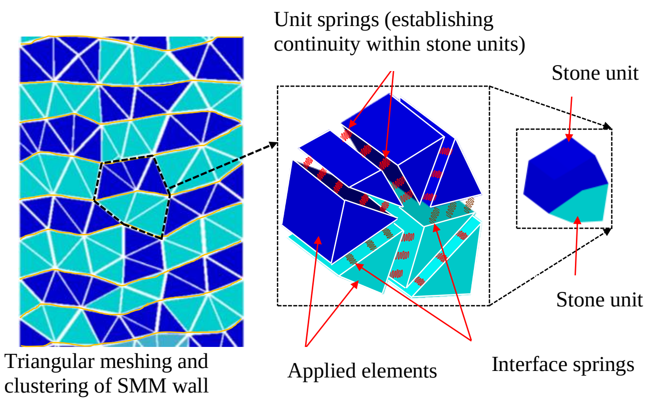


Fig. 3 – Schematic of the simplified micro-modelling of random rubble stone masonry using AEM

4.2 Numerical modelling and pushover analysis of the index buildings

3-D numerical models of the PRE-SMM and R-SMM IBs (Fig. 4) are created using the modelling strategy discussed in §4.1 for the SMM walls. Corner stones (see Fig. 1(b)) are created as rectangular elements at all corners and through stones are provided in the wall at a spacing of about 1.2 m in both the horizontal and vertical directions.

For the PRE-SMM model, all the timber elements (i.e. columns, main girders, floor elements, the timber roof structure, the lintels above the openings and the frames around the openings) are modelled explicitly as elastic elements to represent their stiffness contribution to the global building behavior. These members are meshed such that the element size is about the size of stone units. For the R-SMM model, besides all the existing structural elements of the PRE-SMM model, all the retrofit elements of the RC-SB retrofit approach presented in §3 are modelled explicitly, except the cement-sand plaster. The RC columns, RC ring beam, RC slab strips and the RC dowels are meshed such that the element size is about the size of stone units. RC through elements on the walls are modelled as rigid elements without meshing. The interfaces of the timber elements and newly added RC members with the existing SMM masonry are simulated with the properties of mud mortar, as is the case in actual construction. The IBs are assumed to be fixed at the ground level considering that these constructions have a stepped strip type foundation with depth greater than 0.5 m. An approach discussed in Adhikari and D'Ayala [25] is followed for conducting non-linear pushover analyses for the IBs to determine the damage mechanisms and derive the capacity curves.

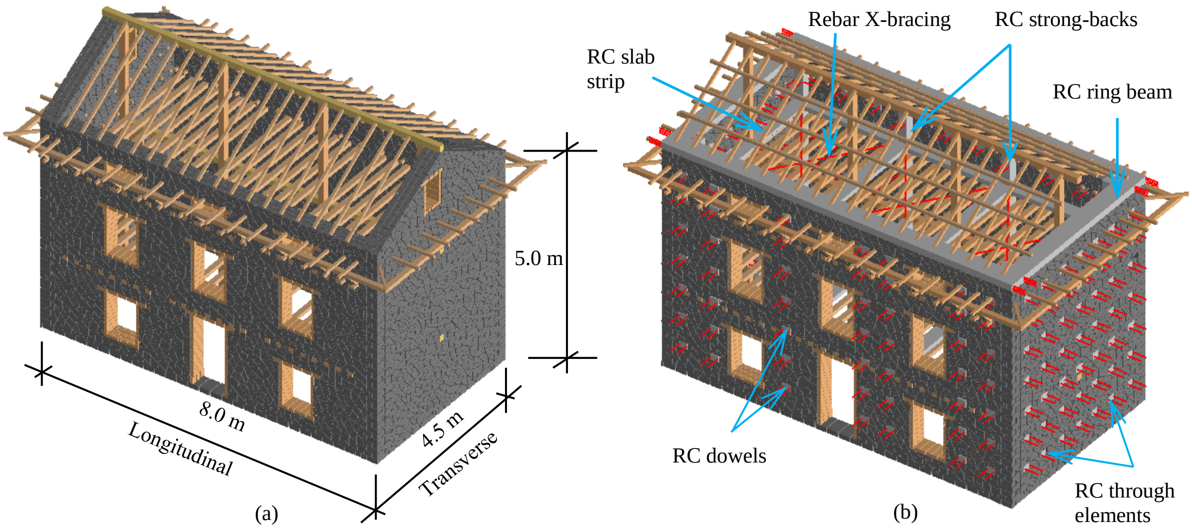


Fig. 4 – Numerical models of the (a) PRE-SMM and (b) R-SMM IBs

Material properties (Table 1) derived from the experimental tests on Nepalese SMM constructions [26] are used for the numerical modelling of the SMM masonry. The properties of masonry can vary greatly from one district to the next, depending on the shape/size, nature of units, quality and mixture of mortar used, workmanship level etc. Thus, a sensitivity analysis is conducted by considering a 'good' material quality case (assumed 50% better than the average values of material properties reported in Table 1 and a 'poor' material quality case (assumed 50% lower than the average values) in order to study the effect of variation of material properties in the seismic capacity and fragility functions of both the PRE-SMM and R-SMM IBs. For all the RC elements of the RC-SB retrofit scheme, M20 grade concrete is used, with a compressive strength of 20 MPa [19].

Table 1 – Material properties for Nepalese SMM masonry [26]

Material properties	**Average value**	**CoV (%)**
Unit weight	2200 kg/m^3	-
Young's modulus	65.10 MPa	31
Compressive strength	2.40 MPa	13
Tensile strength	0.02 MPa	16.5
Cohesion	0.013 MPa	16.5
Coefficient of friction	0.4	-

4.3 Capacity curves and failure mechanisms

Fig. 5(a) compares the capacity curves for the PRE-SMM and R-SMM IB in the longitudinal and transverse directions. The peak lateral capacity attained by the PRE-SMM building is very low at 0.12g and 0.08g in the longitudinal and transverse direction, respectively. Due to the poor strength of mortar as well as the random shape of the stone units, the non-linear response starts at a drift as low as 0.05% and the ultimate drift capacity is only about 0.4% in both principal directions. However, for the R-SMM model, the lateral capacity increases substantially to about 0.20g and 0.26g in the longitudinal and transverse direction, respectively. The ultimate drift capacity is also doubled to 0.88%, due to the integrity and consequent box-type action enforced by the combined action of the RC strong-backs, ring beams and the RC through elements. Fig. 5(b) compares the capacity curves for the PRE-SMM and R-SMM IBs for different material quality cases. Substantial changes in the lateral capacity can be observed in both cases due to the variation in material quality. An analytical study by [27] also found typically low lateral capacity with significant dispersion i.e. 0.07g-0.19g for two-story Turkish SMM buildings which is comparable to the range for the PRE-SMM IB i.e. 0.02g-0.13g. Compared to the PRE-SMM, the variation in lateral capacity is more linear in case of the R-SMM IB. A dispersion of ±10% is observable in the ultimate displacement capacity of both IB cases.

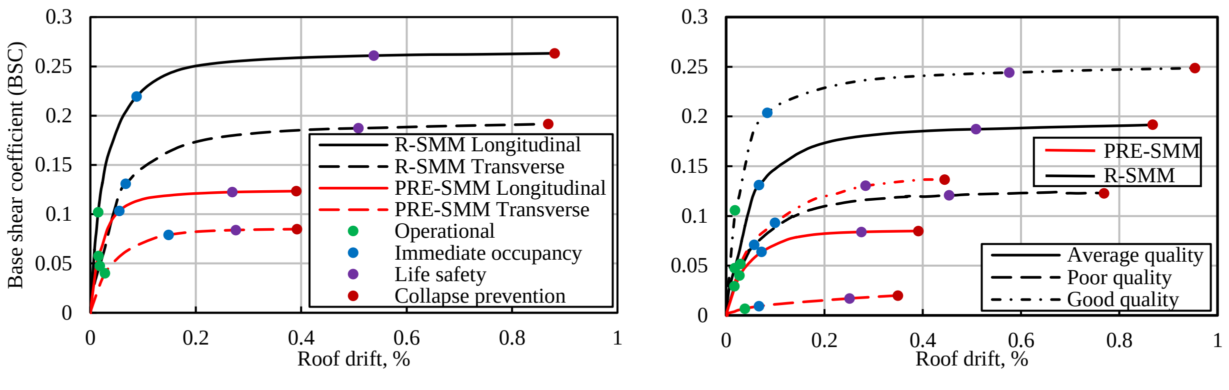
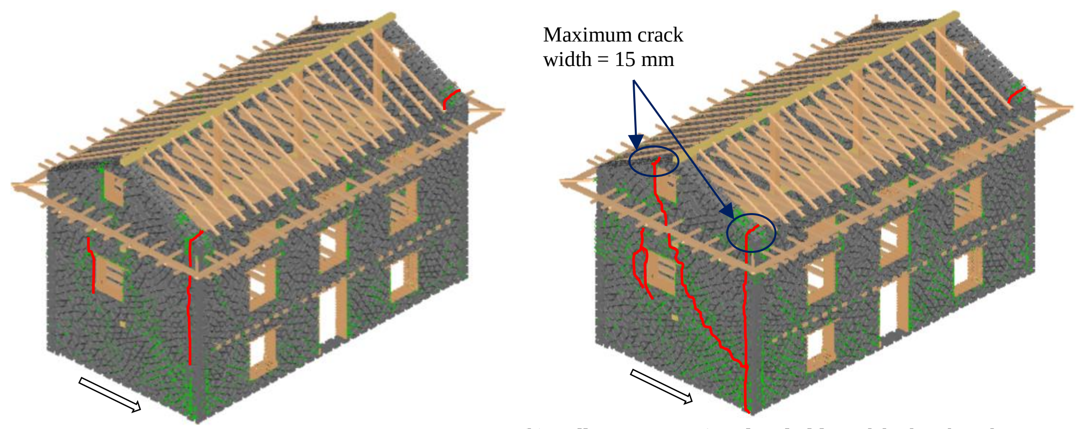


Fig. 5 – (a) Comparison of capacity curves in the two principal directions and (b) effect of material quality on the capacity curves (transverse direction). Thresholds of performance levels [28] are also indicated

The damage patterns obtained for both IBs at the thresholds of life safety and collapse prevention performance levels are shown and explained in Fig. 6 and Fig. 7. For the PRE-SMM IB, the main failure mechanism is the vertical separation of the walls at the cross-wall connections and the diagonal shear damage of the short in-plane walls (Fig. 6(b)). Although walls tend to separate at almost all the corners, out-of-plane overturning of the walls is controlled to some extent by the restraining action provided by timber floor and roof systems as observed in the actual seismic damage experienced by this building [5].

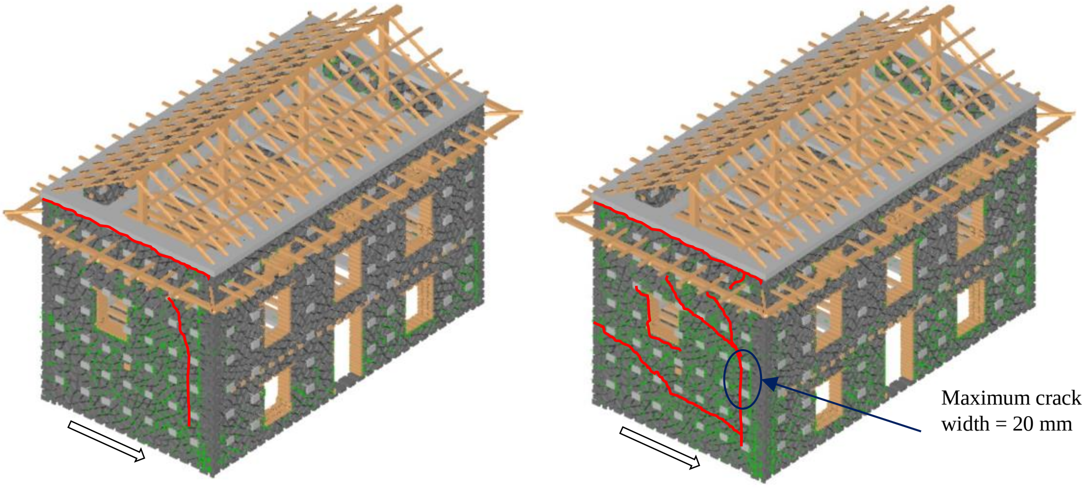


(a) **Life safety threshold**: Minor to major shear cracks (green, up to 5 mm in width) developed through all the SMM wall. The vertical separation cracks (red) reach10 mm in width.

(b) **Collapse prevention threshold**: Widely distributed major cracks (green, up to 10 mm in width) developed through all the SMM walls. A collapse mechanism is formed with a wide diagonal shear crack (red) extending from the gable to the bottom of the short walls.

Fig. 6 – Damage levels and failure mechanisms in the PRE-SMM IB

However, in case of R-SMM model (Fig. 7(b)), these separation cracks at cross-wall connection are restrained, indicating that the box-type action is enforced by the RC strong-back columns and ring beam system connected to the SMM walls by the through-thickness RC dowels. As seen in Fig. 7(b), the latter prevent the development of the main diagonal shear crack through the short wall, thereby allowing more lateral capacity as well as ductility to the building. However, because of the poor tensile strength, cohesion and friction of the mud mortar, distributed shear cracks ultimately find a way around.



(b) **Life safety threshold**: Minor to major distributed shear/flexural cracks (green, up to 5 mm in width) developed through all the SMM walls. A wide vertical crack (red, about 15 mm in width) develops around the corner. Roof ring beam develops shear cracks at the interface.

(b) **Collapse prevention threshold**: Widely distributed major shear/flexural cracks (green, up to 15 mm in width) developed through all the SMM walls. Several wide shear cracks (red) in the short wall become extensive reaching about 20 mm width.

Fig. 7 – Damage levels and failure mechanisms in the R-SMM IB

5. Seismic performance assessment

To conduct a quantitative comparison of the existing (PRE-SMM) and retrofitted (R-SMM) buildings, the seismic capacities of the IBs are first assessed against the seismic demand set out by the Nepalese seismic design code. Detailed comparison is then carried out by deriving and comparing seismic fragility functions of the two IBs for a number of natural ground motions in §6. The transverse (weakest) direction is selected for comparative seismic performance assessment and consequent fragility derivation.

Since the PRE-SMM buildings follow a vernacular construction practice that started much earlier than the introduction of Nepalese building codes, their code compliance can only be verified by seismic assessment. In Nepal, a seismic design code was drafted initially in 1994, and has been revised recently to produce the NBC 105: 2019 [17] (draft) by incorporating the approach of limit states and performance-based design. The code spectrum shape and magnitude being location and soil type specific, Table 2 lists the design parameters chosen for characterizing the elastic spectrum for the site in Sindhupalchowk district, where the IB is located.

Table 2 – Parameters chosen for constructing the elastic site spectrum as per NBC 105: 2019

Parameter	Value
Soil type	Type A (Hard soil site)
Importance factor, I	1 (Residential building)
Seismic zoning factor, Z	0.3 (Chautara, Sindhupalchowk district)

The performance points are obtained by applying the N2 method [29] to the capacity curves (Fig. 5) under the action of NBC 105: 2019 elastic site spectrum as per Table 2 (Fig. 8). The performance results for all different material quality cases are summarized in Table 3.

For the PRE-SMM typology, the seismic demand is far beyond the collapse prevention limit, irrespective of the material quality, hence the seismic design level of PRE-SMM IB as per NBC 105: 2019 code can be said to be poor. On the other hand, the R-SMM model performs well within the life safety performance level for average and good material quality cases. However, for poor material quality case, the performance point of R-SMM building lies in the collapse prevention performance level i.e. the life safety performance limit is exceeded, hence does not meet the performance objective set out by the NRA retrofit manual [6]. This sheds some light on the importance of the quality of construction materials as well as the workmanship of the existing SMM construction in terms of the seismic performance of the retrofitted houses.

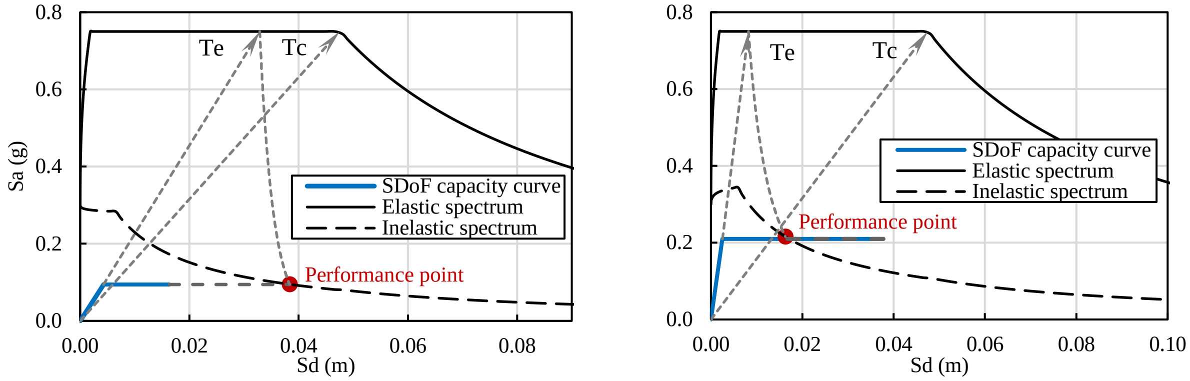


Fig. 8 – Graphical application of N2 method for seismic performance assessment: (a) PRE-SMM IB and (b) R-SMM IB, both with average material quality, using the NBC 105: 2019 site spectrum

Table 3 – Seismic performance assessment results as per NBC 105: 2019.

Material quality	**PRE-SMM typology**		**R-SMM typology**	
	Performance point (Roof drift, %)	**Performance level**	**Performance point (Roof drift, %)**	**Performance level**
Poor	2.50	Collapse	0.74	*Collapse prevention*
Average	0.91	Collapse	0.38	Life safety
Good	0.79	Collapse	0.31	Life safety

6. Seismic fragility evaluation

Seismic fragility functions are vital inputs in probabilistic seismic risk assessments [21]. Although for the 2015 Gorkha earthquake a very detailed record of damage is available, spatially located and for a fairly uniform building stock (e.g. SMM typology), the derivation of empirical fragility functions is impaired by the poor network of seismic recording stations in the country such that the distribution of the intensity of ground shaking is not known with adequate reliability. Thus, for the present study, the analytical approach, outlined in D'Ayala et al. [21], is followed, allowing the consideration of uncertainties in both hazard quantification and response capacity of the building. The uncertainty associated with material characterization and modelling strategy have already been discussed in section 3 and 4. For the hazard description, as there are very limited ground motion records available from seismic events in Nepal [30] a suite of 22 ground motions, containing a wide spectrum of ground motion characteristics, suggested in FEMA [31] is used to consider the record-to-record variability.

A simplified but validated method, the N2 method [29], is applied for the seismic performance assessment. This static equivalent method, based on idealized bilinear capacity curves and μ-R-T relationship reduced spectra, is appropriate when assessing buildings, whose behavior is characterized by the first mode of vibration. While it is recognized that the use of 5% damped spectral acceleration at first-mode ($Sa(T_1)$) as intensity measure (IM) is more efficient for first-mode dominated structures [32], the use of PGA as the IM in this study is advisable given the low-period structures considered and the very low tensile strength and cohesion, leading to highly non-linear behavior even with modest level of deformations, causing the lengthening of the first-mode period of the structure, making $Sa(T_1)$ less reliable.

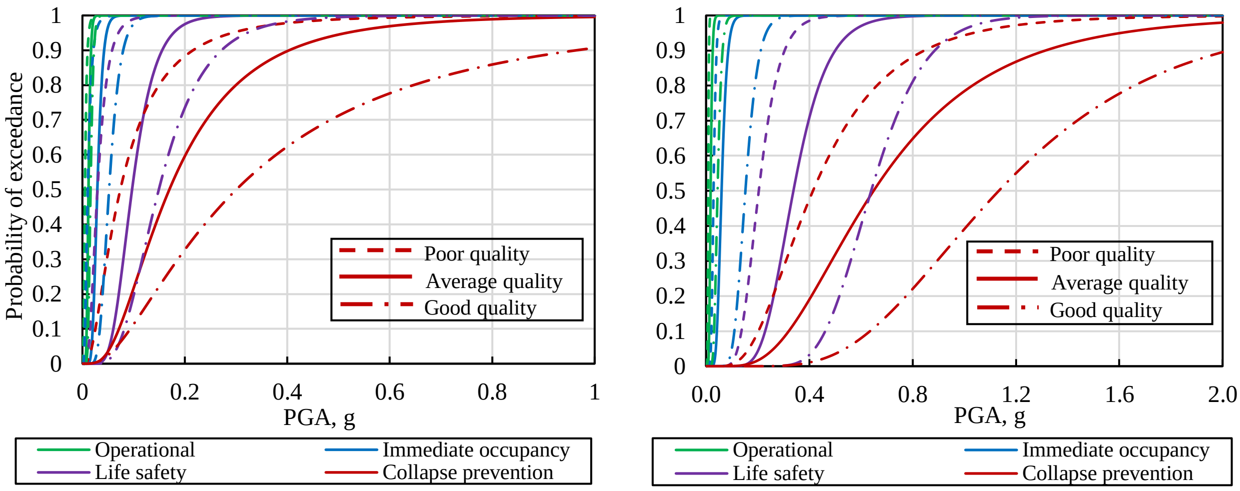
Table 4 – Median and standard deviation (SD) of fragility functions for the PRE- SMM IB

Performance Level	**Poor quality**		**Average quality**		**Good quality**	
	Median PGA (g)	**SD**	**Median PGA (g)**	**SD**	**Median PGA (g)**	**SD**
Operational	0.005	0.567	0.012	0.276	0.016	0.276
Immediate occupancy	0.010	0.569	0.029	0.293	0.052	0.331
Life safety	*0.029*	*0.530*	*0.097*	*0.370*	*0.149*	*0.468*
Collapse prevention	0.07	0.836	0.170	0.676	0.300	0.910

Table 5 – Median and SD of fragility functions for the RS- SMM IB

Performance Level	Poor quality		Average quality		Good quality	
	Median PGA (g)	SD	Median PGA (g)	SD	Median PGA (g)	SD
Operational	0.008	0.255	0.018	0.296	0.045	0.283
Immediate occupancy	0.029	0.271	0.060	0.281	0.152	0.257
Life safety	*0.204*	*0.311*	*0.338*	*0.305*	*0.639*	*0.254*
Collapse prevention	0.414	0.556	0.649	0.551	1.133	0.452

Based on the performance point distribution obtained from the application of N2 method, the derivation of fragility functions is performed statistically using the least square regression method, as detailed in D'Ayala et al. [21]. Table 4 and Table 5 present the median and dispersion of the PGA for different performance levels for PRE-SMM and R-SMM IBs with different material quality. The same information is presented in terms of fragility curves in Fig. 9.



(a) (b)

Fig. 9 – Seismic fragility functions for the (a) PRE-SMM and (b) R-SMM IBs. Dispersion due to the material quality is also shown

The life safety limit is exceeded for the PRE-SMM typology at a median PGA of as low as 0.15g, even with good material quality while the same limit is exceeded for the R-SMM IB only at a median PGA of about 0.20g, even with poor material quality. Similarly, for the PRE-SMM IB, the median PGA for exceeding the collapse prevention limit is about 0.30g, even with good material quality while the same for R-SMM IB is exceeded only at a median PGA of about 0.41g, even with poor material quality; showing considerable increments in the median capacity for both life safety and collapse prevention levels. As seen from Table 4, Table 5 and Fig. 9, for both IBs, the fragility functions, particularly for life safety and collapse prevention performance levels, present significant dispersion due to the variability in the ground motions characteristics.

7. Conclusions

This paper presented a comparative seismic performance assessment results for a Nepalese SMM IB in its existing and retrofitted condition using the RC-SB type design approach. The seismic capacity of the considered PRE-SMM IB is very low (the transverse direction being the weakest) and the median PGA capacity for collapse prevention performance level for the PRE-SMM typology is about 0.17g only, while the PGA distribution in mountainous districts in Nepal varies from 0.25g to 0.35g [17]. Thus, these buildings do not meet the safety requirement set out by the NBC 105: 2019. Moreover, the shake map from the 2015 Nepal earthquake [2] estimated a PGA range of 0.30g to 0.80g in the most affected districts which clarifies the reason for the heavy damage experienced by this construction type. However, the same IB in the retrofitted condition (i.e. R-SMM IB), using the RC-SB type design approach, meets the life safety performance level against the site-specific demand as per the NBC 105: 2019. For the R-SMM IB, the median PGA capacity for life safety and collapse prevention performance levels are about 0.34g and 0.65g, respectively, against the seismic hazard (PGA) range of 0.25g to 0.35g in the rural mountainous districts [17] meaning that the safety factor, particularly for the life safety performance level, in the high hazard zones is marginal.

Due to the lack of quality control in the existing SMM constructions, the material quality varies considerably among the SMM houses. Sensitivity analysis on the uncertainty related to the material quality shows that the seismic capacity can vary significantly from one building to next. For the selected IB, it is shown that if the quality of construction of the existing SMM houses is poor, the RC-SB retrofit scheme may not ensure the life safety under the requirements as per the NBC 105: 2019. Hence, it is a pre-requisite to conduct a thorough inspection of the existing quality of material and workmanship of these houses before applying any retrofit works. Furthermore, the process of making holes in the existing SMM walls for the installation of the RC dowels and RC through elements at 600 mm c/c seems quite invasive. Care should be taken to minimize disturbances to the SMM fabric, as doing so could cause hairline cracks and debonding of the units resulting in reduced material quality. Further research is needed to understand the impact of disturbing the wall and the ability of new RC elements to bond with the existing SMM fabric.

It is believed that the results and discussions presented in this paper will inform the ongoing retrofitting work in Nepal in support of the aim towards increasing the seismic resilience of residential houses. Future work will focus on the uncertainty assessment of the construction characteristics of the existing SMM construction (e.g. wall density, distribution of openings) as well as the quality of newly added RC retrofit elements and the sensitivity analysis on their effects in the seismic performance of the SMM houses retrofitted with the RC-SB type design approach . Few examples of sensitivity analysis that can affect the seismic capacity and fragility include: the effect of the presence of an internal cross-wall; contribution of the plaster layer in the seismic capacity of the R-SMM buildings. As other retrofit approaches (e.g. RC-S&B approach) are also currently being implemented in the country, a comparative appraisal of seismic performance improvement due to different retrofit approaches as well as the cost-benefit analysis will certainly be useful in the overall economic improvement of the seismic resilience of residential buildings in Nepal, as such results and discussions are not yet publicly available.

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