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DYNAMIC BEHAVIOR OF TRADITIONAL COMPOSITE MASONRY BUILDINGS IN BHUTAN

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ABSTRACT

The traditional construction methods in Bhutan consist of rammed earth and stone masonry structures where most of the population live. However, during the 2009 Eastern Bhutan earthquake and the 2011 Sikkim, India earthquake huge numbers of these traditional buildings suffered severe damages. Therefore, it is important to evaluate the seismic performance of these buildings to prevent future disaster. Several studies have been carried out by numerous authors and particularly full-scale specimens representing traditional Bhutanese buildings were studied through quasi static pushover tests.This study aims to discuss the dynamic characteristics of composite masonry structures by shaking table tests on 1/6 reduced scale models under scaled earthquake motions recorded in Bhutan. A total of four specimens comprising of two rammed earth (unreinforced &retrofitted) and two stone masonry (unreinforced &retrofitted) were tested to understand change in dynamic properties and damage propagation. Further numerical analysis was carried by transforming the models to two-degree lumped mass system based on microtremor measurements. The time history analysis was executed both in linear and nonlinear ranges using the input motion from the experimental tests and dynamic behaviors were further studied comparing with the experimental results.

Keywords: Bhutan, composite masonry, dynamic behavior. shaking table, lumped mass.

1. INTRODUCTION

The Kingdom of Bhutan lies in the eastern Himalayan range, bordering India in the south and China in the north. The traditional construction practices are still prevalent in the country and depending on the climatic condition and material availability, construction techniques and methods vary from region to region. The most common forms of construction are rammed earth in the western region and stone masonry in central and eastern parts of the country. General architecture styles and designs remain similar in both areas, and the number of floors varies from two to three stories. The rammed earth construction technique mainly involves compacting the earth in several layers inside the wooden formwork and forming the blocks of walls whereas stone masonry construction involves constructing walls using stones stacked together and bonded by mortar (mud). The materials such as stones, soils and timbers required in both the construction are usually collected from nearby area. However, these composite masonry buildings are vulnerable to the earthquake force due to its poor seismic resistant properties and lack of proper design. The 2009 eastern Bhutan earthquake with magnitude of Mw 6.3 caused severe damages to the stone masonry houses and magnitude Mw 6.9, 2011 Sikkim, India earthquake has devasted rammed earth houses in western region of country.

In the past years, several research have been undertaken to examine the effectiveness of retrofitting measures on rammed earth structures, Yang Wang et al. (2016) by shaking table test.

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Mazzon et al. (2009) evaluated the performance of the 2:3 scaled stone masonry models and influence of natural hydraulic lime injection by shaking table test. Further several researchers a has also undertaken shaking table test as well as numerical analysis using various Finite Element method to study the dynamic behaviors of stone masonry and rammed earth structures. Shrestha C et al. (2019) and Wangmo et al. (2019). based on a push-over test on full-scale two-story stone masonry and rammed earth house, proposed effective retrofitting measures to increase the seismic strength by mesh-wrapping technique. In this research, the seismic performance of the traditional composite masonry houses, rammed earth, and stone masonry are further evaluated based on the shaking table test on reduced scale model specimens with similar retrofitting techniques proposed by Shrestha K C et al. (2019) and Wangmo P et al. (2019). This research aims to study the dynamic characteristics of composite masonry structures while assessing the effectiveness of proposed retrofitting methods by conducting shaking table test on 1/6 reduced scale models. Further, numerical analysis will also be carried out by developing two-degree lumped mass model system to simulate the shaking table test and study the changes in dynamic parameters.

2. EXPERIMENTAL PROGRAM

2.1. Model specimen

Models are prepared to reproduce the prototype's geometrical, physical, and dynamic characteristics. Considering the limitation of the shaking table capacity and difficulties in moving the specimens on the shaking table, the test specimens are geometrically reduced to a scale of 1:6. In total, two rammed earth, Unreinforced (URE) and Retrofitted(RRE) and two stone masonry, Unreinforced(USM) and Retrofitted(RSM) model specimens are constructed which represents the common typologies found in Bhutan. All the models have the same size with a floor plan of 1.35m x 0.9m and a total height of 1.137m. The wall thickness is 100mm. The specimens are constructed by local craft men using the materials locally available and the one each specimen of stone masonry and rammed earth is retrofitted. The retrofitting technique follows the wrapping of the walls by steel wire mesh from both interface and applying 10mm thick cement plaster of 1:3 cement sand ratio. The material properties remain same as prototype buildings. To reproduce the dynamic behavior of the prototype by the scaled model, the simple model similarity (Tomazevic. (1992)) is considered such that acceleration is amplified and time is compressed following the scale factor.

2.2. Test Setup and Instrumentation

Tests were performed on two specimens at the same time: one was unreinforced, and the other was retrofitted, and its comparisons were made on the spot. The response of the structure is measured using the accelerometer STP-300S and the sampling frequency was set at 200 Hz. A total of sixteen accelerometers were used to measure the response of the two specimens, eight on the unreinforced and eight on the retrofitted. For each specimen, 1 sensor was mounted at the base, 4 at the second-floor level and 3 at the roof level. Digital cameras were placed in strategic locations to record the visual shaking behavior of the structure and analysis of damage propagation after the tests. Two types of dynamic excitations were performed, sweep sine waves and real earthquake inputs. A sweep test was carried out with a low intensity of 0.03g by gradually increasing the frequency from 1Hz to 25Hz to obtain the characteristics of a model in the elastic range. Following the sweep test, a series of earthquake motions with increasing intensity were used. The earthquake ground motion recorded in Thimphu, Bhutan on September 12, 2018, was used as an input motion. The original wave was scaled following the similitude rule to suit the scaled model. The test was performed with increasing the intensity of a ground motion at 0.2g in each succeeding step, where 8 sequential runs for the rammed earth and 7 sequential runs for the stone masonry were employed.

Figure 1. Rammed earth

Figure 2. Stone masonry

Table 1. Damping factor

Damping factor	URE	RRE	USM
X	0.018	0.0119	0.0155
Y	0.02	0.0127	0.0152

3. METHODOLOGY

3.1. Experimental data processing and analysis

The shaking table test data for acceleration are obtained directly from accelerometers and the data obtained by accelerometers are base-line corrected and filtered using the band pass filtering technique with cut-off frequencies of 1Hz to 50Hz. The response of the models is evaluated based on change natural frequencies, acceleration factors and damage propagation at each input Peak Ground Acceleration (PGA). The damping of the specimen is also estimated by Random Decrement Technique using microtremor measurement carried out prior to experiment. The result is shown in Table 1

The natural frequency of a model at each input PGA is estimated from a spectral ratio of the top vs base by Fast Fourier transform method. The natural frequencies of specimens at each input level are the average natural frequency of three accelerometers at the roof level. While in case of the unreinforced stone masonry specimen one sensor at the roof level was damaged at PGA 0.6g, therefore only two sensors are considered.

Acceleration Factor is the ratio of the absolute maximum acceleration response of any above story to the maximum input acceleration at the base. This factor describes how many times the input acceleration is amplified at each floor level. The factors at the roof level are average of three sensors while at second floor average of four sensors.

3.2. Numerical analysis

The numerical analysis was carried out considering the lumped mass system. The two-story model is transformed into a lumped mass and shear spring model using the microtremor measurement results to simulate responses of shaking table test. Lumped mass represents the story mass, and the shear spring represents the story stiffness. The Linear Time History Analysis (LTHA) and Nonlinear Time History Analysis(NLTHA) was performed for each model using Software SNAP ver. 8. Analysis was executed applying the acceleration time histories from experimental tests. The method of analysis involves the direct integration of dynamic equations of motions (Eq. 1).

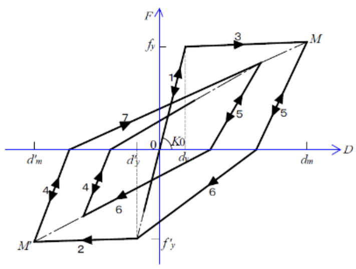

Figure 3. Takeda model

$$M\ddot{U}(t) + C\dot{U}(t) + KU(t) = -M1\ddot{u}_g(t) \quad (1)$$

The non-linearity behavior of the stiffness is described based on the Takeda model and the yield strength (Q_y) are determined from capacity curve of the static test on full-scale buildings. The constant damping ratio of 2% is adopted for the analysis and the damping matrix [C] in the structure is calculated by Rayleigh damping. The relation is shown in Equation 2.

$$\mathrm{C} = \alpha \mathrm{M} + \beta \quad (2)$$

4. RESULTS AND DISCUSSION

4.1. Natural Frequency

The variation of natural frequencies of rammed earth specimen (URE &RRE) at each input PGA is shown in Figure 4. The natural frequencies decreased with the increase in input ground motion due to the degradation of stiffness caused by damages. The natural frequency of the unreinforced rammed earth specimen before the test was 13.79Hz and for retrofitted was 16.2Hz. The frequency dropped to 3.17 Hz and 4.33Hz respectively for URE and RRE at the last test with the specimen showing varying range of damages on the walls.

The change of natural frequency for stone masonry specimen is shown in Figure 5. The natural frequency of the unreinforced stone masonry before the test was 13.18 Hz. The natural frequency dropped to 2.5Hz at nominal PGA of 1.4g with several diagonal shear cracks on the walls. The natural frequency of the retrofitted stone masonry was 38.26 Hz The natural frequency dropped suddenly to 4.3 Hz at nominal PGA of 1.4g with large shear cracks on the side walls.

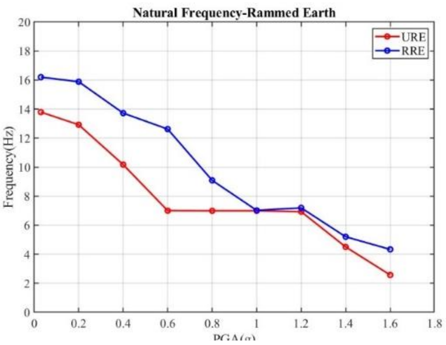

Figure 4. Natural Frequency of rammed earth

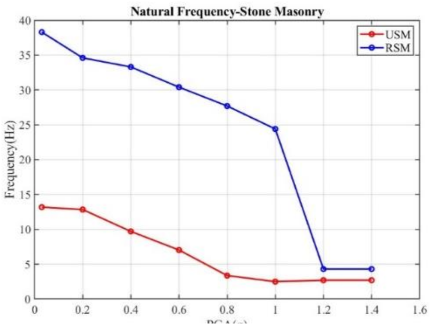

Figure5. Natural frequency of stone masonry

4.2. Acceleration factors

The variation of the acceleration factors at different floor levels indicates the distribution of lateral stiffness. Furthermore, acceleration factors also reflect the damage condition on the structures and usually when damages are increasing the stiffness is reducing leading to elasto plastic phase resulting in lower acceleration amplification factor at above floors.

The acceleration factors at the roof level varied more than the second-floor level, which was caused by irregularity of walls in upper floors. While at second floor level the variation is less indicating the proper distribution of stiffness by wall in all sides. The acceleration factor for rammed earth specimen is shown in Figure 6. The value shows decrement after 0.6g at roof level of URE is due to more crack occurrence with increased PGA. In the retrofitted specimen the acceleration factors gradually decreased. At second floor level the changes in the factors are not large in both specimen which is due to proper distribution of stiffness by walls in lower floor.

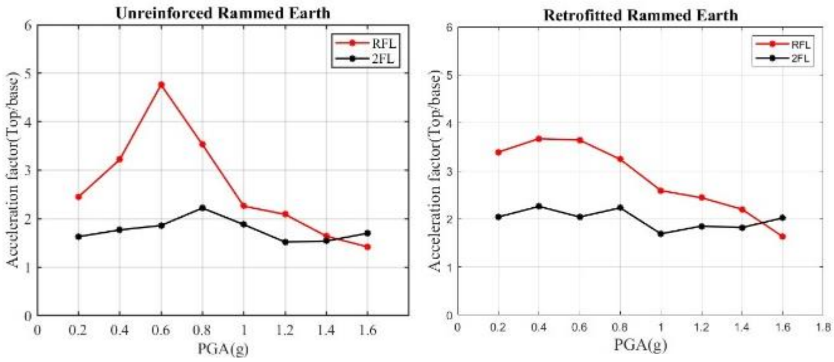

Figure 6. Rammed earth specimen (URE & RRE)

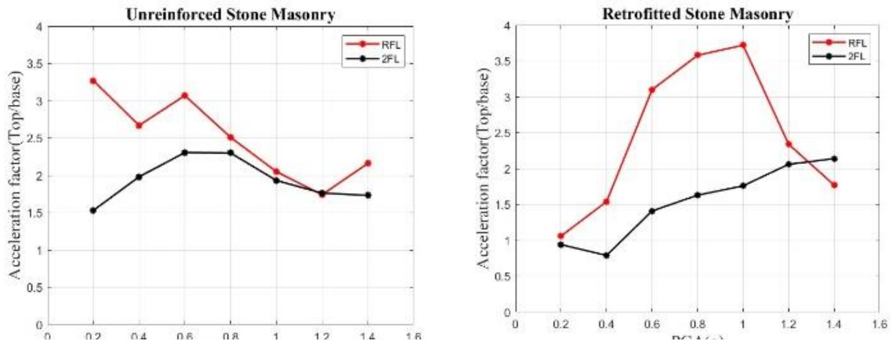

Figure 7. Stone masonry specimen (USM & RSM)

Figure 5 shows the acceleration factors of the stone masonry specimen. The acceleration factor at the roof level showed a decreasing trend in USM whereas in RSM the factor increases, and peak response was recorded at nominal PGA of 1.0g. At second floor the factor increases gradually till 0.6g in USM and then drops with occurrence of cracks on the wall whereas in RSM the factors increase till the end of test indicating less damages and proper distribution of stiffness by walls at lower floor.

4.3. Damage Propagation and crack patterns

The structural system under the study shall be considered as box system. The in-plane wall develops shear resisting mechanism while out of plane walls develops bending or flexure mechanism. The in-plane wall provides the lateral resistance by their self-weight and resist the force transmitted by out of plane to wall during the earthquake excitation. Due to higher flexure moment at the end of in plane wall, corner cracks are induced to structure. While the shear failure in plane wall with diagonal cracks are due development of principle tensile stress because for lateral and vertical load. Due to opening in the front façade at second floor level the in-plane wall is reduce to half which accordingly the shear strength is also reduced. Therefore, the cracks started at the junction of 2fl and propagated to lower floor and lots of cracks at the corners.


Figure 8. Rammed earth (URE & RRE)


Figure 9. Stone masonry (USM & RSM)

4.4. Numerical Analysis results

The experimental results are compared with numerical analysis results in terms of acceleration responses at each floor level. The result is shown in Figure 10 and 11 for rammed earth and stone masonry respectively. In case of the USM only linear analysis was executed as there is lack of capacity curve of full-scale test.

At lower input PGA the acceleration responses in all the specimens are in close range. In addition, during the experimental test there was no significant damage detected on the specimen indicating the structure remains in elastic state. For instance, in URE roof level there is small damages on the wall at 0.6 and 0.8g and the results of all three remains in closed range. The difference between LTHA and NLTHA increases at higher input PGA wherein the specimens have more damages showing the nonlinear behavior. Further, the results of nonlinear analysis agrees with the damage propagation as well as follows similar trend with experimental results.

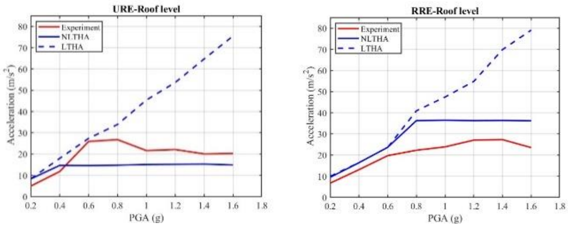

Figure 10. Rammed earth (URE & RRE).

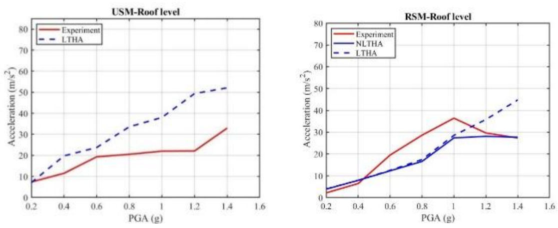

Figure 11. Stone masonry (USM & RSM)

5. CONCLUSIONS

In this study the seismic performance of the composite masonry buildings in Bhutan is evaluated by shaking table test and numerical analysis. The shaking table test was executed on four 1/6 reduced scale models which comprises of two rammed earth models (unreinforced and retrofitted) and two stone masonry models (unreinforced and retrofitted). The numerical analysis was carried by transforming the model specimen into the lumped mass models of the two-degree freedom system. The linear and nonlinear time history analysis was executed using the input motion from the experimental test.

The experimental results show that natural frequency of the specimens decreases with an increase in nominal PGA, reflecting the degradation of stiffness due to damage. Comparing the natural frequencies, the retrofitted models showed a higher value than unreinforced models. The proposed retrofitting measures improved the seismic performance of the structures by preventing the occurrence of cracks and limiting the damage propagation.

The comparative analysis was made between the numerical analysis and experimental test results in terms of the maximum acceleration response at each floor level at each input ground motion. From the results we conclude the numerical simulation results are in close range to the experimental test. Further, the good correlation between the damage occurrence and results of time history analysis is observed in all the models.

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