2019 Conference
Earthquake risk and engineering towards a resilient world
9-10 September 2019, Greenwich, London

NUMERICAL SEISMIC PERFORMANCE ASSESSMENT OF PRE-EARTHQUAKE STONE MASONRY RESIDENTIAL BUILDING TYPOLOGY IN LIGHT OF 2015 NEPAL EARTHQUAKE

Rohit Kumar ADHIKARI[1] and Dina D'AYALA[2]

Abstract: *Despite economic and human losses, disasters teach us very important lessons. It is important to collect, document, analyse and understand the causes and impacts of a disaster such as an earthquake to minimize losses in future disastrous events. This paper thus presents a discussion on the widespread damage sustained by the stone in mud mortar masonry typology after the 2015 Nepal earthquake. Then, the common construction characteristics and major failure modes observed in the 2015 earthquake are identified and a numerical seismic performance assessment is conducted on a representative index building of the existing stone in mud mortar masonry typology. The results of non-linear pushover analyses yield that the lateral capacity of these buildings is very low and the separation of walls in the out-of-plane direction is the major failure mechanism, also widely observed during the earthquake. Seismic retrofitting of these existing buildings is thus urgent, and the results of this study will help informing the decision makers in adopting appropriate effective retrofit measures.*

Introduction

An earthquake of moment magnitude Mw 7.8 occurred in the central region of Nepal on April 25, 2015, at 11:56 Nepal Standard Time with the epicentre (28.147°N, 84.708°E) located in the village of Barpak, Gorkha district, approximately 78 km northwest of Kathmandu (Figure 1) with a focal depth of 15 km (USGS, 2015a). Hundreds of aftershocks with Mw greater than 4.0 were recorded during more than a year after the earthquake (NSC, 2016), with some significant seismic events having Mw 6.7 on April 26, 2015, and Mw 7.3 on May 12, 2015 (Figure 1). The earthquake resulted in a Maximum Modified Mercalli Intensity of IX (Violent) with about 8,790 deaths and nearly 22,300 people injured (NPC, 2015).

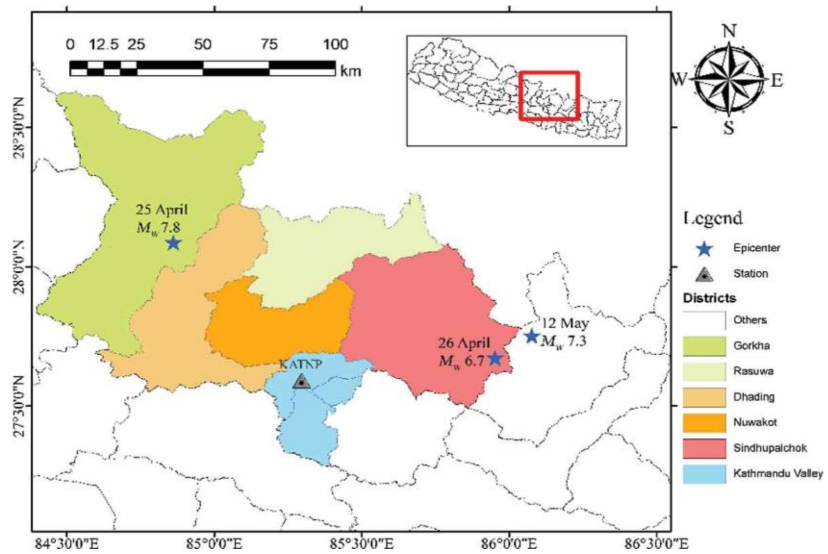


Figure 1. Location of the mainshock and major aftershocks of the 2015 Nepal earthquake (Bhagat et al. 2017).

---

[1] PhD Student, University College London, London, United Kingdom, rohit.adhikari.15@ucl.ac.uk
[2] Professor, University College London, London, United Kingdom

Significant damage to many public and private buildings was reported. The residential houses were hit hard by the earthquake and its aftershocks with about half a million houses destroyed and more than 250,000 houses partially damaged (NPC, 2015). In several cases, whole villages were turned into rubble in areas where old vernacular constructions such as stone masonry in mud mortar (SMM) houses with minimal seismic resistant features were present. In some of the severely hit districts (Figure 2) such as Sindhupalchowk where mostly SMM houses were present, more than 90% of the total houses suffered heavy damage to complete collapse (HRRP, 2017).

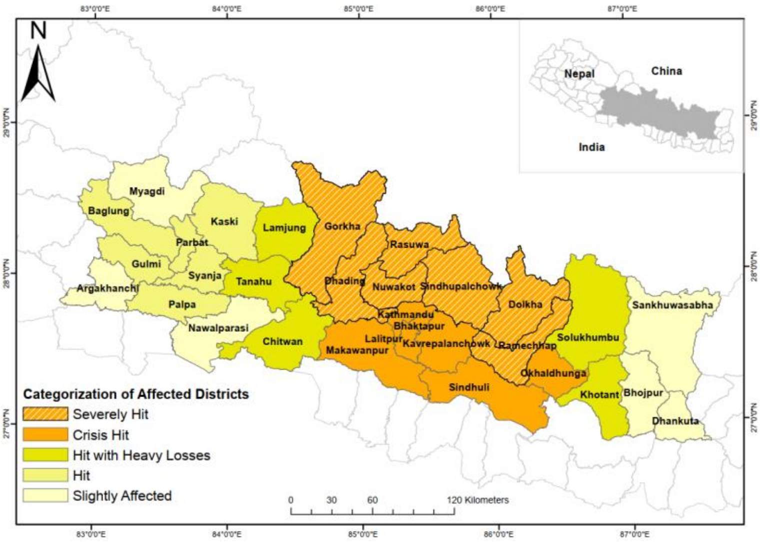


Figure 2. Map showing the categorization of earthquake-affected 31 districts, yellow coloured districts are the 14 most affected districts (NPC, 2015).

A year after the devastating earthquake, the National Reconstruction Authority (NRA) of Nepal developed and started the implementation of a Post Disaster Recovery Framework (PDRF) (NRA, 2016a) based on the findings of the Post Disaster Needs Assessment (NPC, 2015). One of the key objectives of the PDRF is the reconstruction of disaster resilient private houses in the affected areas. According to the PDRF, in the 31 earthquake affected districts (14 of which classified as highly affected districts, see Figure 2), owners are being provided with financial assistance in tranches, supported by timely provision of technical assistance, training and facilitation, so that people can rebuild their own houses as soon as possible. As of 10th April 2019, about 46% of the identified housing grant beneficiaries have completed the construction of their new houses (NRA, 2019). This indicates that even 4 years after the earthquake, about half of the total beneficiaries haven't finished the complete reconstruction of their houses. The reasons for the slower reconstruction process might be several such as political reasons, economic reasons, issues related to the availability of construction materials and skilled labour etc.

This paper first reviews the building typologies hit by the 2015 earthquake. Since SMM is the most common construction type in the country, even in the post-earthquake reconstruction, the damage sustained by this typology is discussed in details and the main failure mechanisms observed in the 2015 earthquake are identified. The results of a numerical seismic performance study of the existing SMM typology to understand the possible failure mechanisms and the quantitative seismic response are then presented in order to explore the reasons of heavy damage sustained by this typology in the 2015 earthquake.

Residential building typologies in the affected districts

Different building materials and construction types ranging from stone masonry to reinforced concrete (RC) framed structures have been used in Nepal in residential building construction. Traditional construction types mainly include stone masonry in hilly and mountainous areas while timber framed and brick (both adobe and burnt clay brick) masonry have been used in plain and urban areas (Gautam et al., 2016). These vernacular construction types are mostly built by local experienced masons but without the use of seismic engineering principles, although aseismic feature can be identified, which the craft has developed over the centuries (D'Ayala, 2004). Accordingly, no codes or standards were followed in the construction of most of these buildings.

Although national building codes for the design and construction types were first drafted in 1994, the implementation side is found to be very poor in the construction of residential buildings. Recently, since early 90s, RC framed construction types have been increasingly used in urban areas as well in peri-urban areas of rural districts. Common construction deficiencies of different typologies of Nepalese houses are discussed in detail in Gautam et al. (2016).

Figure 4 presents a comparison of construction typologies in the 31 earthquake affected districts before and after the 2015 earthquake (HRRP, 2018). It should be noted that the percentage of pre-earthquake housing typologies shown in the figure is computed over the entire population of houses that existed, which was collected during post-earthquake survey by the Central Bureau of Statistics (CBS), Nepal for identifying reconstruction and retrofit grant beneficiaries. However, the data related to post-earthquake typologies is based on a sample of about 500 newly constructed houses in different districts. Nevertheless, Figure 4 provides an indicative comparison of the pre-earthquake and post-earthquake housing typologies and the primary construction type in the affected districts both before and after the earthquake remains the SMM which constitutes as much as half of the total houses. This is mainly due to the problem of transportation of modern construction materials such as cement or steel in rural areas; availability of stone, mud etc. and the skilled masons for traditional construction as well as the lower cost of construction compared to other typologies (Bothara et al., 2018a). The reason for many households choosing SMM typology in reconstruction can also be linked to the amount of financial grant (approximately 3,000 USD in total) provided by the government for each household for house reconstruction. RC framed construction represents a low proportion of the total building population.

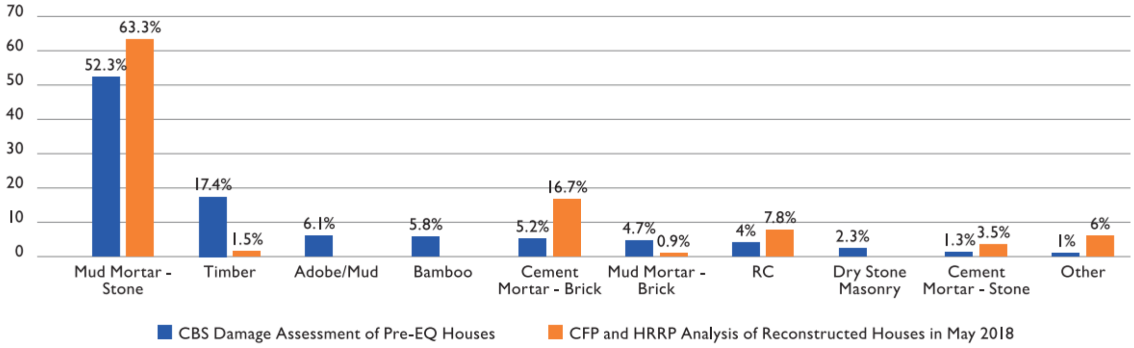


Figure 3. Comparison of the prevalence of pre- and post-earthquake housing typologies in the affected districts. (HRRP, 2018).

For the owner-driven reconstruction of houses, NRA has published several guidelines including a building design catalogue (NRA, 2015) in order to promote the *Build Back Better* (BBB) principle. The design catalogue offers different typologies ranging from RC framed to stone masonry constructions, incorporating the seismic design requirements prescribed in Nepal national building code (e.g. NBC 203, 2015). On the other hand, it is not necessary to adopt the prescribed design types offered in these documents, as beneficiaries can use different designs as long as the codal provisions are met during the inspections at different stages conducted by NRA.

Pre-earthquake SMM buildings

Construction characteristics

Most of the SMM buildings constructed before the 2015 earthquake (named hereafter as PRE-SMM) are unreinforced, often built with random rubble stone in mud mortar thus displaying poor tensile and shear strength. The rubble stone masonry walls are usually thick (400 mm – 600 mm) and have three wythes which are not properly inter-connected using through stones (Bothara et al., 2018b). However, the cross-wall connections are usually made stronger by providing fairly rectangular shaped corner stones. Figure 4 presents a photograph of a typical house in the rural mountainous districts and the same is used as a case study building in the present study. These are usually two-storied buildings with an attic floor covered in multi-pitched timber roof structure. Besides the SMM walls, the vertical load bearing structure consists of a timber frame centrally placed in the longitudinal direction, see Figure 4. The longitudinal girder, resting over the short walls, at each floor level supports a number of transverse joists that span in the transverse direction, resting on the long walls and providing the support for the mud-timber floor structure.

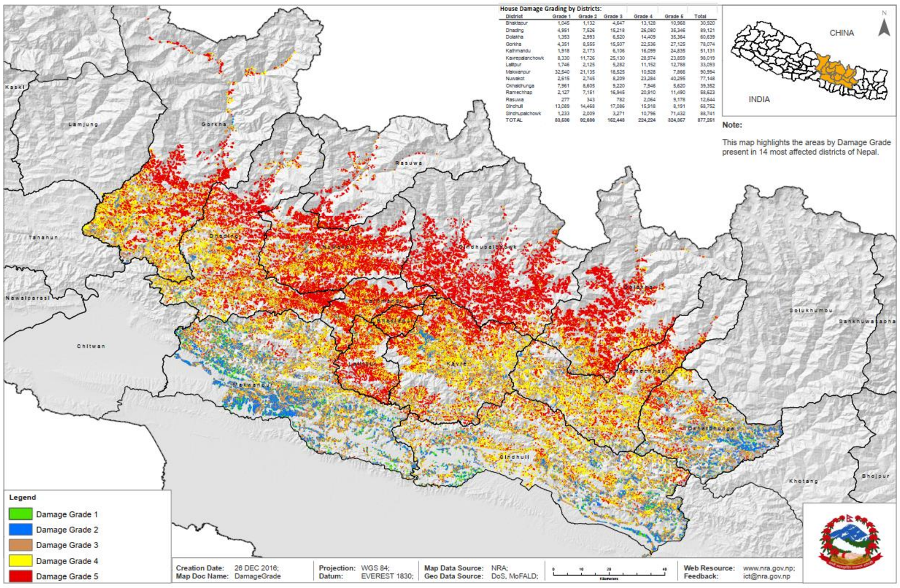
The timber roof structure is supported by a system of compression struts locked to the masonry by timber keys as seen in Figure 5 which improves the floor-wall connections and provides in-plane stiffness at the attic floor level.

Figure 4. Photograph of a typical PRE- SMM building in Sindhupalchowk district (left) and timber framing structure (right).

Figure 5. Timber roofing system with timber keys and compression struts: outside view (left) and inside view (right).

Damage due to the 2015 Nepal earthquake

The damage suffered by the PRE-SMM typology during the 2015 Nepal earthquake was extensive and contributed significantly to both economic and human loss due to the earthquake. Figure 6 shows the damage grade distribution in the building structures due to 2015 earthquake in the 14 most affected districts. High concentration of red dots i.e. building collapse lies in the north part which is mostly mountainous region where PRE-SMM was the most frequent typology.



House Damage Grading by Districts:

District	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5	Total
Bhaktapur	1,045	1,132	4,647	13,128	10,968	30,920
Dhading	4,951	7,526	15,218	26,080	35,346	89,121
Dolakha	1,353	2,993	6,520	14,409	35,364	60,639
Gorkha	4,351	8,555	15,507	22,536	27,125	78,074
Kathmandu	1,918	2,173	6,106	16,099	24,835	51,131
Kavrepalanchowk	8,330	11,726	25,130	28,974	23,859	98,019
Lalitpur	1,746	2,125	5,282	11,152	12,788	33,093
Makwanpur	32,540	21,135	18,525	10,928	7,866	90,994
Nuwakot	2,615	2,745	8,209	23,284	40,295	77,148
Okhaldhunga	7,961	8,605	9,220	7,946	5,620	39,352
Ramechhap	2,127	7,151	16,945	20,910	11,490	58,623
Rasuwa	277	343	782	2,064	9,178	12,644
Sindhuli	13,089	14,468	17,086	15,918	8,191	68,752
Sindhupalchowk	1,233	2,009	3,271	10,796	71,432	88,741
TOTAL	83,536	92,686	162,448	224,224	324,367	877,261

Note:

This map highlights the areas by Damage Grade present in 14 most affected districts of Nepal.

Legend
- 🟩 Damage Grade 1
- 🟦 Damage Grade 2
- 🟫 Damage Grade 3
- 🟨 Damage Grade 4
- 🟥 Damage Grade 5

Creation Date: 26 DEC 2016;
Map Doc Name: DamageGrade
Projection: WGS 84;
Datum: EVEREST 1830;
Map Data Source: NRA;
Geo Data Source: DoS, MoFALD;
Web Resource: www.nra.gov.np;
Feedback: ict@nra.gov.np

Figure 6. Damage grade distribution of structures in 14 most affected districts (NRA, 2016b).

Figure 7 presents the main damage patterns experienced by this typology during the 2015 Nepal earthquake: vertical separation of wall, complete out-of-plane overturning collapse, gable collapse, out-of-plane bulging and delamination, shear cracks in the in-plane walls etc.

(a) Separation of short wall at cross-wall connection

(b) Complete out-of-plane overturning collapse (Photo: Build Change)

(c) Collapse of gable (Photo: Build Change)

(e) Out-of-plane bulging and debonding

(d) In-plane shear damage in piers, tensile failure at spandrel ends (Photo: Build Change)

Figure 7. Main failure mechanisms of PRE-SMM typology observed in 2015 Nepal earthquake.

Numerical seismic performance assessment of PRE-SMM typology

As there still exists a large share of PRE-SMM typology in the rural parts of the country, it is important to study the seismic capacity and possible failure mechanisms of these buildings, in order to adopt economic and effective retrofitting techniques. This section presents a discussion on the numerical modelling of stone masonry using applied element method and the results of a non-linear pushover analysis conducted on a representative index building of the PRE-SMM typology.

Applied element numerical modelling of stone masonry

Different modelling environments and strategies have been used for numerical modelling of stone masonry, e.g. finite element based methods (e.g. Bothara et al., 2018), discrete element based method (e.g. Lemos and Costa, 2017), applied element based methods (e.g. Guragain, 2015) etc.

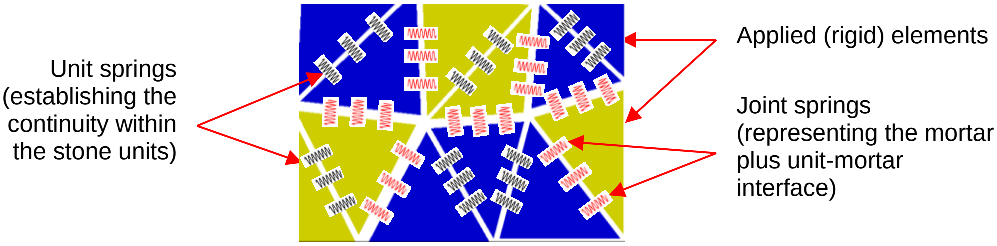


Figure 8. Schematic of simplified micro-modelling of stone masonry using AEM. Blue or yellow coloured cluster represents individual stone unit.

Extreme Loading for Structures (ELS) software (ASI, 2018), based on applied element method (AEM), is used in the present study (Figure 8). Two types of springs are used, 'unit' or 'element' springs connecting the applied elements of the units, and 'joint' springs connecting the individual applied elements to represent the equivalent properties of mortar and mortar-unit interface. In this study, to account for the random irregular shape of rubble stone, triangular elements are used rather than rectangular elements. A detailed overview of the formulation, constitutive laws, failure criteria etc. for masonry modelling in AEM can be found in Malomo et al. (2018).

Validation of AEM technique for SMM masonry

For the validation of the proposed numerical modelling strategy using AEM method, numerically obtained compressive and lateral behavior of SMM walls are compared against experimental tests results. Figure 9 compares the numerical crack patterns and the stress-strain diagrams to the experimental results of a SMM pier subjected to vertical compression and Figure 10 for a SMM wall subjected to vertical bending under a four-point bending test (Pun, 2015). Under both loading cases, the experimental and numerical results are in good agreement. These results confirm that AEM can be effectively used for the gravity and lateral load analysis of SMM structures.

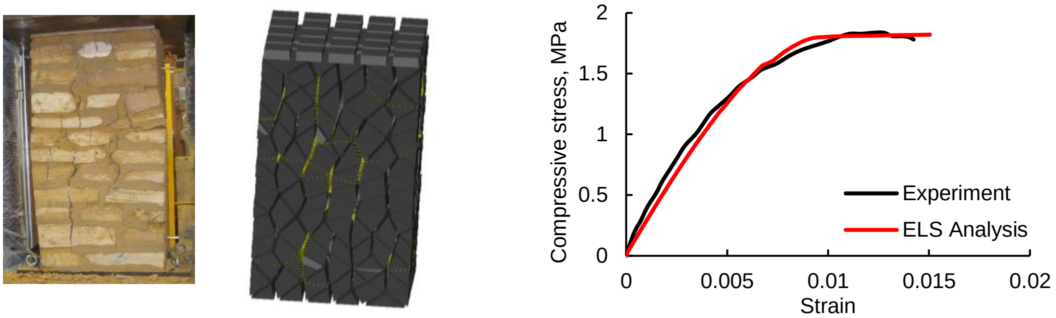
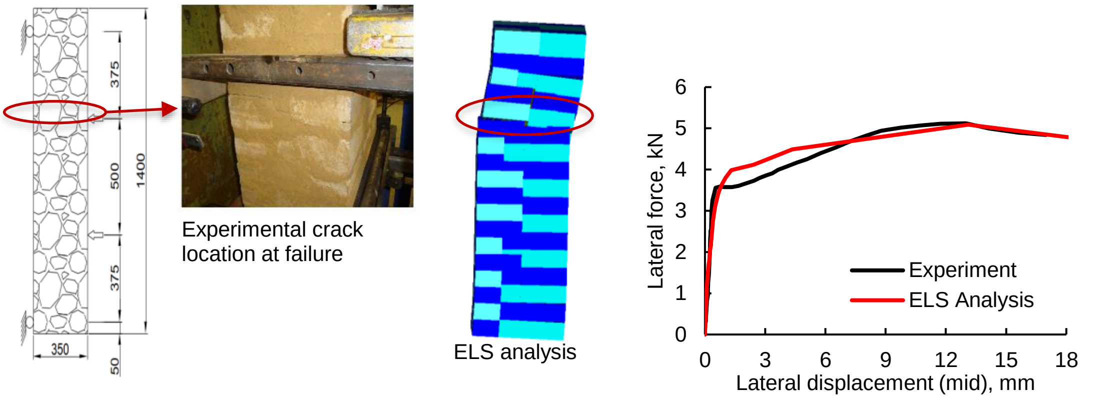


Figure 9. Experimental and ELS analysis comparison: Crack patterns at failure (left) and stress-strain diagrams (right).



Experimental crack location at failure

ELS analysis

Figure 10. Experimental and ELS analysis comparison: Crack patterns at failure (left) and force-deformation curves (right).

Numerical modelling and pushover analysis of PRE-SMM typology

One of the major issues that increases the difficulty in modelling the seismic response of masonry is the uncertainty associated with the material properties of its constituents. Furthermore, in older constructions such as PRE-SMM typology, the present material condition is influenced by deterioration, history of maintenance etc. and the uncertainty further increases. For the present study, results of experimental tests (Pun, 2015) conducted on SMM walls to characterize various elastic and non-linear material properties as listed in Table 1are used.

In ELS, a 3-D numerical model (Figure 11) of an index building of the PRE-SMM typology is created using the strategy discussed in the previous section. For computational efficiency, stone units are modelled as rigid elements i.e. the cracks are assumed to develop through the mortar joints only. For the joint springs, a failure criterion is defined by specifying a separation strain, 0.025 for this particular model. This parameter is obtained from the calibration study reported in the previous subsection. Once this strain limit is exceeded in a spring, this has no further tensile or shear capacity, however contact can occur between the adjacent applied elements depending on the loading condition. The timber lintels above the openings as well as the timber frame elements around the openings are modelled as elastic elements. The timber framed roof structure, including the keys and compression struts are also modelled to reproduce a realistic model. Foundation are assumed to be fixed. It is worth noting that the building is non-symmetric in the longitudinal direction due to the typical distribution of opening.

Material properties	Average value	CoV (%)
Unit weight	2200 kg/m^3	-
Young’s modulus	240 MPa	58
Shear modulus	100 MPa	-
Compressive strength	1.8 MPa	4
Flexural tensile strength	0.048 MPa	7
Cohesion	0.048 MPa	-
Coefficient of friction	0.4	-

Table 1. Material properties of SMM used in this study.

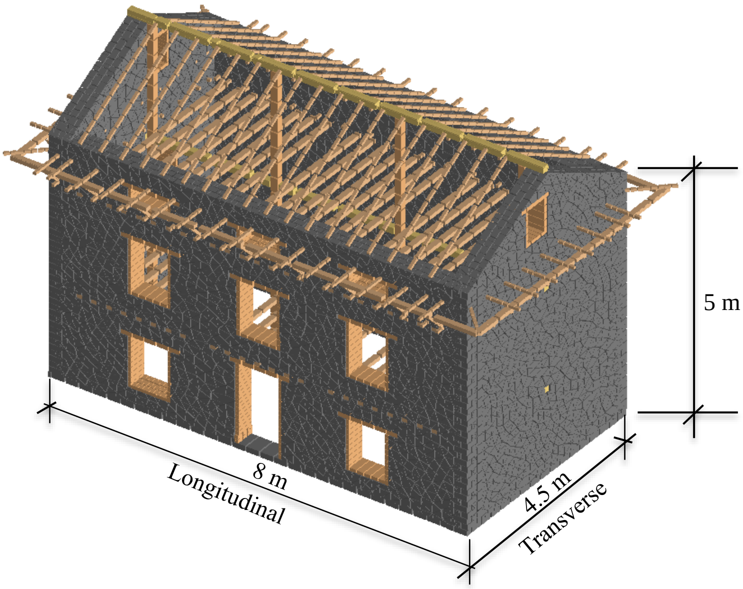


Figure 11. Numerical model of an index building of the PRE-SMM typology created in ELS.

Conventional pushover analysis of masonry structures modelled using element-by-element modelling technique, with discontinuous joint represented by finite-strength springs, is complex as the application of pushover force or displacement imposed on the structure often causes stress concentration on a particular element or region thereby causing local failure without affecting the rest of the structure. Thus, a different approach for applying pushover loading is proposed in which the numerical model is subjected to a linearly increasing ground acceleration, rather than a force pattern on the structure, until collapse. This works by applying an increasing ‘effective earthquake force’ on the structure which is mass proportional. Such analysis represents a force-based non-linear pushover analysis, opposed to the displacement-based pushover analysis usually implemented for framed structures.

Results and discussion

Figure 12 compares the capacity curves of the PRE-SMM index building in the longitudinal and transverse directions. The peak lateral capacity attained by the building is 0.16g and 0.12g in longitudinal and transverse direction, respectively. An analytical study on similar construction types of Turkish two-storey SMM buildings by D’Ayala and Kishali (2012) also found typically low lateral capacity (0.07g - 0.19g) for such buildings. Due to the poor strength of mortar as well as the randomness of the stone, the non-linear response starts at a drift as low as 0.05% and the ultimate drift capacity is only about 0.5% in both principal directions. Bothara et al., (2018b) also obtained a similar level of yield and ultimate drift values for similar SMM buildings from Nepal.

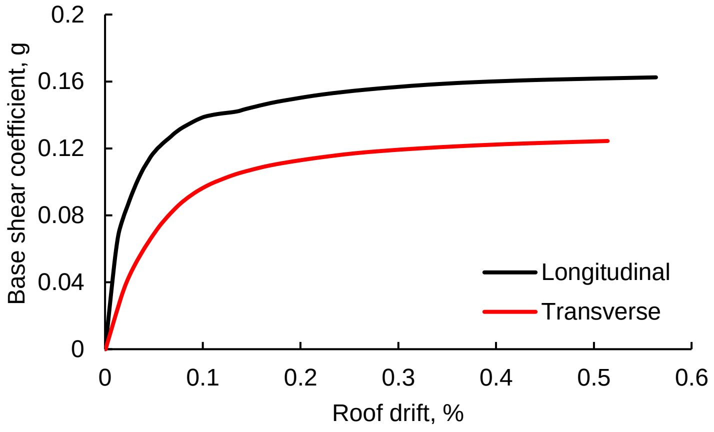


Figure 12. Capacity curves for the PRE-SMM typology in two principal directions.

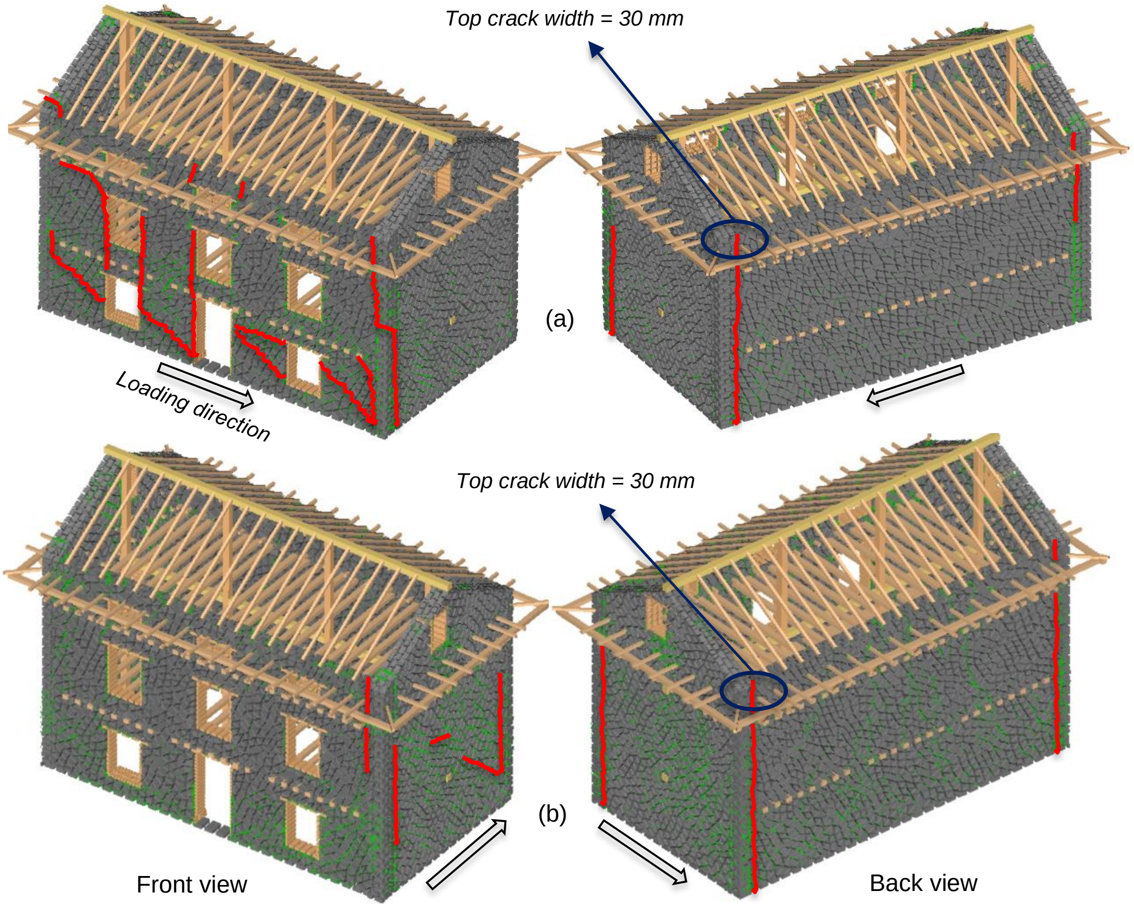


Figure 13. Ultimate failure mechanisms obtained from pushover loading in (a) longitudinal and (b) transverse directions. Green coloured cracks represent tensile and shear cracks of width up to 3 mm while red coloured cracks represent major cracks of width more than 3 mm.

The ultimate crack patterns developed in the building when loaded in the two principal directions are shown in Figure 13. The most dominant failure mode includes continuous vertical separation cracks at the cross-wall connection triggering the overturning of the out-of-plane loaded walls. The long in-plane loaded wall with windows suffers diagonal shear cracks in the lowermost piers as well as tensile damage in the spandrels. Piers also tend to separate from the wooden frames around the openings. These damage patterns compare well with the actual damage observed in the case study building due to the 2015 earthquake (Figure 14) in which major vertical separation cracks in both direction walls can be seen.

Figure 14. Actual damage due to the 2015 earthquake in the case study building from Sindhupalchowk district. Vertical separation cracks have a maximum width of about 25 mm.

Both in the numerical analysis as well as in the observed damage, excessive out-of-plane overturning of the walls is restricted to some extent, and the ultimate failure includes the collapse mechanisms involving damage in both in-plane and out-of-plane walls. This indicates that the timber floor system and the roof system, including the arrangement of timber keys and struts, provide sufficient level of stiffness for the diaphragm action.

The shake map from the 2015 Nepal earthquake (USGS, 2015b) estimated a PGA range of 0.3g - 0.8g in the most affected districts which is far more than the lateral seismic capacity of the PRE-SMM typology (Figure 12). However, due to the lack of site-specific seismic records, no direct comparison of the actual and numerical seismic performance of the case study building, for example using capacity spectrum approach, could be made.

Conclusions

From the study presented in this paper, the following conclusions are drawn.

1. One of the main reasons of the widespread damage sustained by the residential buildings in the 2015 Nepal earthquake is the poor seismic performance of the SMM typology which was the most common construction type in the mountainous area.
2. The seismic capacity of the PRE-SMM typology is very low in both principal directions, the shorter direction being the weakest. Vertical separation cracks triggering the out-of-plane overturning of walls is the major failure mode in this typology.
3. The lateral seismic capacity and failure mechanisms obtained in this study are beneficial in the understanding and quantifying the seismic performance of existing buildings and will inform the development of effective retrofitting solutions.
4. Sensitivity analysis to quantify the effect of uncertainty associated with the material properties and construction characteristics is needed to understand the spectrum of the seismic response of PRE-SMM typology.
5. Applied element modelling can be used with sufficient accuracy to simulate the seismic behavior of rubble stone masonry.
6. A comparison of construction characteristics and seismic capacity of PRE- and POST-SMM typology is important to understand the improved seismic resilience of the communities hit by the earthquake and will follow as a future study.

Acknowledgement

The funding provided by both the Global Challenges Research Fund and the EEFIT Research Grant Scheme for the research work presented herein is gratefully acknowledged.

References

ASI (2018), Extreme Loading for Structures V6. Applied Science International LLC, Durham (NC), USA, 2018

Bhagat S, Samith Buddika HAD, Adhikari RK, Shrestha A, Bajracharya S, Joshi R, Maharjan R and Wijeyewickrema AC (2017), Damage to cultural heritage structures and buildings due to the 2015 Nepal Gorkha earthquake, *Journal of Earthquake Engineering*, 22(10): 1861-1880

Bothara JK, Dizhur D, Ingham JM (2018), Masonry building design for earthquake-affected remote areas of Nepal, *10th Australasian Masonry Conference*, Sydney, Australia

Bothara JK, Giongo I, Ingham J, Dizhur D (2018), Numerical study on partially-reinforced semi-dressed stone masonry for build-back-better in Nepal, *10th International Masonry Conference*, Milan, Italy

D'Ayala D (2004) Correlation of fragility curves for vernacular building types: houses in Lalitpur, Nepal and in Istanbul, Turkey, *13th World Conference of Earthquake Engineering*, Vancouver, Canada

D'Ayala D & Kishali E (2012), Analytically derived fragility curves for unreinforced masonry buildings in urban contexts. *15th world Conference of Earthquake Engineering*, Lisbon, Portugal

Gautam D, Rodrigues H, Bhetwal KK, Neupane P and Sanada Y (2016), Common structural and construction deficiencies of Nepalese buildings. *Innovative Infrastructure Solutions*, 1(1), p.1

Guragain R (2015), *Development of Earthquake Risk Assessment System for Nepal*, PhD Thesis, University of Tokyo

HRRP (2017), District Profile – Sindhupalchok (as of 10 Apr 2017), Housing Recovery and Reconstruction Platform. Available at: https://reliefweb.int/sites/reliefweb.int/files/resources/170410_Sindhupalchok.pdf

HRRP (2018), *Housing Typologies: Earthquake Affected Districts*, Housing Recovery and Reconstruction Platform, Nepal.

Lemos, JV and Campos Costa A (2017), Simulation of shake table tests on out-of-plane masonry buildings. Part (V): discrete element approach. *International Journal of Architectural Heritage*, 11(1): 117-124

Malomo D, Pinho R and Penna A (2018) Using the applied element method for modelling calcium silicate brick masonry subjected to in-plane cyclic loading. *Earthquake Engineering & Structural Dynamics*, 47(7): 1610-1630

NBC 203: 2015 (2015), *Guidelines for Earthquake Resistant Building Construction: Low Strength Masonry*, Nepal National Building Code, Government of Nepal.

NPC (2015), *Nepal Earthquake 2015: Post Disaster Needs Assessment, Volume A: Key Findings*, National Planning Commission, Government of Nepal

NRA (2015) *Design Catalogue for Reconstruction of Earthquake Resistant Houses: Volume I*, Notational Reconstruction Authority, Nepal

NRA (2016a), *Nepal Earthquake 2015: Post Disaster Recovery Framework (2016-2020)*, National Reconstruction Authority, Government of Nepal

NRA (2016b), Structures Damage Grade at 14 Earthquake Affected Districts, National Reconstruction Authority, Nepal.

NRA (2019), Central Level Project Implementation Unit Official Website. Available at: http://202.45.144.197/nfdnfis/clpiu/index.htm (Accessed 10/04/2019)

NSC (2016), Nepal National Seismological Centre Official Website. Available at: (http://www.seismonepal.gov.np/index.php?listId=161) (Accessed on 01/10/2016).

Pun, R (2015), *Improvement in Seismic Performance of Stone Masonry Using Galvanized Steel Wire*, PhD Thesis, University of Technology, Sydney, Australia

USGS (2015), U.S. Geological Survey Official Website. Available at: http://earthquake.usgs.gov/earthquakes/eventpage/us20002926#general (Accessed 10/04/2019).

USGS (2015), U.S. Geological Survey Official Website. Available at: https://earthquake.usgs.gov/earthquakes/eventpage/us20002926/map?shakemap-code=atlas20150425061125&shakemap-source=atlas&shakemap-pga=true&shakemap-stations=true&shakemap-intensity=false (Accessed 10/04/2019).