THE SIMPLIFIED SEISMIC PERFORMANCE EVALUATION OF THE STONE MASONRY HOUSES AND SEISMIC BAND'S EFFECTS TO PREVENT THE SEISMIC FAILURE

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ABSTRACT

The frequent and subsequent earthquakes in Bhutan and around the Himalayan Thrust significantly damaged masonry structures in Bhutan, particularly in rural regions. Potential harms are likely to hit the nation if a similar or higher earthquake occurs within or peripheral. The masonry houses scattered across the country towards the rural region are vulnerable. The damage is likely to happen almost all across the districts when there is an earthquake. The past 2009 and 2011 earthquakes also showed similar patterns of damage all over the country. They mostly failed in shear and out-of-plane (Fig. 1) in different severity. This study applies the simplified method for seismic diagnosis of a masonry structure and investigates the effect of seismic bands by carrying out numerical analyses. We aim to mitigate earthquake disasters in Bhutan's rural regions and save the community there, and the methods discussed here will also meet the financial requirements.

Keywords: Earthquake, Masonry, Seismic hazard, Economic, Disaster, Rural, Vulnerable, Culture

1. INTRODUCTION

Bhutan is a small landlocked country with 20 different districts. Almost all districts have public essential masonry infrastructures with stone and other materials such as bricks, adobe, rammed-earth, etc. Bhutan's main existing masonry structures are Random Rubble Stone Masonry with mud mortar. Those essential structures are administrative buildings, monasteries, school buildings, health infrastructures, office buildings, and rural houses, which were highly exposed to seismic risk. In the 2009 and 2011 earthquakes, 4950 and 6977 masonry structures were damaged respectively across the country, Fig-1.


Figure 1. Damage of stone masonry houses during an earthquake

Similarly, many stone masonry houses were coming up every year. Understanding the earthquake in Bhutan is extremely limited; research on past and future earthquakes are notably scarce. Although recent studies have clearly shown the potential for large earthquakes, the impacts from potential future earthquakes in Bhutan are entirely unknown (Robinson, 2020). The continuity of stone masonry houses' construction leads to additional risk to the communities, focusing on the seismic-resistant new construction of houses and the simplified techniques studied

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to check the design process considering the in-plane and out-of-plane seismic diagnosis considering the seismic zone ‘V’ as per the IS code.

2. TARGET STONE MASONRY HOUSE

A common type of single-story stone masonry house with clear dimensions was carried out for the analysis—the details of the drawing related to a common type of single-story stone masonry house in the country Figure-1. The thickness of the wall is 400 mm, and the room height is 3000 mm considered. The primary stone masonry material properties, shear strength 0.40MPa and tensile strength 0.25 MPa, were considered for the simplified seismic diagnosis (AIJ Guidelines.)

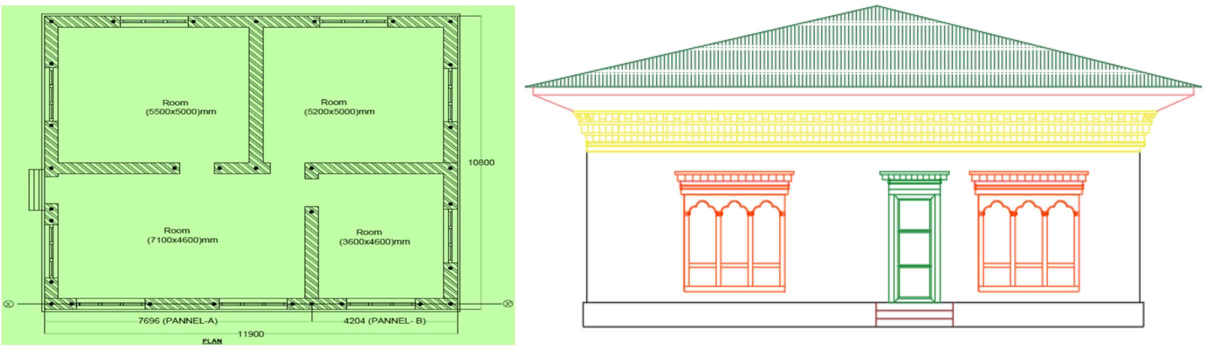

Figure 2: Stone-masonry house plan and elevation (Single story)

Similarly, the mechanical properties of the materials were studied to apply for the FEM pushover analysis to check. The mechanical properties of masonry, concrete, timber, and reinforcements data more or less similar properties were assumed to run the analysis.

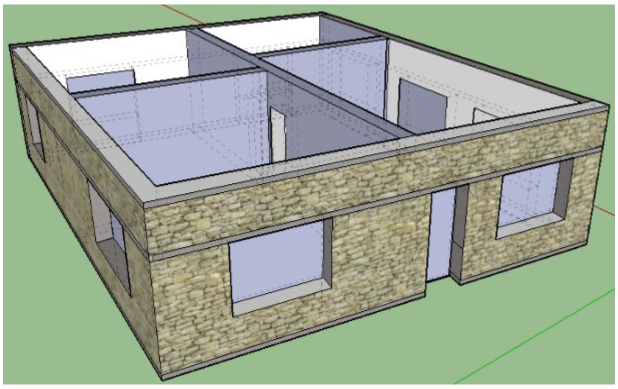

Figure 3. Stone Masonry with seismic bands

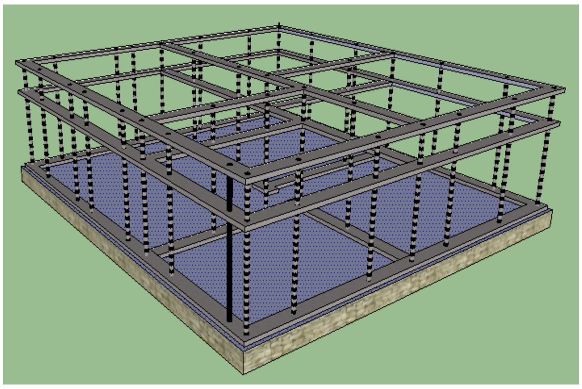

Figure 4. Seismic bands layout details

Fig-3 and Fig-4 show seismic bands in a masonry wall and seismic bands layout details, respectively.The three continuous horizontal seismic bands were provided along the wall length connected with vertical bands. The vertical seismic bands from the corners, T-Junctions, adjacent to openings and from the continuous wall of 1.5m interval of the wall were erected simultaneously along with the progress of the masonry wall. The horizontal seismic band connected all three levels with vertical bands. The connection binds the structure as a whole and provides a box effect during the strong ground motion by an earthquake.

3. SIMPLIFIED SEISMIC DIAGNOSIS METHOD

The simplified seismic diagnosis method evaluates the seismic performance of the structure considering in-plane and out-of-plane wall earthquake response. We assume that the walls separate from the orthogonal walls at their intersections for random rubble stone masonry oscillated by earthquake ground motions. Thus, if the wall is subjected to horizontal forces in-plane direction, the wall tends to fail or collapses in shear. And similarly, if the wall is subjected to horizontal force in the out-plane direction, the wall tends to overturn due to bending.

In the in-plane seismic diagnoses, the walls are segregated from the opening edges and analyzed for the shear strength analysis Q_i. The wall qualified for bearing the shear force is directly related to the wall length and width (the wall thickness). Higher the length of the wall and thickness, better the stability to withstand the in-plane shear in strong ground motion.

The vertical axis's rectangular portion of the wall is applied with the equally distributed load horizontally considering half portion of the self-weight, including the roof load brought forward for the analysis considering the seismic zone V. The important equations for the analysis, is elaborated below. The study's methodology is based on past earthquake damage studies on masonry houses, including considering the same practice with seismic intervention as an additional to walls across the regions.

We evaluate the seismic safety by comparing the ultimate shear strength of the wall by equation 1 with seismic design shear force by equation 2.

$$\boldsymbol{\tau}_u A \tag{1}$$

$$Q_i = C_i * W \tag{2}$$

From the above equations $'\boldsymbol{\tau}_u'$ is the shear coefficient, 'A' is the cross-sectional area, "Q_i"is the seismic shear force, C_i coefficient calculated in the i^{th} and "W' the total weight of the wall.

$$C_i = A_h * A_i \text{ and, } A_i = (1 + (1/\sqrt{\alpha_i} - \alpha_i)\ 2T/(1+3T)) \tag{3, 4}$$

$$A_h = \frac{Z\,I\,S_a}{2R\,g} \tag{5}$$

The design horizontal seismic coefficient 'A_h' for the structure is obtained from equation (5) (IS:1893, 2002), and the A_i is the distribution coefficient in the height direction. Where 'Z' is the zone factor 'I' importance factor, depending upon the functional use of the structures, 'R' response reduction factor, 'Sa/g' Average response acceleration coefficient for rock or soil as per figure 2 (IS:1893, 2002). In equation (4), $'\alpha_i'$ divides the weights from the top floor to the i^{th} floor by the total weight of the above-ground part value. Thus, 't' is the time in seconds (S), the natural period of the building.

The seismic diagnosis in out-of-plane failure, the ultimate bending Moment (M_{sm}), is calculated as expressed in equation (6), the Moment of the random rubble masonry wall without seismic interventions. The ultimate Moment is the capacity of the wall, beyond which the wall tends to fail.

$$M_{(sm)} = \{f_t + [(H - x)\rho + RL]\}\, Dt^2/6 \tag{6}$$

To compare with the ultimate bending Moment, moment distribution, or overturning Moment, calculated and checked. Finally, considering the walls were fixed with the seismic bands, the restrained Moment is calculated, checked with the ultimate Moment.

In the equation 6, 'f_t' is the tensile strength of the stone rubble masonry, 'H' is the overall height of the wall, 'ρ' is the density of the rubble masonry; 'RL' is the roof load; 'D' is the length of the wall.

4. RESULT AND DISCUSSION

The result and findings are explained in two sub-topics, and each describes the analysis result. The seismic analysis for the stone rubble masonry wall was carried out with in-plane and out-of-plane diagnoses and further analyzed with FEM non-linear pushover analysis. The masonry unit was assembled and joined together with mortar (Hokelekli and Yilmaz, 2019) which behaves together in force. The details of the results were discussed in each outcome and represented through graphs.

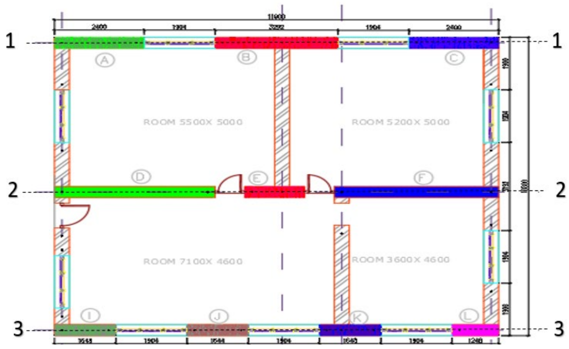

Figure 5. Walls for seismic diagnosis X-direction

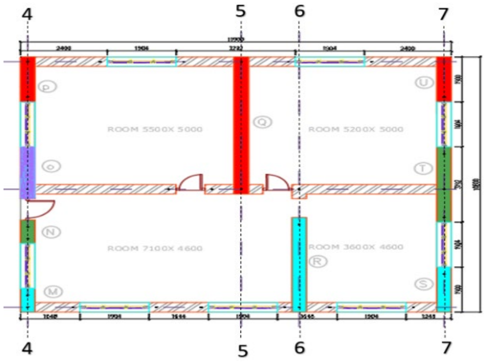

Figure 6. Walls for seismic diagnosis Y-direction

4.1. In-plane diagnosis

The seismic diagnosis in-plane as per Fig-6, calculated. According to the design practice in Bhutan, the ground motion during an earthquake is considered 0.36*g* as per the seismic zone 'V' of IS code. The wall thickness is adequate; however, the seismic intervention components such as cornerstone, through/bonding stone, and the proper bonding of the masonry wall are necessary to avoid the unpredictable cracks and separation from the orthogonal direction during the strong ground motion.

The result was compared with the ultimate shear force that the wall can withstand horizontally. The graphical representation Fig-7 shows the calculated design shear force and the maximum shear force that the wall can resist against strong ground motion during an earthquake. All walls were within the range of the ultimate shear force that each wall held. The walls in both directions were checked, excluding the opening considering detached in all openings and all solid walls merged following the one straight centerline.

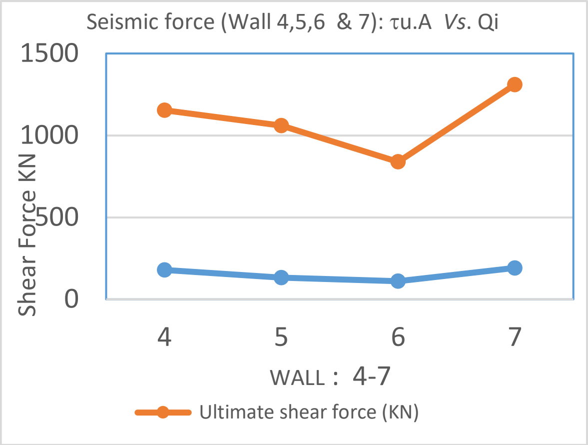

Figure 7. The graphical representation of design and ultimate shear force (Wall 4-7)

The analysis shows that the walls are safe against in-plane seismic action Figure-7. However, the mortar joint may vary the actual tensile and shear strength of the stone masonry wall. The random rubble stone masonry does not have proper stone shapes; When the cement mortar goes inside, the rubble masonry will have a different thickness within the short span of the wall with various shapes of the stones. Therefore, the primary failure modes can occur within the cement mortar and stone rubble interface (Vasconcelos and Lourenço, 2009).

4.2. The Out-Of-Plane diagnosis

The out-of-plane seismic diagnosis was carried out in each wall in X-direction and Y-direction as per the plan Fig-5 and Fig-6. The ultimate Moment (M_{sm}) is the maximum Moment of the masonry wall, beyond which the wall tends to overturn or collapse. Similarly, considering the different conditions of end support, Moment is calculated for each wall and compared with the ultimate Moment.

The end of the walls is assumed hinged and the Moment is calculated and compared. Figure-8 shows that Moment is beyond the ultimate Moment, which is not safe. And secondly, moment distribution (M_x) is checked against each wall Figure-8, Which shows that it is beyond the ultimate Moment in each wall, and it is not safe.

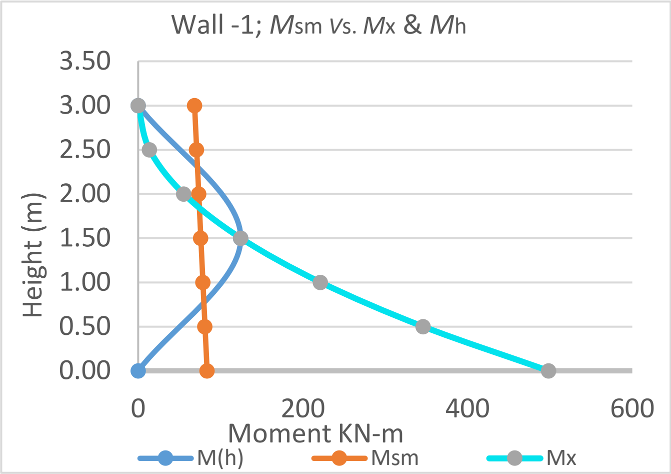

Figure 8. The Moment M_h and M_x compared with ultimate bending Moment M_{sm} (Wall-1)

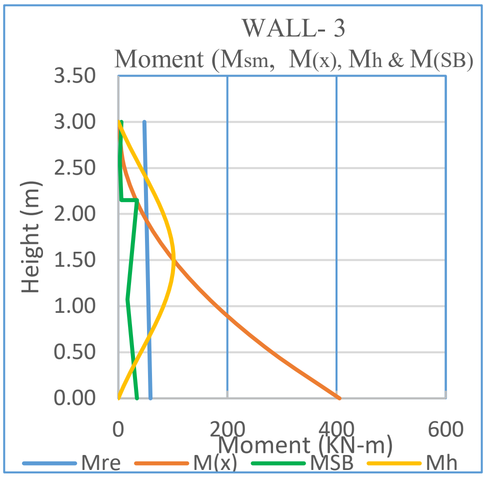

Figure 9. The all Moment Mx, M_h, and M_{sb} compared with ultimate Bending Moment M_{sm} (Wall-3)

Finally, The Moment (M_{SB}) is checked considering three levels of the walls were fixed conditions with the seismic bands in Figure-9. The result shows the possibility of the seismic bands to prevent walls from overturning in the out-of-plane direction during seismic action.

4.3. FEM Analysis

Figure 10 shows the model for FEM analyses. Figure 11 shows the analysis results for force-deformation relationships. According to this figure, the wall with seismic bands carries a shear strength instantly 27% higher than the typical random rubble stone masonry. The analysis stopped while displacement was 40mm and 80mm for typical stone masonry and stone masonry with seismic bands, respectively; the loading capacity difference at the analysis stopped is 85%.The typical stone masonry started forming the shear crack from the edge of the openings, and the load gradually dropped after reaching the maximum of 1426.49KN. The displacement was 7.0 mm at the failure point. The stone masonry wall with a concrete seismic band attained the maximum load of 1809.24 KN with a displacement of 5mm. Suddenly, loading dropped to 1373.43 KN with a displacement of 8 mm. Gradually, the load increased to 1665.61KN with displacement up to 80mm and stopped the analysis.

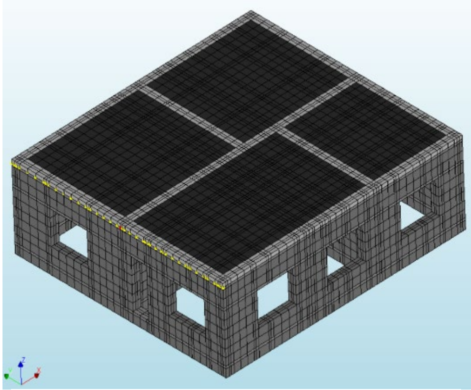

Figure 10. Model for FEM analysis

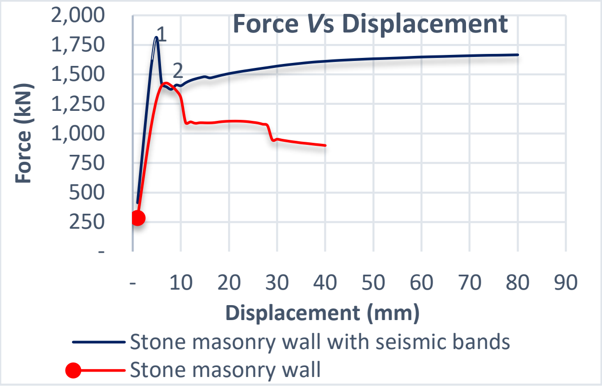

Figure 11. Graph representing FEM Results

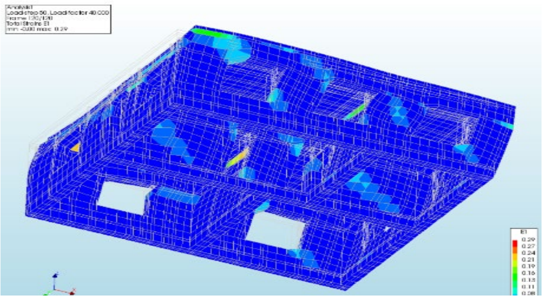

Figure 12. Stresses on stone masonry wall without seismic bands

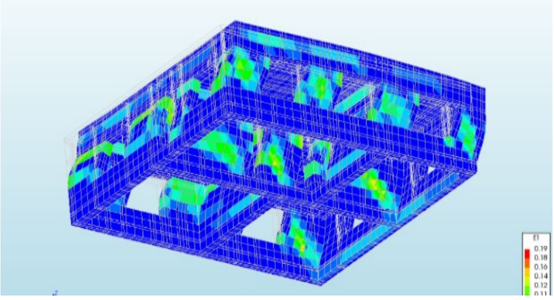

Figure 13. Stresses on stone masonry wall with seismic bands

Figures 12 and 13 present stress districtutions of the models with or without the seismic bands, respectibely at their force-peak point 1 or 2 in Figure 11. It is found out that stresses are distributed more widely due to effects of the seismic bands, comparing Figure 13 with Figure 12.

These results confirm that the seismic load carrying capacity is more and drift is higher with seismic bands and ductile compared with a brittle masonry wall, which withstands the force longer duration during strong ground motion of an earthquake.

5. CONCLUSIONS

The study shows that incorporating the seismic bands provides better stability to rural masonry houses than normal stone masonry houses. The simplified seismic diagnosis method shows that the normal masonry houses were vulnerable to strong ground motion during the seismic action, particularly in the out-of-plane direction. However, seismic bands improve seismic performance, minimize the Moment, bind all structures together, and provide a box effect. The whole structure behaves together along with the action of the force. The seismic bands also increase the ductility and prevent sudden failure. The cost difference of within 10% with simplified techniques for the construction saves lots against earthquake disasters and casualties. The design method would be more useful for rural regions for masonry houses design and check as per the zone seismic design requirement. The capacity building for these simplified seismic diagnosis methods towards the region was more important to improving rural houses.

ACKNOWLEDGEMENTS

This research was conducted during the individual study period of the training course "Seismology, Earthquake Engineering, and Tsunami Disaster Mitigation" by the Building Research Institute, JICA, and GRIPS. I would like to express my sincere gratitude to my Supervisor Dr.Takoyoshi AOKI and Dr. Miyamoto MITSUHIRO, for their valuable support and experience, which helped me to complete my research successfully, and to Dr. Haruhiko SUWADA for his guidance and advice during my individual study. I would also like to acknowledge Dr. Tatsuya AZUHATA for his permanent support from the beginning to the end of the program.

REFERENCES

IS:1893 (2002) 'Criteria for Earthquake Resistant Design of Structures - General Provisions & Buildings
Robinson, T. R. (2020) 'Scenario ensemble modeling of possible future earthquake impacts in Bhutan',
Vasconcelos, G. and Lourenço, P. B. (2009) 'Experimental characterization of stone masonry.