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Advancing Seismic Design Of Rammed Earth Structures In Nepal Through Strengthening Techniques And Numerical Simulation

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A B S T R A C T

This study presents the seismic performance of rammed earth buildings in Nepal using finite element analysis. Three single-storey and two double-storey typologies of Rammed Earth (RE) buildings were modeled for unstrengthened and strengthened cases in DIANA FEA. Non-linear pushover and incremental dynamic analyses were performed to analyze their response to seismic loads. The seismic performance analysis of roof beam addition or horizontal band addition strengthening strategies show base shear capacity increase from 40 kN to 152 kN in one storied building and to 170 kN in two two-storied building when strengthened enhancing seismic performance. Collapse probability for one storied building for PGA of 0.35 g decreased from 40% without any strengthening to 35% when strengthened with beam and to 30% when strengthened with both beam & bands i.e. 10% less probabilities of reaching critical damage states in reinforced counterparts showing acceptable risk levels for MPEs in the Nepalese context.

1. INTRODUCTION

Rammed earth construction is a method of creating solid walls by compacting subsurface material occasionally stabilized with cement or other binders into successive layers inside temporary formwork [1]. It is also one of the most often used modern earth building techniques. Rammed earth constructions have been there since antiquity; researches conducted in Southwest Asia, Africa and middle east have shown structures dating as far back as 10,000 BCE [2]. When the Iberian Peninsula was under Islamic rule, RE practices flourished between the eighth and thirteenth centuries [2]. Roman Pliny the Elder first documented about rammed earth in 79 AD. In 18th century, François Cointeraux popularized rammed earth in Europe with his writings on "pisé de terre". During the 19th century, rammed earth techniques spread to the United States, especially in areas with limited timber [3]. The locals in the Himalayan range like

Ladakh in India, Mustang in Nepal, China, and Bhutan still practice traditional rammed earth construction [4]. RE construction techniques are known by different names in different parts of the world like Chineh in Iran, Taipa in Portugal, Tapial in Spain, Pisé in France, Terra battuta in Italy, Stampflehm in Germany, Hangtu in China, and Pakhsa in Uzbekistan [5]. Some prominent RE structures include Vaugirard castle in France, the Great Wall of China, Palace Kleinmachnow near Berlin, Alhambra in Spain, Borough House Plantation, and Church of the Holy Cross in the United States [6], five-story rammed chalk houses in Winchester, U.K., a seven-story loadbearing rammed earth building in Germany, and mud-brick buildings up to ten stories in Yemen [1].

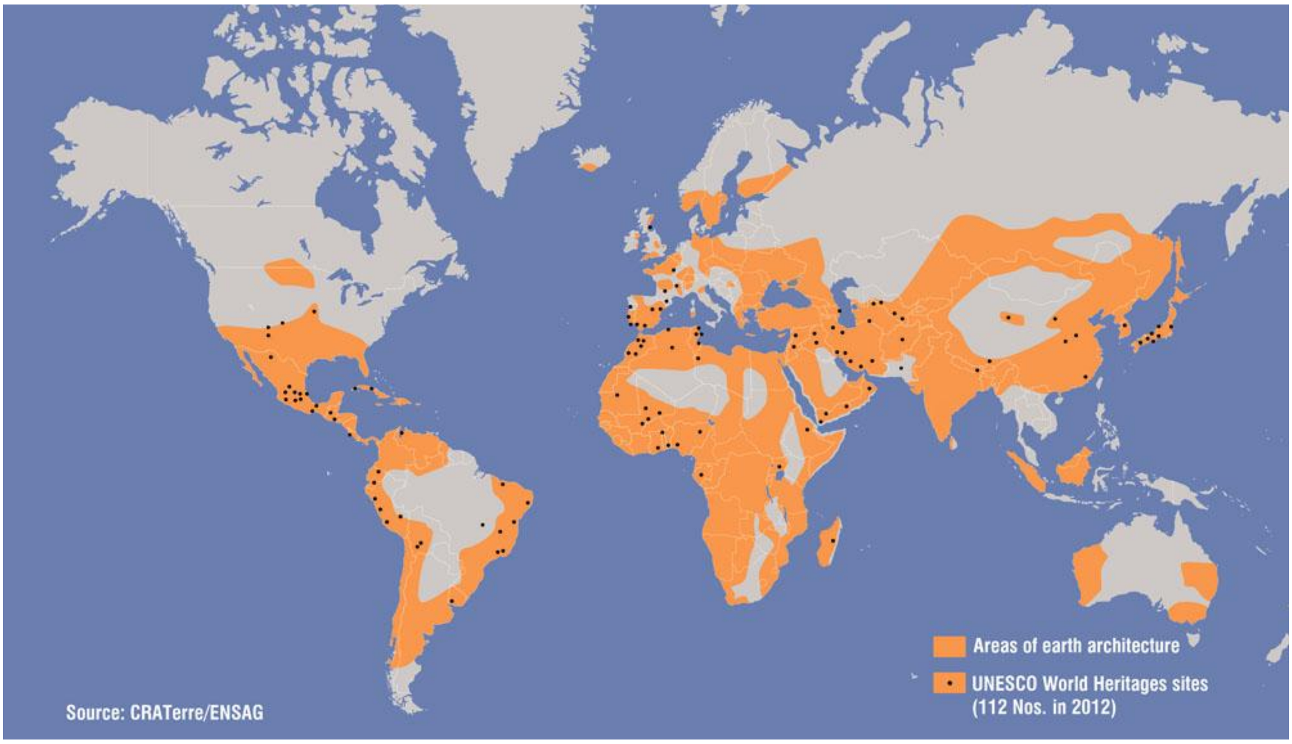

Fig. 1. Rammed earth practices around the world [7].

The origins of rammed earth in Nepal have been found in upper Mustang, where houses were constructed from small, plastered pieces of rammed earth [8]. In rural Nepal, traditional building materials like stone masonry with mud mortar, and rammed earth (RE) are widely used. RE has many benefits, including being economic, culturally significant, easily accessible, high thermal mass, and sustainable. Rammed earth attained renewed interest since 20th century as it can serve for the long-term environmental, economic, and social sustainable development of poor rural areas and contribute to the local endogenous development significantly. Late 20th century brought about advancements in construction technology improving the durability and efficiency of rammed earth buildings. Recently, rammed earth has seen a resurgence as an eco-friendly architecture, with innovations in stabilization & design and builders have begun constructing rammed earth houses using earthquake resistant techniques.

Rammed earth has a long history in Nepal, dating back to upper Mustang, when small, plastered pieces of rammed earth were used to create dwellings. Rammed earth has altered dramatically since its humble beginnings. Nowadays, large formworks are utilized instead of little blocks, and there is no plastering or painting at all [8]. The Chhode monastery was built using the rammed-earth technique, which is widespread across Mustang. People across this rough land have erected Buddhist chortens, or small stupas atop hills, on pathways leading into villages, and even inside caves, in part to ward off evils that would do them harm, and the Loba people, the inhabitants of the region, have also built and lived in rammed earth houses enclosed for centuries [9]. Traditional RE buildings' architectural design can improve seismic performance through simpler geometries and construction processes. As modern RE architectures become more sophisticated, advanced engineering technologies for seismic assessment are required [5].

Non-stabilized and stabilized RE walls behave differently in-plane when subjected to cyclic loading and different vertical pre-compression stresses [6]. Rammed earth (RE) is becoming more and more popular as a sustainable building material because of its minimal environmental impact, excellent thermal and acoustic performance, and utilization of readily available local materials [10]. While stabilizers like lime and cement greatly enhance the mechanical qualities of RE, they can also have negative effects on the environment and the economy requiring careful selection [11]. Well-engineered and reinforced rammed earth buildings can function effectively in seismic zones [11, 12]. The rammed earth walls constructed with drier soil are both flexible and stable [13, 14] . Upper stories are not favorable as they increase vertical stresses and seismic action [15]. The inner reinforced RE structures can be constructed which provide better seismic protection and structural integrity [16]

The seismic performance of Rammed Earth structures is found to be greatly influenced by the production process [16, 17]. Walls with curved arch-type openings are generally stronger than those with rectangular openings. Strength is also greatly impacted by soil type and moisture content [18, 19]. Reinforcement techniques, including internal reinforced concrete columns and horizontal reinforced concrete belt beams, increase the seismic capacity of RE structures [20]. Higher energy dissipation capabilities, or improved ductility, were seen in cement-stabilized RE walls [21]. With damage progression, progressive reduction in frequencies is seen in the models [5] .

The elasticity moduli, and compressive strengths are comparable in both directions, indicating that rammed earth may be regarded as isotropic provided the layers continue to adhere [22]. Bond beams and good interlayer strength are essential for improving the out of plane seismic performance of RE walls [23]. Suitable retrofitting greatly improves the seismic performance of rammed earth walls, making it an easy, affordable, and practical choice for rural locations [4, 23-25]. Although rammed earth can be designed using masonry design principles, higher load eccentricities require modifications [1]. Traditional rammed earth buildings benefit from their architectural features, while modern constructions need sophisticated engineering tools for reliable seismic evaluation [2]. For higher cement content, Cement Stabilizes Rammed Earth (CSRE)'s shear strength and cohesiveness are also higher and in dry conditions, the shear strength was almost twice as high as it was in wet conditions [26]. Post-tensioned reinforcement, particularly in seismic zones, can be a good substitute for conventional reinforcement in rammed-earth walls, albeit certain problems, including rod failure, require more research [27]. In terms of stiffness and elasticity, the behavior of rammed earth is comparable to that of contemporary concrete [28]. The compressive strength of rammed earth is much lower compared to other conventional building materials like concrete. Figure 2 shows that the compressive strength of rammed earth is usually high if density is also on the higher side. Figure 3 exhibits compressive strength and elastic modulus generally correlate positively.

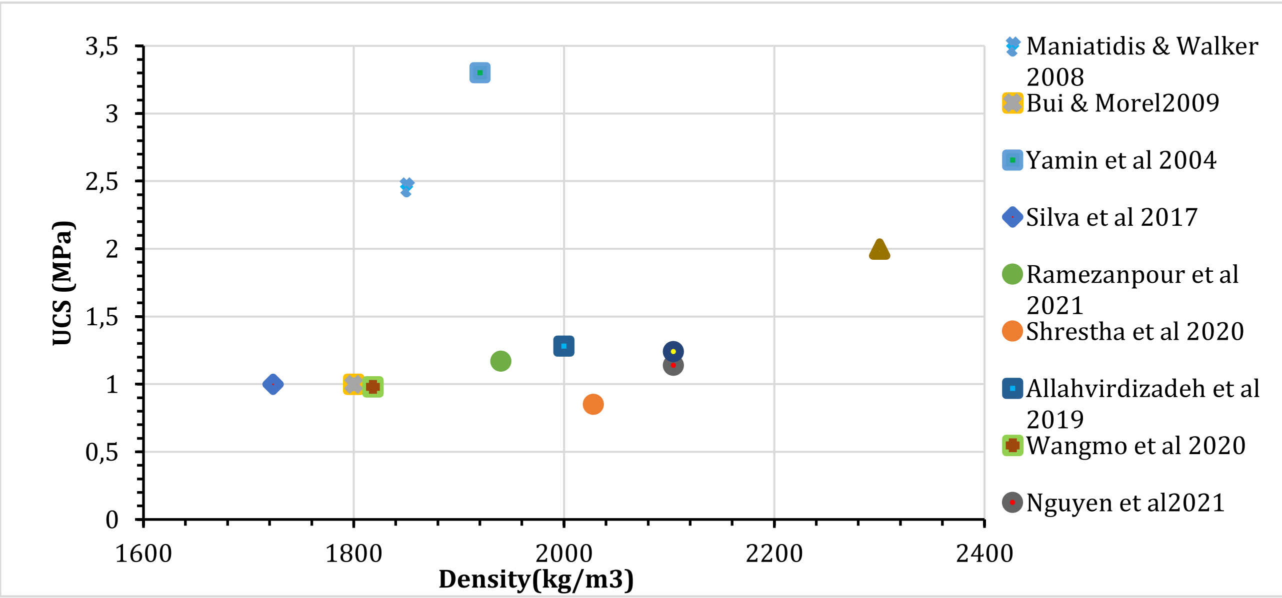

Fig. 2. Compressive strength as a function of density as per different studies.

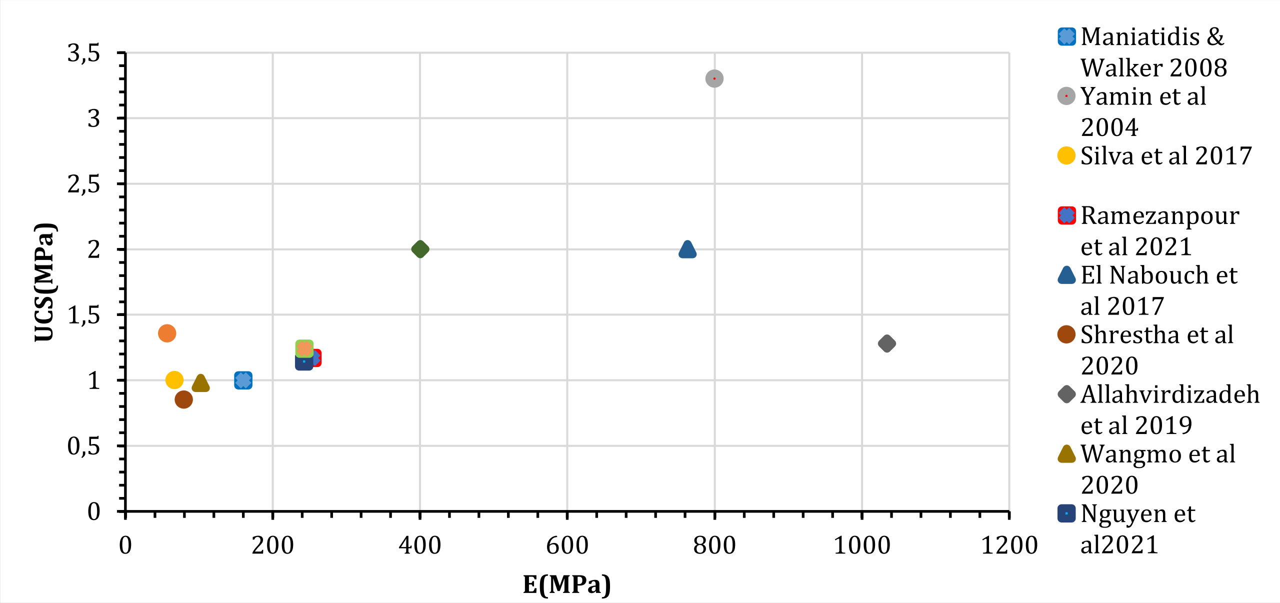

Fig. 3. Compressive strength as a function of Young's Modulus as per different studies.

The 2015 Gorkha earthquake struck Barpak, Gorkha in central Nepal on April 25, 2015. It had a magnitude of 7.8 Mw and killed approximately 9,000 people, leaving thousands more injured. Over 600,000 structures in Kathmandu and surrounding areas were damaged or destroyed. On May 12, 2015, a second large earthquake, magnitude 7.3, struck eastern Nepal near Mount Everest, causing further deaths and injuries, as well as catastrophic damage to historic landmarks [29]. This is not the sole case of large earthquakes in this country. The Himalayan country has experienced large-magnitude earthquakes in 1934 and 1988.

Past earthquakes have demonstrated the inadequate seismic behavior of rammed-earth buildings, emphasizing the need for a deeper understanding of their performance and the development of efficient strengthening solutions [5]. The earth quake-resistant aspects of traditional Nepalese construction are explored, as well as the likely causes for their unsatisfactory performance in this earthquake [30]. Important failure mechanisms such as foundation problems, in-plane shear cracking, and out-of-plane wall collapse have been identified by studies [31]. While historical documents and anthropological research demonstrate these buildings' endurance in typical circumstances, they also indicate their susceptibilities to seismic activity. Structures made of rammed earth are brittle by nature and perform poorly when subjected to seismic loads. Earthquakes in Nepal, like the one that struck Gorkha in 2015, have shown how easily these constructions can collapse, causing a great deal of deaths and financial damage.

The seismic performance of rammed earth structures in Nepal has not been extensively studied even when a great deal of study has been done worldwide. Although numerical simulations have been carried out, there is still a lack of validation of these models against experimental data. This validation is essential to develop suitable seismic strengthening schemes and ensure the accuracy of seismic performance forecasts of rammed earth structures. Some studies have shown the significance of seismic strengthening strategies to enhance the out-of-plane behavior and seismic resistance. However, extensive studies have not been conducted on the effects of strengthening methods used in Nepalese rammed-earth constructions. This study aims to evaluate the seismic performance of existing RE buildings in Nepal and investigate the effectiveness of strengthening techniques in RE buildings under simulated seismic loads to develop recommendations for seismic design and strengthening of RE buildings in Nepal's seismic zones.

2. RESEARCH SIGNIFICANCE

Given Nepal's geological susceptibility to earthquakes and the abundance of the rammed earth (RE) houses in rural Nepal, more studies about the seismic capability of rammed earth (RE) buildings in Nepal are highly needed. The structures' vulnerability was definitely indicated by the 2015 Gorkha earthquake, which caused substantial damage to buildings. The study is important as it uses finite element analysis (FEA) for exploration of the seismic capability of RE buildings offering effective strengthening measures like roof beams and horizontal band addition. One of the outstanding measures that have been found to be more effective in the weak earthquake resistance is the mitigation of inter-story drift and base shear capacity. The findings give a lot of useful information for the development of RE structure strength, safety, which is economically viable, sustainable, and socially responsible issue.

By giving evidence-based suggestions, the research is actualizing the formulation of seismic code and improvement of construction practices in Nepal plus it is contributing to disaster risk reduction and facilitating the creation of a sustainable environment in earthquake-prone areas.

3. BUILDING TYPOLOGY

RE buildings in Nepal have been inspected for typology development and to assess their construction techniques. From these investigations, three different typologies of a single-storied, two typologies of a double-storied have been decided for analysis. The single storied building has been analyzed for three cases, first without any strengthening, second with beams at the top and third with both beam & bands. The two storied building has been analyzed for second and third strategies. DUDBC has published two volumes as “Design Catalogue For Reconstruction Of Earthquake Resistant Houses” with four types of construction techniques in Volume I and twelve types of construction techniques in Volume II [32]. Since the rammed earth technique is not included in both these volumes, the single and double-storied RE buildings were designed following the recommendations of DUDBC for stone masonry structures.

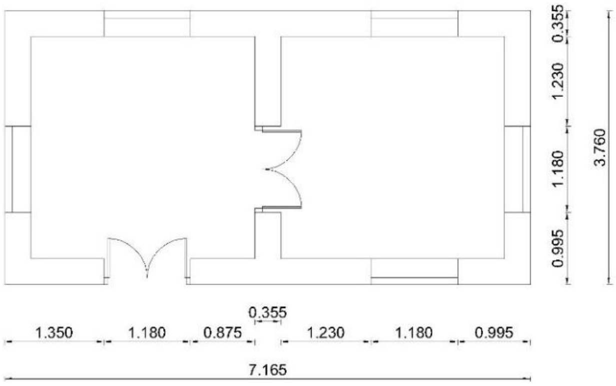

Fig. 4. Plinth Floor Plan of One-Storey Building.

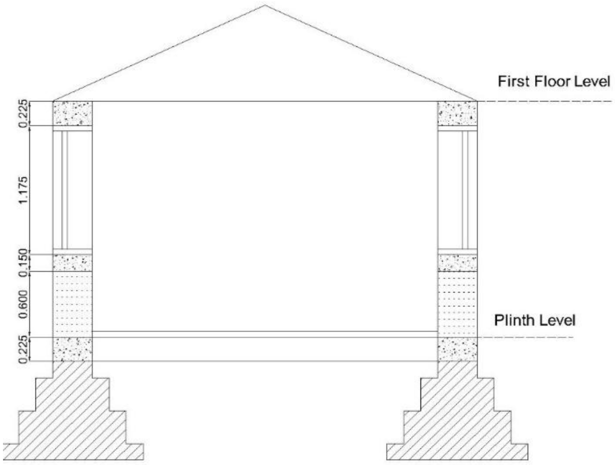

Fig. 5. Section of One-Storey Building.

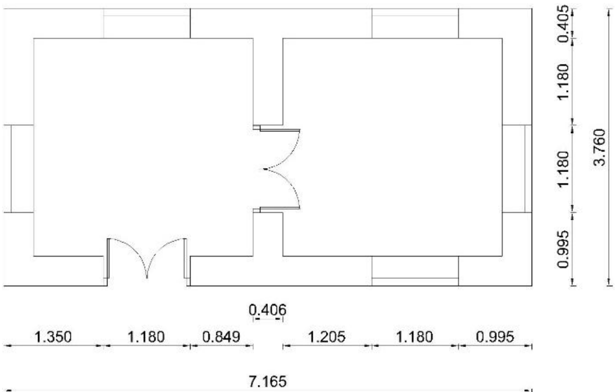

Fig. 6. Plinth Floor Plan of Two-storey Building.

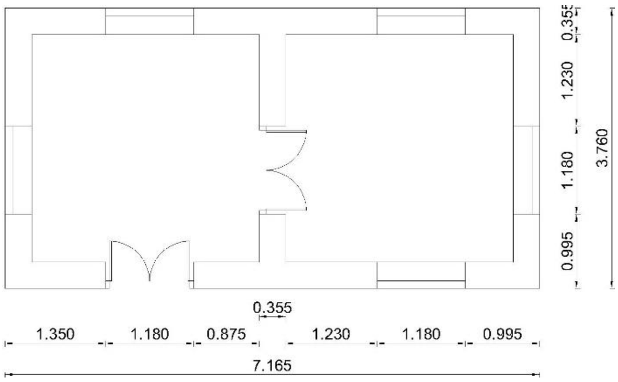

Fig. 7. First Floor Plan of Two-storey Building.

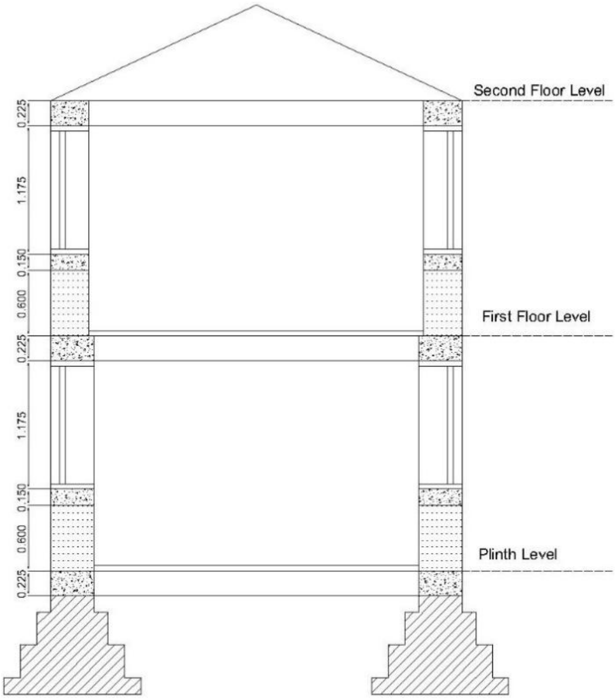

Fig. 8. Section of two-Storey Building.

4. VALIDATION FROM EXPERIMENT

Quasi-static cyclic shear-compression tests as part of an experimental investigation on unstabilized rammed earth wall specimens [6]. The proposed FE modeling approach is verified using the outcomes of compression-shear tests conducted on unreinforced rammed earth walls having width of 1 m, height of 0.9 m and thickness of 0.2 m. As shown in Fig. 9, the wall was constructed on a sturdy RC base that was fastened to the earth. The top of the wall received an average axial stress of 0.5 N/mm2, and the actuator imposed a displacement-controlled horizontal in-plane load on the top of the wall.

The rammed earth masonry wall is modeled using a solid element macro-modeling technique for validation purpose. The geometry of the FE model is identical to that of the experiment's tested wall. A regular hexahedral meshing with a discretization interval of 0.1 m is chosen in accordance with the results of a mesh sensitivity analysis. The bottom face of the wall is completely constrained against displacement and rotation in all directions since the wall specimens were firmly fixed at their base to a sturdy floor. Displacement tying in the in-plane direction is used, with the loaded node acting as the master node and the top of the wall acting as the slave face, to replicate the rigid beam at the top that stops the specimens from moving out of plane. In order to create overburden pressure consistent with the test specimens, a vertical compression load of 0.5 N/mm^2 is applied to the top face of the wall. The top node of the wall is then subjected to a displacement-controlled, cyclic lateral load increasing 2.5 mm after every three cycles with a 0.25 mm load step. Self-weight and vertical compression were applied first during the analysis, and then the cyclic lateral load is introduced gradually.

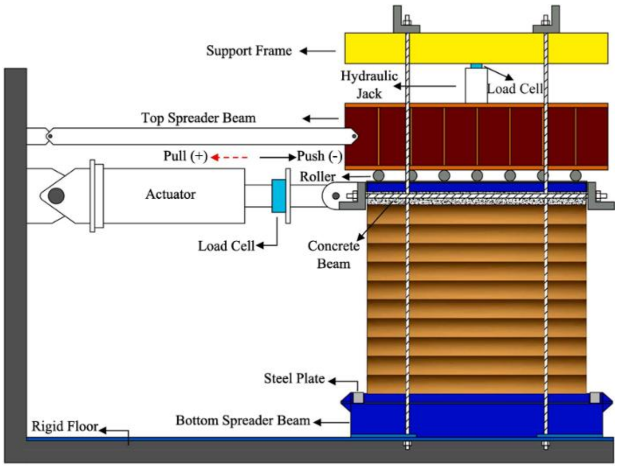

Fig. 9. Unstabilized Rammed Earth Wall and test set up.

For rammed earth masonry walls, the material total strain crack (TSC) model—which is exponential in tension and parabolic in compression—is used. The softening curves depicted in Fig. 10 and Fig. 11 illustrate the usual behavior in total strain crack models for rammed earth. They explain how the stress (σ) declines with increasing strain (ε) once the material reaches its peak stress. These curves play a key role in modeling the post-peak softening behavior. The curve of parabolic compression softening shows the stress starts to decline after reaching maximum value i.e. fc (compressive strength). The curve gradually decreases to one-third of the compressive strength. The area under the curve gives value of the fracture energy in compression (Gc) divided by the characteristic length (h). This is an indication of the energy the material absorbed before failure in compression. The curve of exponential tensile softening shows exponential decay of strength after reaching the tensile strength ft. Tensile crack propagation and the material's loss of tensile strength are captured by the softening. The mode I fracture energy is represented by the area under the curve and is a measure of the energy needed to propagate a crack in tension.

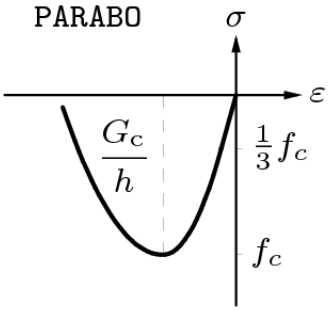

Fig. 10. Parabolic Compression Softening Curve.

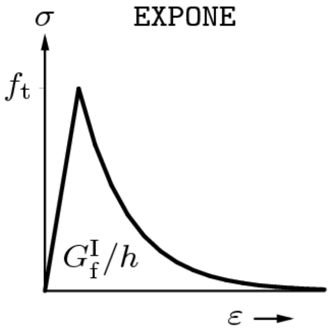

Fig. 11. Exponential Tensile Softening Curve.

Based on test results from Ramezanpour et al., Table 1 displays the material qualities that are used for validation. The fracture energy values of rammed earth control its softening behavior in both compression and tension. The mean values of compressive strength (fc) for rammed earth masonry material are obtained from experiments. Some parameters not available in the experiment were derived from established relationships. Fig. 12 displays the hysteresis envelope plot obtained from the numerical analysis. There is a clear correlation between the numerical and experimental results, as shown by this plot and the experimental data. The experimentally observed average maximum horizontal shear force of around 45 kN is well matched by the numerical simulation. Additionally, the crack pattern is also predicted well from the numerical modeling as the crack patterns in simulations shown in Fig. 13 and Fig. 14 similar to the actual cracks shown in Fig. 15.

Table 1. Rammed Earth Properties used for validation purpose.

Compressive strength, fc (mpa)	Tensile Strength ft (mpa)	Young Modulus E (mpa)	Bulk Density (kg/m3)	Poisson Ratio	Compressive fracture energy Gc=1.5fc (N/mm)	Mode-I tensile fracture energy Gt=0.12 ft (N/mm)	Shear wave velocity Vs (m/s)
1.17	0.106	253.9	1940	0.15	1.755	0.013	238.6

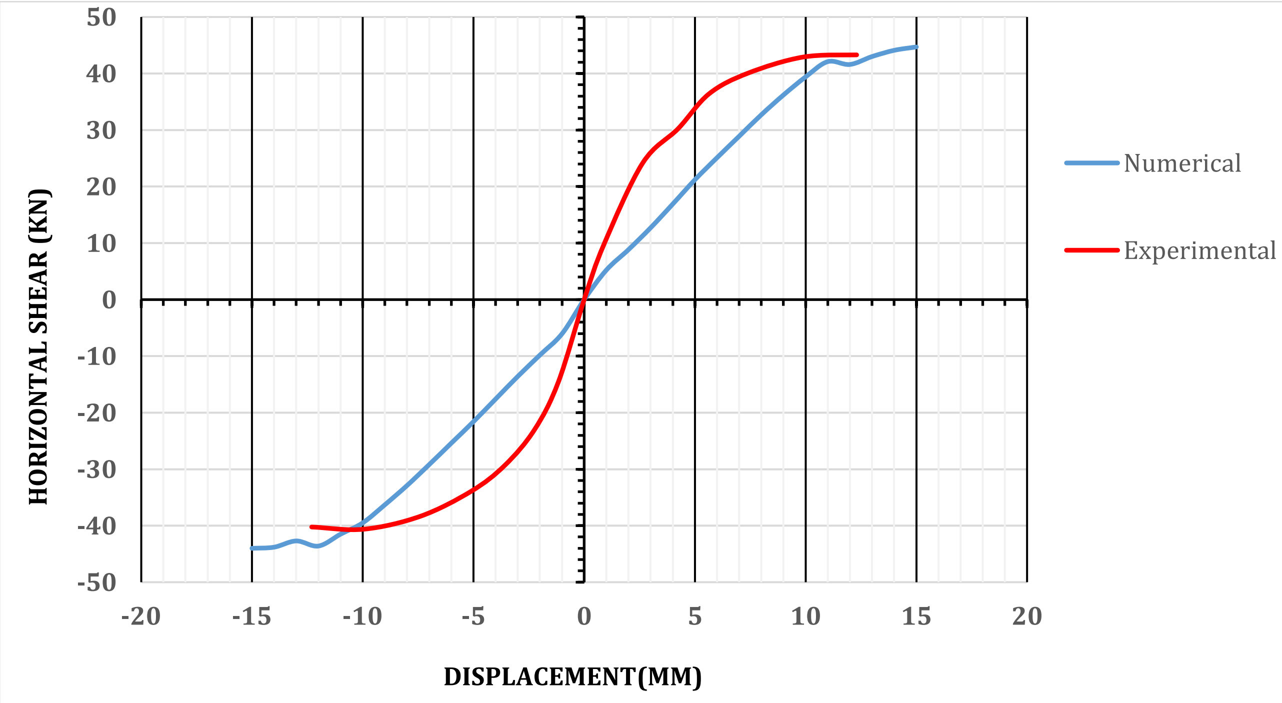

Fig. 12. Numerical and experimental Force deformation Hysteresis envelope for rammed earth masonry.

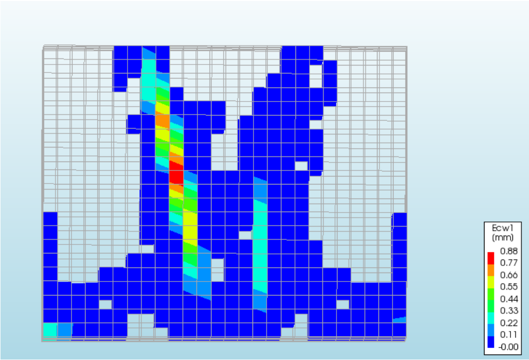

Fig. 13. Principal Crackwidth for pull of 15 mm.

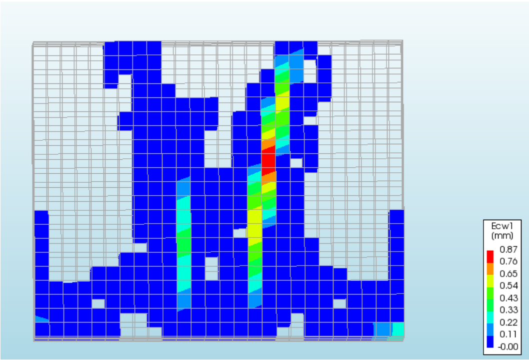

Fig. 14. Principal Crackwidth for push of 15 mm.

Fig. 15. Crack Pattern from experiment [6].

5. MODELING STRATEGY

FE model of the selected three building typologies are developed in DIANA FEA 10.5. The model is developed using macro-modelling approach where structural elements, including wall components, RC beams and bands were modeled as 3D solid elements. The hexahedron mesher type offered by DIANA FEA is used to discretize the model with the approximate element size of 300 mm. As the focus of the study is primarily on the behavior of walls and strengthening components (horizontal bands and beams), the lightweight roof portion is not modeled. Vertical reinforcements have not been considered in the model and horizontal beam and bands are modeled with homogeneous RC material. The masonry wall material has been modeled as RE material with isotropic properties.

6. MATERIAL PROPERTIES

Material testing for the rammed earth was done in Bhutan[25]., and as Nepal is located in the same geological belt, the same properties have been used in this work The material parameters of Rammed Earth and M20 grade concrete are displayed in Table 2 and Table 3. Sieve analysis was done as per IS: 2386 (Part I)-1963 for the samples collected from a construction site and particle size distribution curve is obtained which is found to be mostly within the limits given by [33] as shown in Fig. 16.

Table 2. Parameters of RE materials used to model buildings.

Compre-ssive strength fc (mpa)	Tensile Strength ft (mpa)	Young Modulus E (mpa)	Bulk Density (kg/m3)	Poisson's Ratio	Compressive fracture energy Gc=1.5fc (N/mm)	Mode-I tensile fracture energy Gt=0.12ft (N/mm)	Shear wave velocity Vs (m/s)
1.31	0.07	250	1895	0.15	1.965	0.0084	239.5

Table 3. Concrete Properties.

Compre-ssive strength fc (mpa)	Tensile Strength ft (mpa)	Young Modulus E (mpa)	Bulk Density (kg/m3)	Poisson's Ratio	Compressive fracture energy (N/mm)	Mode-I tensile fracture energy (N/mm)	Shear wave velocity Vs (m/s)
20	2	20000	2500	0.2	30	1	1690

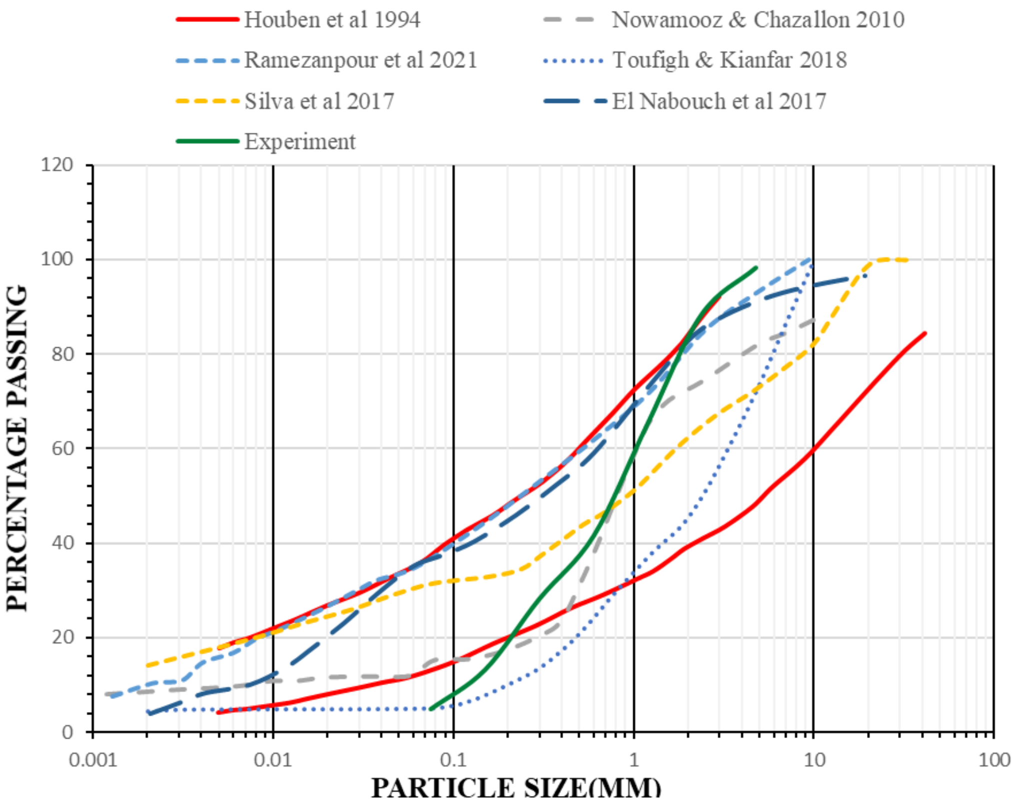

Fig. 16. Particle Size Distribution for rammed earth in different studies.

7. PUSHOVER ANALYSIS

The FE model of the prototype buildings are analyzed by eigenvalue and nonlinear pushover analysis. The time periods and directions of initial modes are found from eigenvalue analysis. The nonlinear pushover analysis of three cases of one storied buildings is performed along the direction of their fundamental mode. The static pushover load is applied post the application of the gravity load case. For the pushover load, the displacement controlled load was applied at the story level. The iterative process for solving of system of equations follows the Secant (Quasi- Newton) method for the static pushover load case with the parallel direct sparse method. The pushover curves plotted for base shear against displacement is shown in results section. To examine the damage sequences and fracture progression in various scenarios, an investigation of the major crack width has been conducted for buildings.

8. TIME HISTORY ANALYSIS

Incremental Dynamic Analysis is the adopted time history method for developing fragility curves. The same building models are subjected to ground motions from ten near field earthquakes all scaled from 0.1g to 1g in order to cover the wide range of seismic demands. Then maximum inter storey drifts are obtained from each cases. IDA curves are generated for each earthquake with the drift values in x-axis and maximum acceleration values on y-axis. Different strengthening strategies such as beam and bands are taken as case studies. One storied buildings have been simulated in three distinct scenarios: without beam or bands, with beams only and with both beam & bands. The thickness of beam at the top of wall is 9 inches and the band at the sill level is 15 cm thick. The two storied building has been modeled for the second and third strategies

From the IDA curves, probabilities of attaining different limit states for each values of maximum acceleration are obtained. For different cases of strengthening, limit states are defined separately as shown in Table 4. For each limit state, probability of attaining them for any PGA is given by,

$$(LS\ /(IM = x)) = \emptyset\left(\frac{ln(x)-\theta}{\beta}\right) \quad (1)$$

where,
P = probability of structural damage,
Φ = standard normal function,
β = standard deviation from mean,
x = Ground motion parameter, PGA (g),
θ =Mean of ln (x).

Table 4. Definition of Limit States for Rammed earth buidings.

Limit States	OP	IO	LS	CP
Drift Ratio (%)	0.05	0.1	0.15	0.2
Interstorey Drift (mm)	1.075	2.15	3.225	4.3

9. RESULTS AND DISCUSSION

From the eigenvalue analysis, the direction of the fundamental mode for building is found along the Y-direction.

Table 5 displays the fundamental time periods that were generated from the analysis for each case of the building. Naturally, the unstrengthened building model is more flexible than their strengthened counterparts, and the time period for the unstrengthened model is longer than that of the strengthened model. It has been found that the introduction of strengthening elements shortens the time period while increasing stiffness by enhancing the buildings' structural integrity.

Table 5. Fundamental Time Period of the Building Models.

One-storied Building with	Fundamental Time Period (sec)
No strengthening applied	0.0962
Only beams	0.0719
Beam and bands	0.0662

The pushover curves plotted for base shear against displacement are shown below. For one storied building the peak base shear for no strengthening, only beam, and both beam & band cases are 42 kN, 132 kN, and 152 kN at drift level of 3.1 mm, 2.2 mm and 2.1 mm respectively. The building without beam & bands attains maximum base shear at a lower drift level than the other buildings. The base shear increases for the buildings with seismic strengthening components.

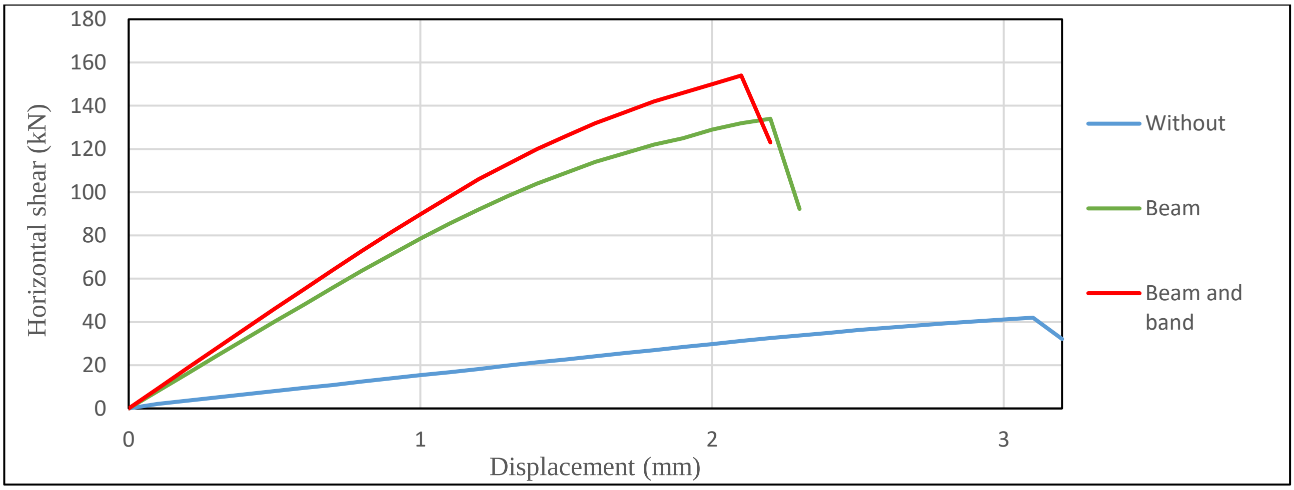

Fig. 17. Pushover Curve for one storey building without beam or band, with beam only and with both beam and bands.

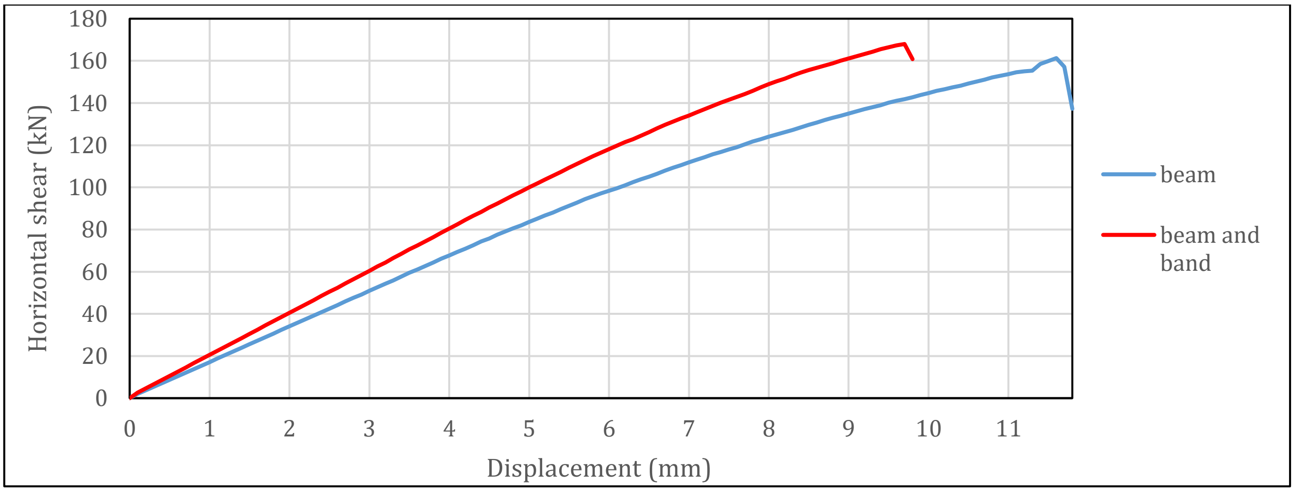

Fig. 18. Pushover Curve for two storey building with beam only and with both beam and bands.

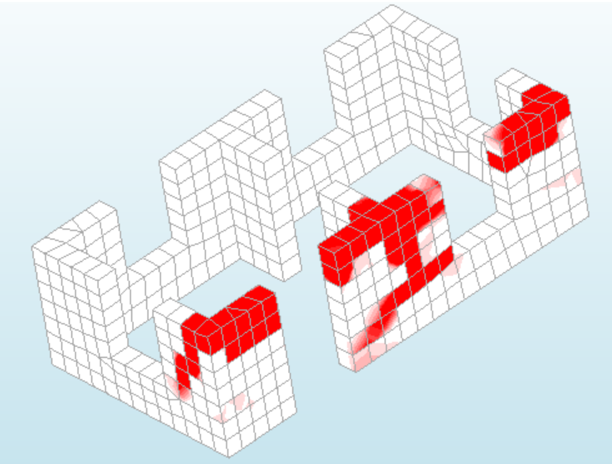

Fig. 19. Crack pattern in building without beam and bands.

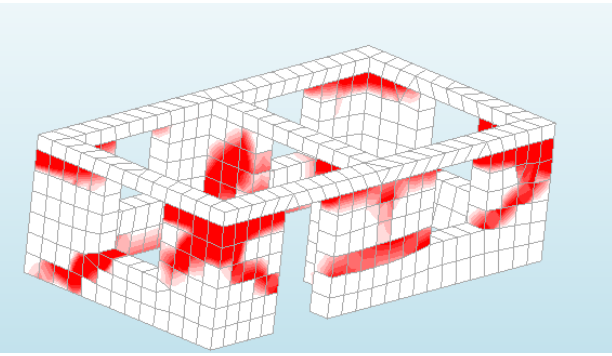

Fig. 20. Crack pattern in building with roof level beam.

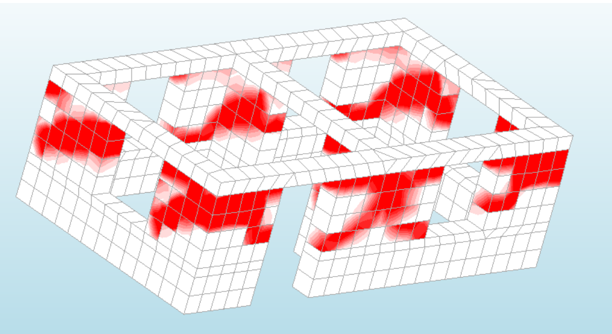

Fig. 21. Crack pattern in building with beam and bands.

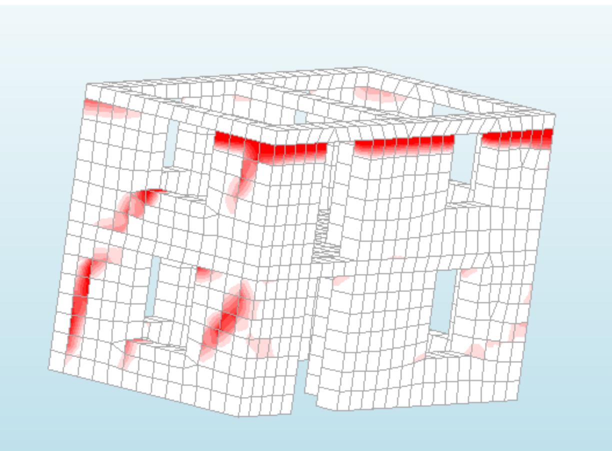

Fig. 22 Crack pattern in two storied building with beam.

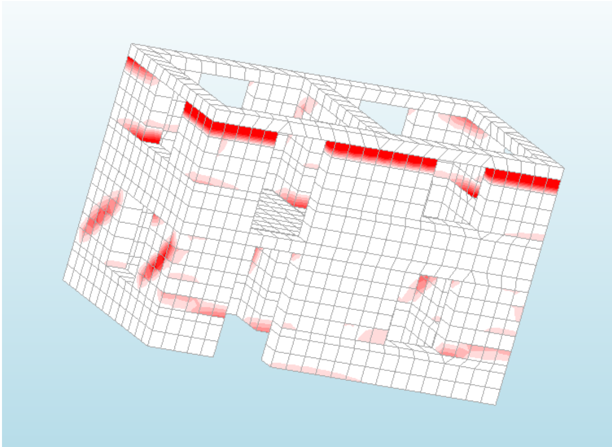

Fig. 23. Crack pattern in two storied building with beam and bands.

Fig. 19, Fig. 20, Fig. 21, Fig. 22 and Fig. 23 display the crack propagation pattern for five distinct scenarios of one storied building and two storied building. Here, the color scale is constrained to 0–2 mm in order to clearly display the major crack width distribution. While cracks are dispersed throughout floor levels in a reinforced model, they are mostly concentrated at the first wall in an unreinforced model. In contrast to unreinforced instance, where the fracture is focused at specific locations, primarily around the wall's opening and corner, reinforced cases exhibit scattered crack patterns. The installation of horizontal bands breaks the continuity of the wall crack, delaying the formation of crack openings.

From the time history analysis, IDA curves for three typologies of one storey building and two typologies of two storied building are given in Fig. 24, Fig. 25,Fig. 26.These curves show that same building performs differently for the same magnitude of different earthquakes. This is due the difference in frequency content and time duration of the earthquakes. Also the drift values decrease for the same magnitude of earthquake when strengthening is applied.

The fragility curves for the four limit states OP, IO, LS and CP for the different cases have been developed. These curves show decrease in probability of attaining any limit state when beam and band are incorporated. The probability of collapse of one storied building for PGA of 0.35g decreases from 40% without any strengthening to 35% when strengthened with beam and to 30% when strengthened with both beam & bands. These levels of risks can be further reduced by adding the levels of strengthening.

The levels of risks are considerably lower for trans-Himalayan areas like Manang and Mustang where Maximum Credible Earthquake values are lower than other regions of Nepal.

The probability of collapse of building for PGA of 0.35g decreases from 90% when strengthened with beam to 70% when strengthened with both beam & bands for two storied building shown in Fig. 27 and Fig. 28. Since these are unacceptable levels of risk, thicker walls or other additional level of strengthening is required.

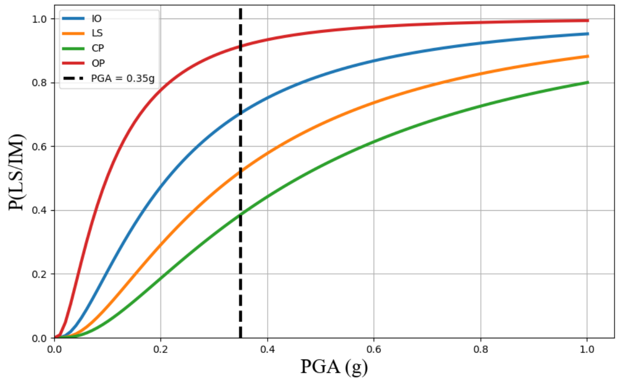

Fig. 24. Fragility curve for One Storey Building without beam and bands.

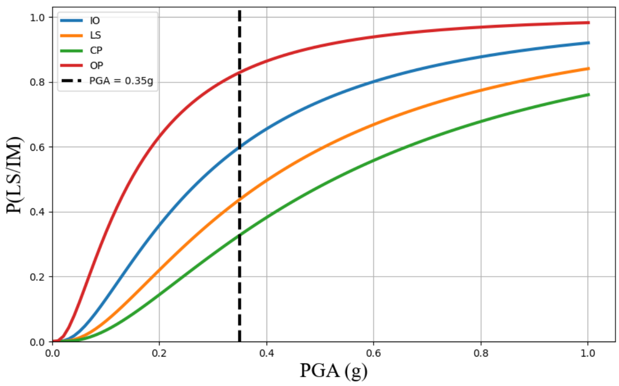

Fig. 25. Fragility curve for one storied building with beam as strengthening.

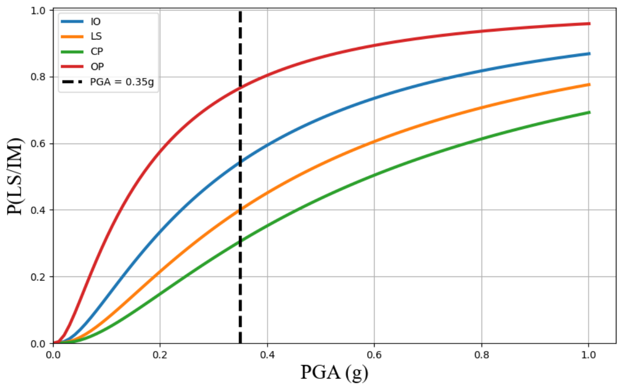

Fig. 26. Fragility curve for one storied building with beam and band as strengthening.

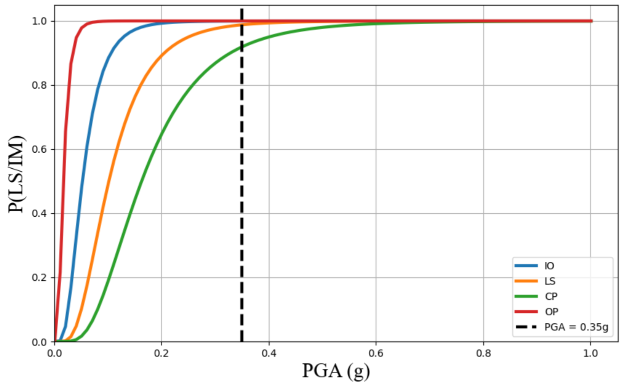

Fig. 27. Fragility curve of Two Storied Building with beams.

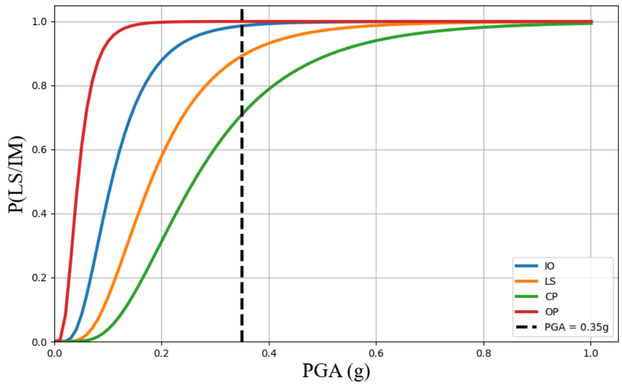

Fig. 28. Fragility curve for Two Storied Building with both beam and bands.

10. CONCLUSION AND RECOMMENDATIONS

Three building typologies of rammed earth structures were modeled in finite element software DIANA FEA and compared based on the pushover curves and time history analysis to study the efficacy of applying lintel level beam and sill band. Following conclusions are drawn from this study:

The modeling approach adopted seems well suited for modeling the behaviour of rammed earth structures. The crack patterns and maximum shear capacity of wall closely matched with the results from experiment.

Results from nonlinear pushover analysis indicate larger base shear in strengthened buildings than unstrengthened ones as it increases from 40 kN to 152 kN in one storied building and to 170 kN in two storied building when strengthened. The rammed earth buildings become stiff as they are provided with strengthening strategies like beam or bands and perform much better during seismic events. The crack patterns of the buildings indicate that providing horizontal bands breaks the continuity of diagonal cracks, disrupts crack distribution, delays crack formation and reduces further development of cracks, aiding to prevent the events of unexpected building collapse.

According to the fragility curves, adding sill level bands and lintel beams considerably lessens the susceptibility of rammed earth structures. The probability of attaining any limit state in strengthened cases is lower compared to unstrengthened ones. For one storey buildings of lower importance, 30% collapse probability in strengthened cases show acceptable levels of risk for MPEs in Nepal. In the Trans-Himalayan region of Manang and Mustang, collapse probability reduces to 15% in strengthened cases as these regions have lower magnitude of MPEs. However, for two storied building, the damage probability is still very high, which is 70% for the wall thickness taken demanding thicker walls or more levels of strengthening.

In this study, pushover and time history analysis are carried out in the fundamental mode direction. More comprehensive representation of vulnerability would be obtained by performing these analyses in both directions. Material properties from local site, use of greater number of ground motion data and improved time history methods, modeling of floor and roof diaphragms, and timber parts attached in these structures could present more realistic representation of their fragility during seismic events. More extensive research about material behavior in dynamic conditions, further levels of strengthening such as steel or concrete columns, fibre integration and retrofitting for existing vulnerable buildings of such techniques is recommended.

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Competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author contributions

Paudel, A. conceptualized the research, collected data, and wrote the manuscript; and Suwal, R. was the supervisor who helped in finite element modeling and proofread the article. All authors contributed critically to the drafts and gave final approval for publication.

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