Bhutanese Ornamental Windows and Its Contribution to Inter-story Drift In Rammed Earth Structure- A Case Study

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Abstract

The vernacular structures in Bhutan attributes to the country's rich tradition and culture.These structures built during 15th – 16th centuries without any technical guidelines still exist with profound pride as Bhutanese traditional buildings even after experiencing great earthquake in the past. Bhutanese vernacular structures exist in various types; while this research paper focuses only on the structural analysis of a commonly found rammed earth house in Paro, considering the effect due to Rabsel. Rabsel is a Bhutanese ornamentalwindow having significant aesthetic and cultural values. These heavy timber components fixed to the wall has tendency to add weights to the wall. During seismic activity this might lead to vertical acceleration and overturning moment, which generates typical P-delta effect inducing lateral as well as vertical loads on the walls. Hence, it is the primary cause of tilting Rabsel, cracking and buckling of walls as observed in post-earthquake scenario. Hence, the effect of Rabsel as shear and moment contributing component will be looked into which isnot incorporated in any design process and software. Linear static analysis is performed considering varying weights of Rabsel and results obtained are used for numerical modelling. The results found forms the paramount philosophy of designing and executing construction of future traditional buildings in Bhutan.

Key words - *Rabsel, Vernacular, Base shear, Overturning moment, Rammed earth, Traditional buildings*

Introduction

Traditionally, dwellings in the Inner Himalayan valleys of Bhutan were constructed from rammed earth and adobe blocks in the western regions, quarry stone in the central and eastern regions and timber structure in south(Chettri et al., 2019). The population and housing survey conducted in 2017 reveals that 54.77% of total houses are traditional vernacular structures. The figure 1 shows the percentage of each types of dwellings in Bhutan. The conventional reinforced cement concrete with either burnt clay bricks or cement concrete block comprises of 42.76%. Earthquakes of various sizes have occurred in Bhutan inflicting heavy casualties and damages for centuries (K. Thinley et al., 2017). Bhutan government enforced to use Indian code from the year 1997 to suffice its needs however, there were several reinforce cement concrete structures existing before that. RC buildings built prior to 1997 weredesigned only for gravity load and only those built after 1997 were designed for seismic load according to the Indian seismic code IS 1893(K. Thinley & Hao, 2017).

Traditional Bhutanese structures is always accompanied by its unique architectural features particularly the aesthetic ornamental windows called Rabsel. It's the external timber components found along walls of Bhutanese houses in the periphery of windows. They have various architectural and religious significances as well as symbolic representation of country's rich culture. Traditional Rabsel were made out of locally available timber with dimension varying from 3×4 inch to as large as 4×5 inch (as per field measurement). However, considering the site scenario of defects seen on wall, it was felt that improper fixation and design limitations of vernacular structures lead to shear, moment and sway contributing nature during seismic action resulting in cracks and buckling on wall (Figure 3). To study the effect of Rabsel in overturning moment contribution, static analysis is done and results are presented in the paper.

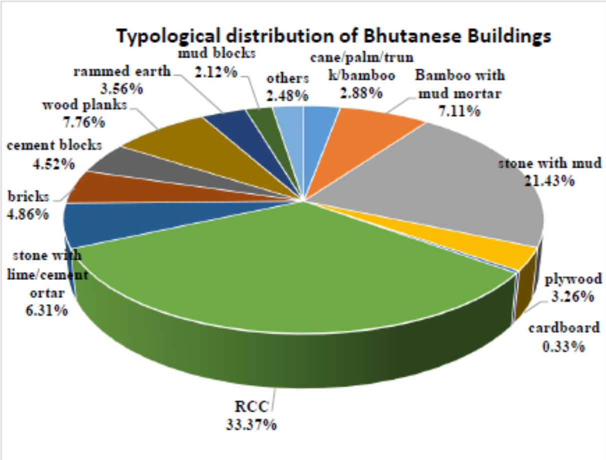


Fig.1 Typological distribution of houses in Bhutan

Summary of Construction Ethics in Bhutan

The City Corporation and Thromdae offices in the dzongkhag (equivalent to state) arebuilding rules implementing agency. They are responsible for verifying the technical drawings (architecture, structural, electrical and sewage) in Bhutan. They make sure that the drawings submitted for acceptance are as per the regulations set up in "Bhutan Building regulation 2018" and "Guidelines on Traditional Architecture Guidelines". "Traditional Architecture Guidelines" stipulates important building aspects like height of building, room size, parking spaces, offset distance, paintings and other culturally determining aspects. It also emphasis on fire safety provision, ventilation, water supply and access to the disabled(Traditional Architecture Guidelines, n.d.). The building height in rural areas shall be maximum of three floors. The table 3.0.2 of Thimphu Municipal Development ControlRegulations 2004 in urban village maximum of five floors are permitted(Thimphu Thromde, 2004) only with lift system.

Rabsel, The Bhutanese Ornamental Window

The decorative windows (Rabsel) are one of the most prominent decorative components in traditional Bhutanese architecture. Traditionally it consists of timber frame structure with multiple windows and panels that cantilevers from the masonry wall. “Rab” means “good” and “Sel” means “clarity”, and thus, it provides light and clarity into a building through its multiple window openings(Sharma, 2017). Such a heavy component has high probability of generating vertical acceleration due to sudden increase in overturning moment. The design software has no option kept to incorporate such a unique external component. Therefore, proper analysis and guidelines are deemed to be explored.

Fig.2 Rabsel -nonstructural component in Bhutanese structure

Earthquake Scenario in Bhutan

The great Himalayas fault line running parallel the entire east to west of Bhutan has made the country prone to severe hazard zone. The Indian Institute of technology (IITR) demarcates Bhutan in severe hazard zone IV and V in their preliminary investigation. For the purpose of construction of reinforced cement concrete structures, Bhutan uses IS 1893 the Indian Standard Codes of Practice since 1997. In the past several earthquakes had occurred in the region namely, The 1713 Arunachal Pradesh earthquake (magnitude 7.0), the great Shillong earthquake (magnitude 8.3), the 1905 Kangra earthquake (magnitude 8.0), the great Bihar- Nepal earthquake (magnitude 8.4), the 1947 Assam earthquake (magnitude 7.8), the great 1950 Assam earthquake (magnitude 8.7), the 1988 Eastern Nepal earthquake (magnitude 6.8) and the 2011 Sikkim-Nepal border earthquake (magnitude 6.9) had caused severe damages totiny Himalayan kingdom.

In 2009 (Mw 6.1) and 2011 (Mw 6.9) earthquake, around 4614 houses and 7965 houses were totally damaged respectively(Joint Rapid Assessment for Recovery, Reconstruction and Risk Reduction. Royal government of Bhutan, 2009) and (Joint Rapid Assessment for Recovery, Reconstruction and Risk Reduction. Royal government of Bhutan, 2011). The most of the damaged houses were either rammed earth and stone masonry houses. Substantial damages to lives, properties and infrastructures were sustained whose details are presented by Royal government of Bhutan in partner with UNDP(Situation Report Earthquakes in Bhutan, 2009). However, several vernacular structures stood strong and are performing good seismically. The fundamental reason for such skeptic structural behaviorsare author’s impending research subject. The current paper will only analyze a case study rammed earth structures (Paro) using equivalent lateral force method and FEM modelling to determine the base shear and their distribution in each floor level with and without Rabsel of various weight.

Cracks along the wall

Cracks due to corner

buckling wall

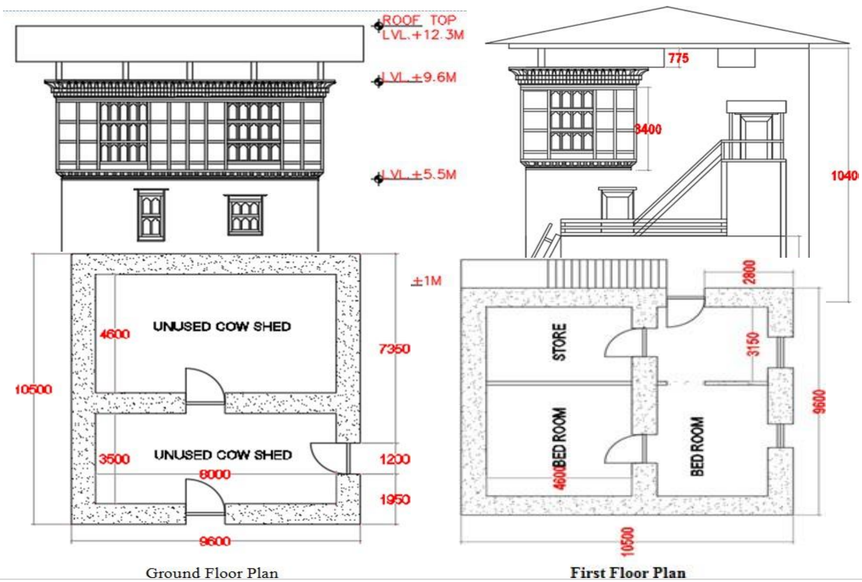
Fig.3 Effects of over stressed

Rammed Earth Structure Considered For Analysis

Fig.4 Rammed earth house for analysing Rabsel dislocation

General Description

The house is located at Bonday in Paro. The age of the construction is 46 years old. The construction types are traditional Bhutanese construction in rammed earth with traditional Rabsel architecture with traditional Bhutanese roof. It is three story traditional rammed earth rural house in the traditional Bhutanese architecture with ground floor used for livestock. Thedimensions of each floor are shown in the figure 5. The dimension of the joist is 130×160 mm with varying spacing of 600 to 300 mm c/c. The foundation of the building is made up ofstone



masonry and it is extended up to the plinth level. Thickness of the rammed earth wall was 800 mm. The dimension of the lift used for ramming was approximately 2.5 m length, 0.8m width and 0.75m height. There was no major visible damage on the wall but lots of minor cracks are present on the wall; vertical cracks, horizontal cracks, lintel cracks and corner cracks are some to mention. There were also cracks that are originated through putlog holes. A Bhutanese roof has a distinct character of the Bhutanese architecture but are non-engineered. It is constructed based on indigenous knowledge of carpenter. The roof truss is constructed using the timber and roofing material as corrugated galvanized iron sheet simply supported on the rammed earth wall. The roof element is not anchored with the wall and the connection of the roof members are weak. For the resistance against wind load, roof member was tied with the supporting string to the cholo (wall extended above roof floor) and also to pack on the ground(Chettri, 2018).

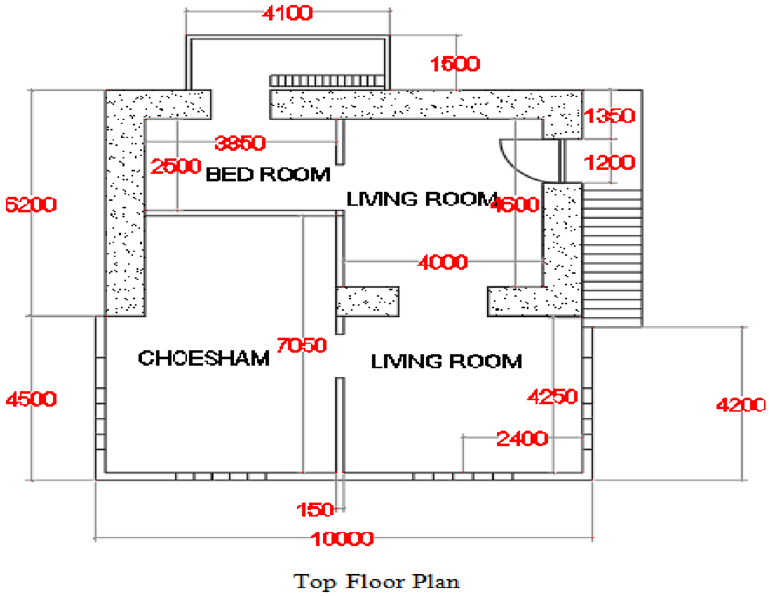


Fig.5 Technical details of structure under analysis (all dimension in mm)

Initial Static Calculation

A common type of rammed earth house in Bhutan is of three storey, which is considered for the purpose of structural analysis. Weight of the structure is calculated which forms the basis for the equivalent lateral force (ELF) analysis. The figure 4 is the pictorial representation of structure under consideration. The details of structural configuration and the processes involved in calculating seismic weight and the parameters used are tabulate below. Theresults and figures are also illustrated. Along with the dead load, certain percentage of live load (as per IS 1893) is also considered. The code provision of IS 875 (part 1) and IS 875(part 2) are specifically used to calculate dead load and live load respectively. The densities tabulated in table 1 is used for the calculation of Dead load. These values are obtained from literatures and Indian standard code for material properties.

Table 1 Densities of material used.

Materials	**Unit weight (kg/m³)**	**Unit weight (kN/m³)**
Earth	2000.000	19.60
Bamboo (wattle)	400.000	3.924
deodar (frame to wattle and roof truss)	560.000	5.494
straw (as roof)	170.000	1.668

As per IS 875 (part 2), live loads for residential dwellings are taken as shown in Table 2.

Table 2 Live load-IS 875 (part 2)

Residential building components	**Live load (kN/m²)**	**Remarks**
All areas inside	2	
balconies	3	

Roof < 10°	0.75	access not provided min 0.4kN/m²
Roof >10°	0.75-0.02*degree greaterthan 10	

Equivalent Lateral Force Method

Equivalent Lateral Force (ELF) method is used to perform a seismic assessment of the building considered. The ELF method is a linear static approach to calculate the equivalent seismic forces for which the building needs to be designed. This analysis is based on the formulas obtained from IS 1893 (Part 1). This method uses a formula derived from Newton's second law of motion to calculate the maximum base shear. The seismic mass of the building is such that it comprises of 100% of the permanent mass and 25% of the variable load on the structure is taken into account. This mass is multiplied with the expected PGA in the regionof the building to obtain the base shear force. Several factors are considered to this formula to take the importance, the ductile behaviour and damping of the structure into account. Furthermore, the natural frequency of the structure versus the dominant frequencies of a general accepted earthquake are taken into consideration in the response spectra. Thesefactors are obtained from empirical formulas in the Indian code. The following formula describes how the base shear of the building can be calculated according to IS 1893 (Part1), with an expected PGA as input parameter.

$$V_B \qquad \frac{S_a}{g} W \qquad (1)$$

Where,

V_B = base shear force.

Z = Seismic Zone factor, is for the Maximum Considered Earthquake

(MCE) and service lifeof structure in a zone.

I= importance factor, Based on functional use of building.
R = response reduction factor, which takes into account the ductility of the building.T = natural time period of the structure determined by an empirical formula
S_a/g= average response acceleration coefficient based on the period of the structure built onrock or other rock-like geological formation and takes 5% damping.
W = seismic weight of the building i.e. where 100% permanent load and 25 % of the variableload is taken into account.

The spectrum used to obtain the spectral acceleration coefficient is obtained from IS 1893 (Part 1) and can be found in figure 6. In general, the design acceleration response spectrum is the smoothened envelope of all acceleration response spectra of the ground motions for which the building should be designed. The time period of the total building is estimated and response reduction value is decided by an empirical formula from the Indian code, which is normally used for the masonry building.

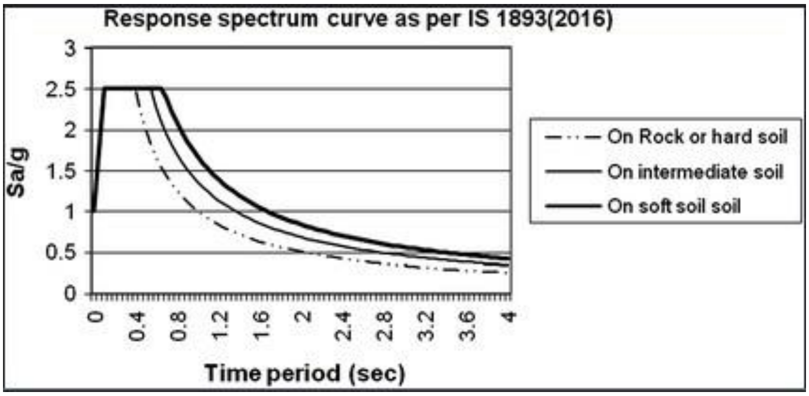


Fig.6 Response spectra for rock and soil, 5% damping according to IS 1893 (part1)

Table 3 Parameters required for ELF method

Parameter	**Value**	**Unit**
T (x, y)	0.2496, 0.3000	s
Sa/g	2.5	
I	1	
R	1.5	
W (without Rabsel)	6924.741	kN

The seismic weight of each floor of the structure under consideration is shown bytable 4 and lateral forces are tabulated in table 5

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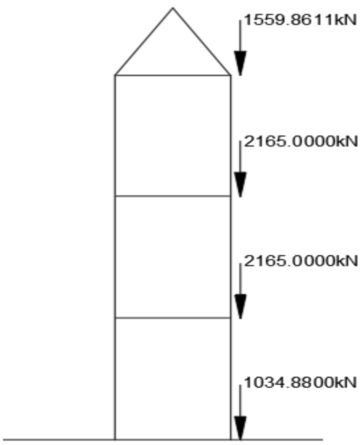

Fig.7 Seismic weight- no Rabsel condition

Results And Discussion

The equivalent lateral force method which is linear static method is used for the analysis structure. It shows the severe variation of seismic weight with respect to the weight of Rabsel increment. The tremendous increase in overturning moment with respect to the Rabsel weightas shown in figure 12 has profuse probability to cause instability problems particularly duringearthquake action. Many a times Rabsel are located at the corners where there is transition of load flow and no precaution measures are available and implemented. Moreover, the option for such nonstructural component is not given in design software and therefore the Bhutanese designer has been overlooking its impact always. Therefore, the vertical acceleration produced is always been neglected and may severely damage the structure during moderate to high earthquake.

Table 4 Lumped mass and total seismic weight

Floor Level	**without Rabsel**	**Rabsel 5kN**	**Rabsel 10kN**	**Rabsel 15kN**	**Rabsel 20kN**
Roof Level	1559.8611	1562.3611	1564.8611	1567.3611	1569.8611
Second Floor	2165.0000	2170.0000	2175.0000	2180.0000	2185.0000
First Floor	2165.0000	2170.0000	2175.0000	2180.0000	2185.0000
Ground Floor	1034.8800	1037.3800	1039.8800	1042.3800	1044.8800
Total seismic weight	6924.7411	6939.7411	6954.7411	6969.7411	6984.7411

Table 5 Lateral forces- without Rabsel condition

Design Lateral Force at roof level (Qr (kN))	1092.136463	Roof Level
Design Lateral Force at second Floor level (Qs (kN))	742.7539521	Second Floor
Design Lateral Force at First Floor level (Qf (kN))	242.5319027	First Floor
Design Lateral Force at ground Floor level (Qg (kN))	0	Ground Floor

Table 6 Summary of lateral forces for all conditions

Rabsel Configuration	**without Rabsel**	**Rabsel 5kN**	**Rabsel 10kN**	**Rabsel 15kN**	**Rabsel 20kN**	**Floor Level**
Design Lateral Force at roof level (Qr (kN))	1092.1365	1094.1360	1096.1354	1098.1346	1100.1336	Roof Level
Design Lateral Force at second Floor level (Qs (kN))	742.7540	744.6389	746.5239	748.4091	750.2945	Second Floor
Design Lateral Force at First Floor level (Qf (kN))	242.5319	243.1473	243.7629	244.3785	244.9941	First Floor
Design Lateral Force at ground Floor level (Qg (kN))	0	0	0	0	0	Ground Floor

The FEM models were developed in Abaqus and induced with lateral load. The numerical model was developed with solid elements (Figure 9) and pushover results are obtained. The roof as physical element is not modelled but roof load is considered as dead load applied on the tops of the walls. The results obtained in static linear analysis are used as essential parameters to perform numerical modelling. To assess the seismic behaviour of the buildings, pushover analyses were performed by incrementally applying a load distributed to the mass on both horizontal directions in each floor level. The analysis of the damage framework allowed interpreting the causes of wall failure such as cracks, wall buckling and dislocation of Rabsel based on stress intensity on the wall as shown in figure 10. Due to the limitations ofthe numerical modelling for this type of buildings such as variability in material properties, boundary conditions, the effect of openings, a lack of continuum and cracking, this cannot be fully relied upon(Bothara et al., 2018). Moreover, there are no previous research on Bhutanese rammed earth houses, therefore some of the mechanical properties are taken from Indian code and research done in other countries.

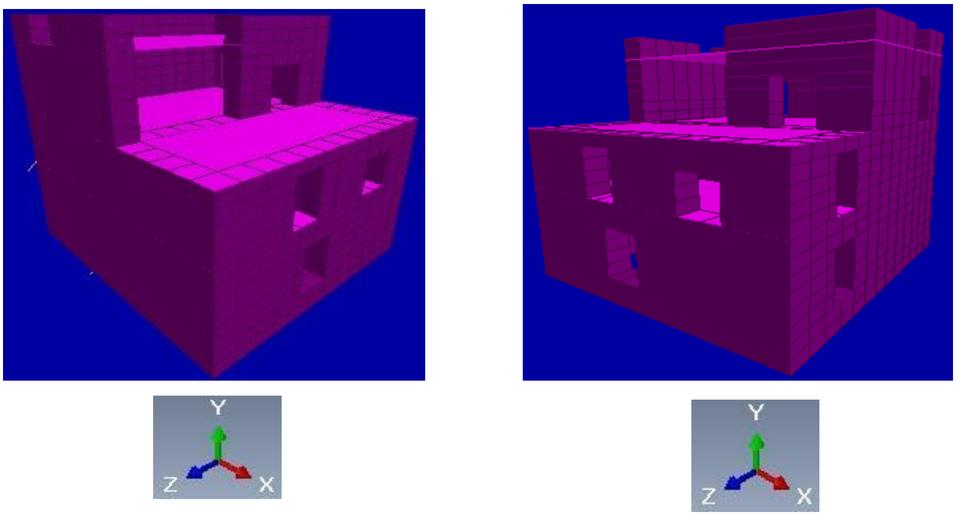

Fig.8 Different views of models under analysis

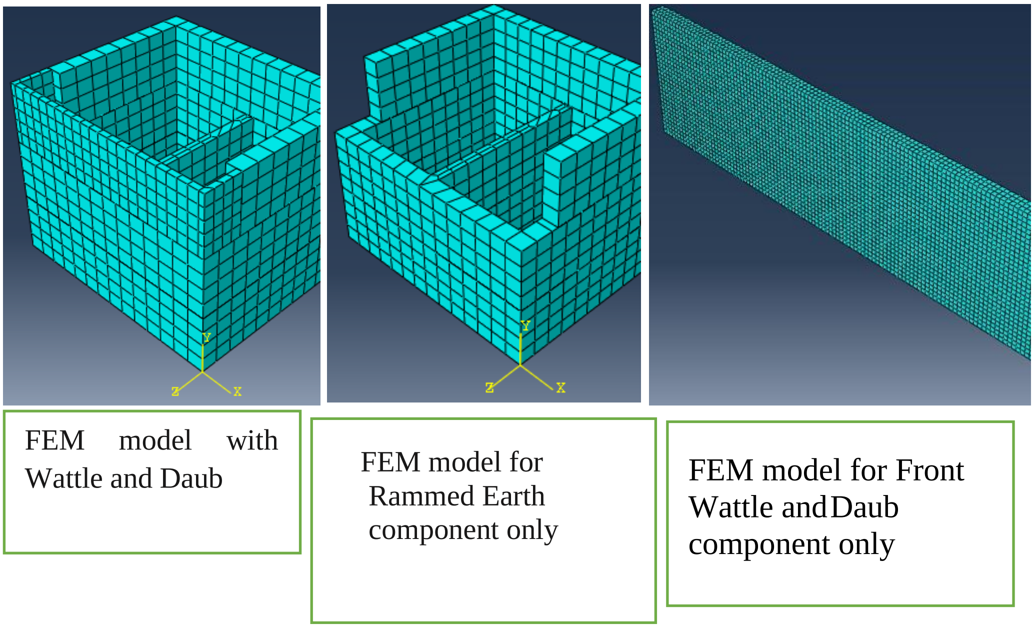

Fig.9 Snapshots of different analysis performed

Stresses(N/m²) on wall (withWD)

Stresses(N/m²) on wall (withoutWD)

Maximum Principle strain Distribution

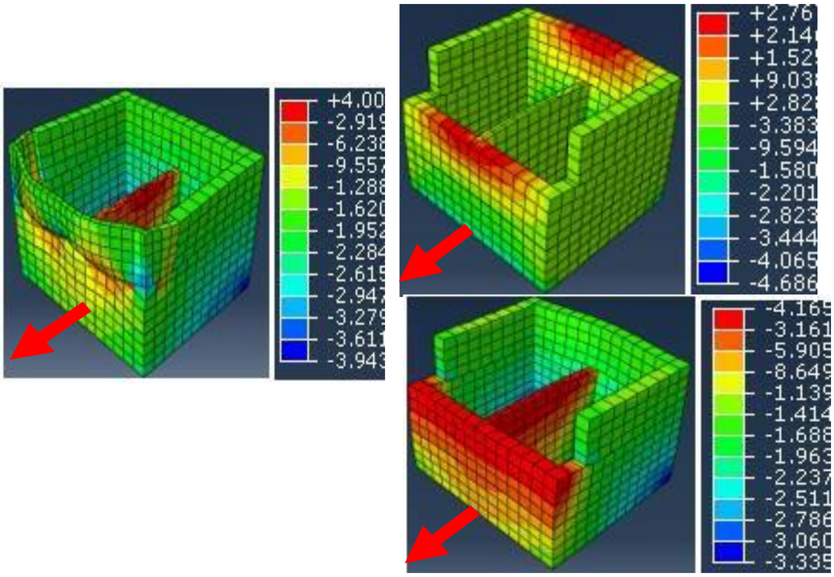

Fig.10 Stress and strain distribution contours with load in Z direction

The past post-earthquake damage analysis done by UNDP and royal government shows casesof various types of crack on wall and dislocation of Rabsel away from the wall. The weight ofthe Rabsel generates additional P-delta effect which induces lateral as well as vertical loads on the traditional walls. This as indicated in stress intensity (Figure 10) must be the primary cause of tilting of the Rabsel, cracks of the wall and bucking as observed in post-earthquake scenario. Moreover, the effect of Rabsel as shear and moment contributing component will belooked into which is not incorporated in any design process and software. Linear static analysis is performed and the various overturning moment, seismic weight and shear forces are presented in the paper along with the varying weights of Rabsel. The results found forms the paramount philosophy of designing and executing construction of future traditional buildings in Bhutan. The paper presents the cognizable aspects of design which were never considered in past design and construction. Its recommended to properly analysis the results presented and replicate in future design works.

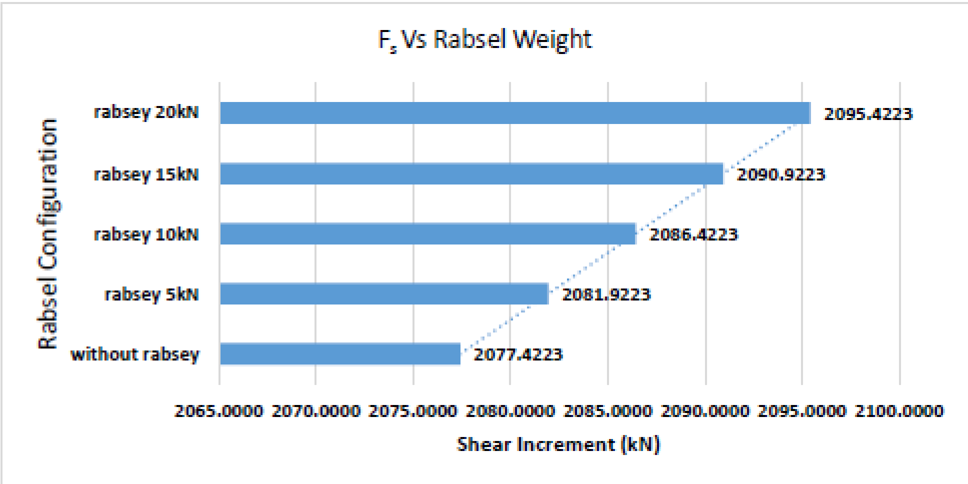

Fig.11 Representation of Shear increment vs Rabsel weight

The results of numerical simulation are close enough to the site condition of the building showing cracks exactly around the high stress intensity. Also, to note that in the case of past earthquake (2009 and 2011) most walls in western Bhutan failed along out of plane direction which confirms the case predicted by numerical simulation. It is also observed that the shear demand increases with additional weight which is not taken care particularly in Bhutanese design.

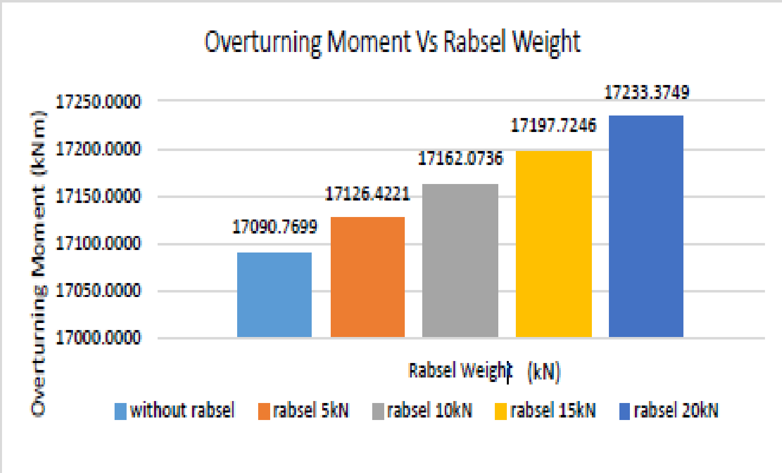

Fig.12 Variation of overturning moment with Rabsel weight

Figure 12 shows the relationship between structural weight and overturning moment. It portrays the considerable increase of overturning moment with respect to Rabsel weight which becomes concern for the stability of the structure. The storey displacement for each floor with varying degree of Rabsel weight is shown in table 7. It's clear that the values exceeded the limit mentioned in IS 1893 -2000. Therefore, it's important for designer to calculate such discrepancies during the design.

Table 7 Storey displacements (mm) and drift ratio with varying Rabsel weight

FloorLevel	**without Rabsel**	**drift ratio**	**Rabsel 5kN**	**drift ratio**	**Rabsel 10kN**	**drift ratio**	**Rabsel 15kN**	**drift ratio**	**Rabsel 20kN**	**drift ratio**
RoofLevel	8.7000	0.0015	15.9000	0.0027	18.4000	0.0031	24.8000	0.0045	36.1000	0.0076
Second Floor	4.3000	0.0011	7.8000	0.0021	9.1000	0.0023	11.4000	0.0029	13.2000	0.0033
FirstFloor	1.1000	0.0004	1.4000	0.0005	2.2000	0.0007	2.6000	0.0009	3.2000	0.0011
Ground Floor	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

The case study structure was simulated with PGA of 0.3g and it was found out that the driftof roof level is 8.7mm. Since there are no previous research parameters on similar structures, many parameters are assumed to quantify the behavior of the case study building. Also, to note that during analysis floors are assumed as flexible floor with no significant contribution to the overall response against earthquake.

Conclusion

Therefore, considering the results projected above its recommended to manually calculate thetime period and average acceleration coefficient and incorporate in the design process for similar vernacular structures. The results obtained through static linear analysis are used as parameters to perform static numerical modelling. To understands the seismic performance of the proposed building typologies and effectiveness of the proposed interventions, finite element models for similar wall elements were constructed using the finite element (FE)software. The stresses on the wall due to increment value of Rabsel are clear indication of causes of various wall failures. The research done in Japan on usage of Polypropylene band (PP band) will be a useful solution to the increase vertical acceleration(Sathiparan & Meguro, 2013). It's also recommended to reinforced the corners of the wall in rammed earth to facilitate better transfer of load. Other strengthening elements like using band in Rabsel sill and top level would serve to preventing tilting and dislocation of Rabsel during seismic action. This way we counteract the vertical acceleration generated due to cantilever projection of Rabsel. Authors recommend the detail study of dynamic analysis of suchvernacular structure for better seismic performance.

Reference

Bothara, J., Ingham, J., & Dizhur, D. (2018). Understanding , Experience and Research on Seismic Safety of Low-Strength Loadbearing Masonry Buildings, (December), 2018.

Chettri, N. (2018). Structural Assesment of Bhutanese Traditional Bhuildings, *4*(May 2017).Chettri, N., Thinley, J., & Koirala, G. S.

(2019). The Comparative Study on Vernacular Dwellings in, *01*(02), 42–47.

Joint Rapid Assessment for Recovery, Reconstruction and Risk Reduction. Royal government of Bhutan, the W. B. and U. nation. (2009). Joint Rapid Assessment for Recovery , Reconstruction and Risk Reduction, (October).

Joint Rapid Assessment for Recovery, Reconstruction and Risk Reduction. Royal government of Bhutan, the W. B. and U. nation. (2011). *Recovery , Reconstruction and Risk Reduction*.

Sathiparan, N., & Meguro, K. (2013). Shear and Flexural Bending Strength of Masonry Wall Retrofitted Using PP-Band Mesh. *Constructii*. Retrieved from http://constructii.incerc2004.ro/Archive/2013-1/Constructii_2013_Vol.14_No.1_ID2013140101.pdf

Sharma, D. (2017). Architectural Conservation of Decorative Timber Windows and Ornamental Columns at Buli Monastery. *American Journal of Civil Engineering and Architecture*, *5*(5), 204–207. https://doi.org/10.12691/ajcea-5-5-4

Situation Report Earthquakes in Bhutan, I. and M. (2009). *Situation Report Earthquakes in Bhutan , India and Myanmar*. Retrieved from https://reliefweb.int/sites/reliefweb.int/files/resources/6E87CE33FB74A607C125763900 4C09B1-Full_Report.pdf

Thimphu Thromde. (2004). Thimphu Municipal Development Control Regulations.

Thinley, K., & Hao, H. (2017). Seismic performance of reinforced concrete frame buildings in Bhutan based on fuzzy probability analysis. *Soil Dynamics and Earthquake Engineering*, *92*(February 2016), 604–620. https://doi.org/10.1016/j.soildyn.2016.11.004

Thinley, Kinzang, Hao, H., & Tashi, C. (2017). Seismic Performance of Reinforced Concrete Buildings in Thimphu, Bhutan. *International Journal of Structural Stability and Dynamics*, *17*(7). https://doi.org/10.1142/S0219455417500742

Traditional Architecture Guidelines. (n.d.). *Traditional Architecture Guidelines*. *Traditional Architecture Guidelines*. Retrieved from http://www.kuenselonline.com/plastic-ban-no-fooling-matter/

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