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Effectiveness of base-isolated low-rise masonry building under excitation from earthquakes

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Keywords: masonry building, base isolation, seismic isolation technology, seismic vulnerability, fiber reinforced elastomeric isolator, floor acceleration response, inter-storey drift response, earthquake

Abstract. Low-rise masonry building is one of the most commonly adopted structural types even in earthquake prone regions in developing countries. The building is generally susceptible to damage due to earthquake induced motion and may suffer partial or total collapse. Un-bonded fiber reinforced elastomeric isolator (U-FREI) is a relatively new seismic base isolator and is expected to be an attractive option for seismic mitigation of low-rise buildings. In this paper, the effectiveness of a base-isolated masonry building supported on U-FREIs subjected to earthquakes is investigated by finite element (FE) analysis using SAP2000. The prototype building is a two-storey masonry building located at Tawang, Arunachal Pradesh State, India and is the first such U-FREIs supported prototype low-rise building constructed anywhere in the world. Mechanical characteristics of U-FREIs obtained from both experiments and FE analysis are utilized in defining the nonlinear property of the model used for simulating U-FREIs. The force-deformation behaviour of the isolator is modelled as bi-linear hysteretic behaviour, which can be effectively used to model all isolation system in practice. Time history analysis of the building for both fixed-base (FB) and base-isolated (BI) conditions under the action of various recorded real earthquakes are investigated. Comparison of the dynamic response of both FB and BI buildings is computed to evaluate the effectiveness of the base isolation system. The FE analysis results show that floor acceleration and inter-storey drift responses of the BI building under earthquakes are significantly lesser than those of the FB building. U-FREIs are recommended for seismic isolation of low-rise masonry building.

1. Introduction

Low-rise building, especially masonry building, which includes residential quarters, schools, government offices, markets, etc., is one of the most commonly adopted structural types in developing countries like India, Bangladesh, Nepal, Indonesia, etc. Vast majority of these buildings are also located in high seismicity regions. The building can sustain gravity loads very easily due to high compressive strength of masonry, but are highly susceptible to ground shaking due to their low tensile as well as shear strength making them often susceptible to damage. Thus, mitigation of seismic vulnerability of the buildings is an important area of research.

Base isolation system is a class of passive control system which can reduce the seismic vulnerability of a structure located in high seismic regions. The system decouples the building from the horizontal components of earthquake ground motion by interposing structural elements with low horizontal stiffness between the foundation and superstructure. Thus, it results in reduction in the magnitude of fundamental frequency of the base-isolated structure to a much lower value than both its fixed-base frequency and the predominant frequency range of the ground motion. The goal is to simultaneously reduce inter-storey drifts and floor accelerations to limit or avoid damage, not only to structure but also to its contents.

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Conventionally, a laminated elastomeric isolators consisting of elastomer / rubber layers interleaved and bonded with thin steel reinforcing plates and commonly known as steel reinforced elastomeric isolator (SREI) are used. This class of isolators is very stiff in the vertical direction, but is highly flexible in horizontal direction to deflect the earthquake energy associated with strong ground motion. However, SREI has some disadvantages, limiting its use in low cost low-rise buildings. The limitations are mainly due to their heavy weight as well as cost and thus restricting their applications primarily in important and expensive buildings. The development of light weight, less expensive isolators has made implementation of the seismic isolation technology to low-rise masonry building vulnerable to seismic ground motions, feasible.

Seismic isolators designed using layers of elastomer / rubber vulcanized with thin layers of bi-directional fiber fabric as reinforcement [1] are known as fiber reinforced elastomeric isolators (FREI). Both weight and height of isolators can be reduced by replacing steel with fiber fabric as reinforcement material. Traditionally SREIs are installed in any structure by connecting the top end plate of the isolator with the bottom surface of superstructure and bottom end plate with the top of foundation, and hence SREIs are also called as bonded isolator. Study on un-bonded fiber reinforced elastomeric isolator (U-FREI) is a significant step towards enhancement of ease of installation of isolators in buildings. Heavy steel-end-plates are not provided in U-FREIs and these devices are installed at the interface of foundation and superstructure without any connection. Thus, elastomer layers at top and bottom of U-FREIs will be in frictional contact with superstructure and foundation respectively. Reduced weight and ease of installation would thus facilitate implementation of U-FREIs for control of seismic response of low-rise vulnerable lifeline buildings in developing countries.

Various studies have been conducted with the purpose of evaluating the seismic vulnerability or the effectiveness of base isolation systems. The fragility function was developed to determine optimum design parameters of isolation devices to maximize effectiveness of seismically-isolated bridges in California, United States of America (USA) [2]. The study showed that the mechanical properties of isolation devices had a significant influence on the damage probability of isolated bridges. An analytic review of various modern methods for seismic insulation was conducted [3]. The seismic vulnerability assessment of typical bridge classes supported on elastomeric bearings in eastern Canada was studied by [4]. The methods to determine the optimal damping parameters for seismic isolation systems were developed by [5]. The study was conducted for both linear and nonlinear damping model of seismic isolation system. The seismic vulnerability assessment of a class of bridge retrofitted with seismic-isolation devices in Canada was presented by [6]. The reduction of acceleration response of base-isolated (BI) three-storey building with lead plug bearings constructed at Indian Institute of Technology Guwahati, India as compared to that of fixed-base (FB) building was studied by [7]. The seismic vulnerability of a retrofitted historical masonry structure in Bayburt Yakutiye Mosque, Turkey using base isolation was investigated [8]. Most of these above-mentioned studies were carried out on base-isolated structures with conventional SREIs.

In view of the above, U-FREI is relatively new seismic base isolator and is expected to be effective in reducing the seismic vulnerability of low-rise buildings. Some studies in literature have been conducted with the purpose of evaluating the mechanical properties of the U-FREIs [9–13]. In recent time, a few studies have been investigated the effectiveness of BI low-rise buildings supported on U-FREIs. Shake table tests of BI buildings supported on U-FREIs were carried out to ascertain its effectiveness in controlling seismic response by [14–16]. A little effort to apply the FREIs for low-rise buildings was presented by [17, 18]. Most of these studies were carried out the seismic performance evaluation of scaled model of low-rise building supported on U-FREIs. Thus, the effectiveness of base isolated prototype masonry building supported on prototype U-FREIs under the action of earthquakes should be further studied.

This study presents seismic performance evaluation of prototype low-rise masonry building supported on square U-FREIs by finite element (FE) analysis. A prototype masonry building supported on U-FREIs at Tawang, Arunachal Pradesh State, India is considered for this study. The building is simulated by three-dimensional (3D) nonlinear FE model for FB and BI conditions using SAP2000. Dynamic responses of both FB and BI buildings under the action of various recorded real time history ground motions of earthquakes are investigated. Comparison of floor acceleration and inter-storey drift responses of both FB and BI buildings is carried out to evaluate the effectiveness of the BI building under earthquakes. In addition, the hysteresis loops of the U-FREIs under these earthquakes are also investigated.

2. Research subject and Method

2.1. Research subject

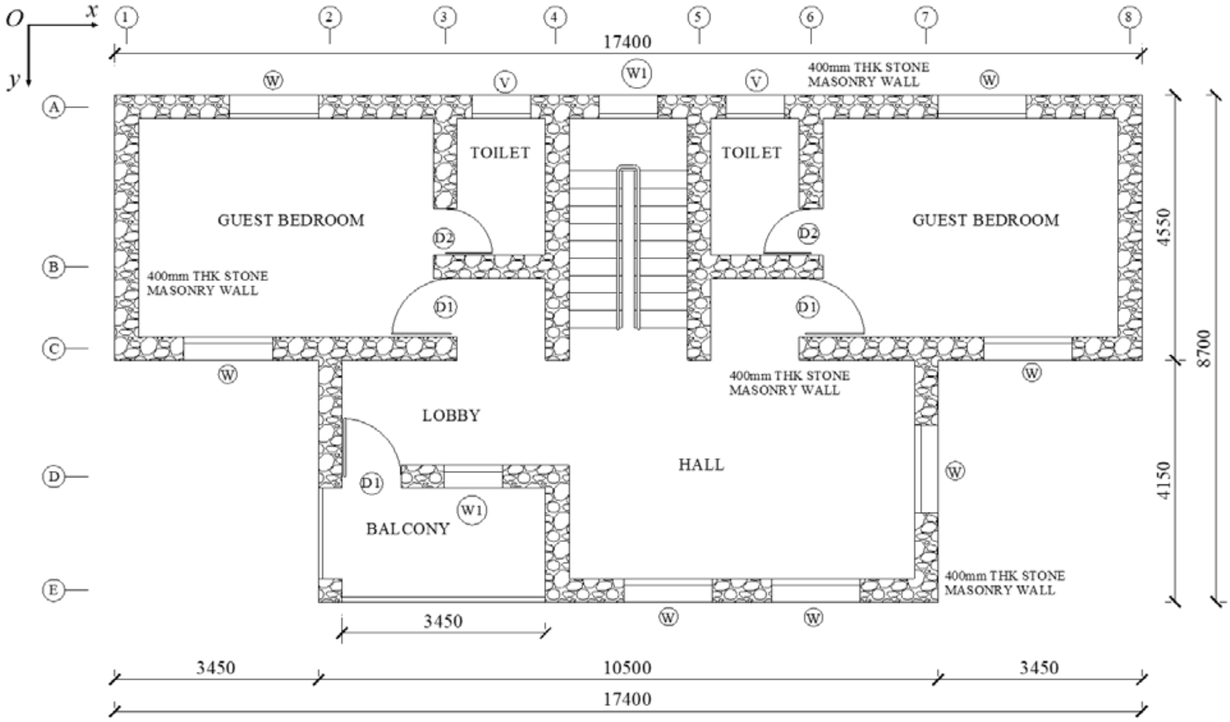
A two-storey base-isolated stone masonry building located at Tawang, Arunachal Pradesh State, India is considered for this study. The building is supported on square U-FREIs for seismic isolation. This is the first U-FREI supported prototype low-rise masonry building constructed anywhere in the world [17].

Such the buildings are representative of the common building types in the north-eastern part of India even in the highest seismic zone (zone V) [19].

In the prototype building, the structure is comprising of two main components including of stone masonry walls and reinforced concrete floors. The roof is covered by galvanized iron sheets, which are supported on truss structures. A view of the building is shown in Fig. 1. A typical floor plan of the building is shown in Fig. 2a. U-FREIs are placed between the two beams (level A and B) without any connections at fourteen numbers of locations shown in Fig. 2b.

Figure 1. A view of the prototype base-isolated building [17].

Base isolation using square U-FREIs for the building is designed to resist strong ground motions. Total fourteen square U-FREIs are used, which comprises of nine isolators of 250×250×100 mm size and five isolators of 310×310×100 mm size. Each isolator is made from eighteen elastomer layers interleaved and bonded with seventeen layers of carbon fiber reinforcement sheets. The thickness of each elastomer layer is 5.0 mm, while that of each fiber layer is 0.55 mm and total height of each bearing is 100 mm. The shear modulus of elastomer (G) is 0.90 N/mm^2 and the elastic modulus of carbon fiber laminate (E) is 40000 N/mm^2.



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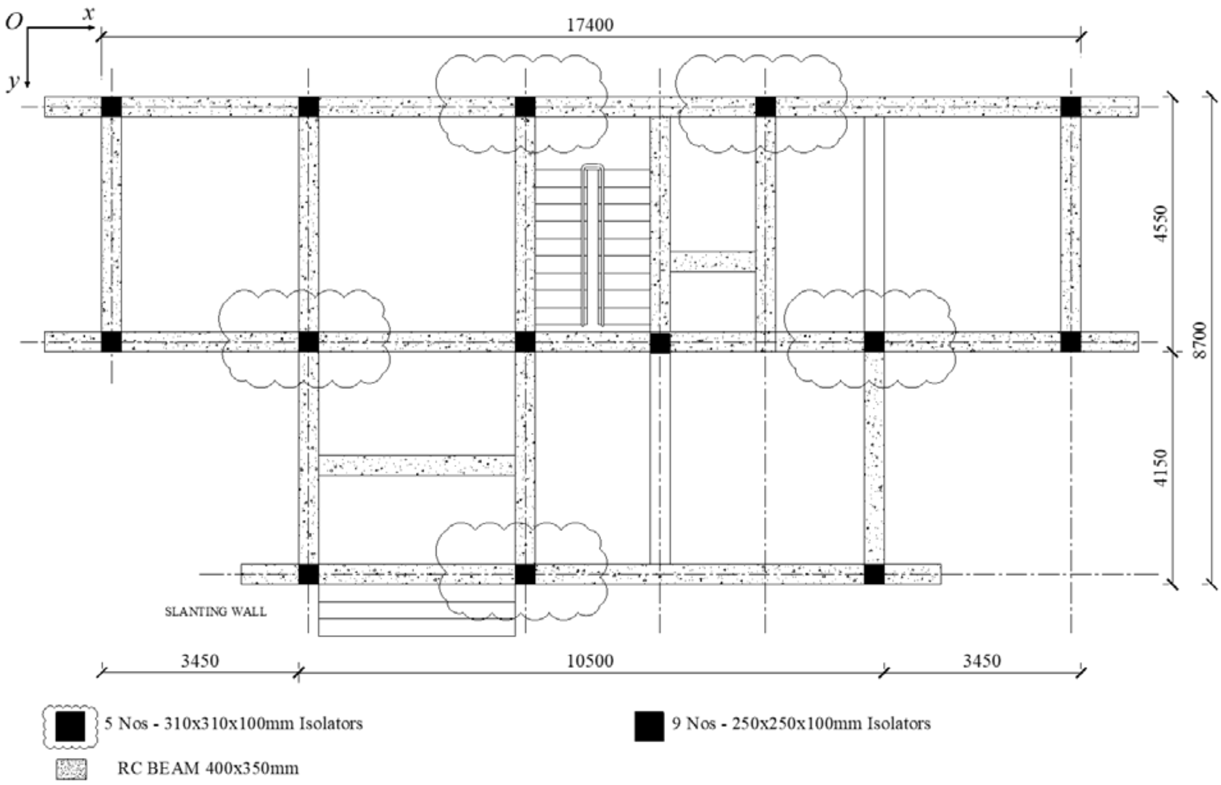


(b)

Figure 2. Plan views of the building [17]: a – Typical floor plan; b – Plan showing locations of base isolators.

2.2. Numerical method

Three-dimensional FE model of BI masonry building as shown in Fig. 3 is simulated in SAP2000 nonlinear [20]. Isolators are modelled by rubber isolator element defined under link type of elements. The force-deformation behaviour of an isolator is modelled as bi-linear hysteretic behaviour which can be effectively used to model all isolation system in practice. The fixed-base condition is simulated by providing fixity at the basement beam level A. The reinforce concrete floors are modelled using shell elements, in which each floor is assigned by a diaphragm constraint. Masonry walls are modelled using nonlinear layered shell elements [21]. The anisotropic behaviour of masonry is modelled by stress-strain curves for compression, tension and shear behaviour.

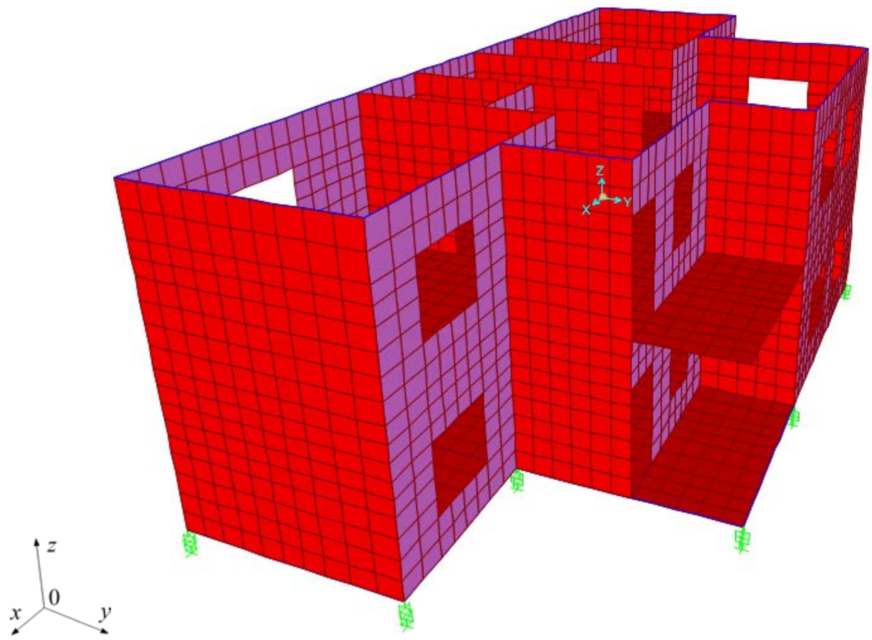


Figure 3. Three-dimensional FE model of the base-isolated masonry building.

Uniaxial compressive and tensile behaviour of masonry prism. Stone masonry building is considered since similar structures are prevalent in the north-eastern zone of India. Material properties are selected to represent the masonry material used in almost all masonry buildings of the zone. In this study, stone masonry with a compressive strength of 7.5 MPa and mortar with a compressive strength of 2.5 MPa are used [17]. Uniaxial compressive and tensile behaviour of masonry prism is defined using the relationship suggested from a number of laboratory tests carried out by [22, 23]. The uniaxial compressive as well as tensile behaviour of masonry prism are shown in Fig. 4.

Stress-strain behaviour of masonry prism in shear. Shear resistance is represented by cohesion and friction between stone (or brick) and mortar, which can be expressed with Mohr-Coulomb friction [24, 25] as

$$\tau = c + \sigma \times \tan\varphi, \quad (1)$$

where σ is compressive stress and $\tan\varphi$ represents friction between stone and mortar. Numerical analysis is carried out using SAP2000 considering a Mohr-Coulomb failure criterion with a cohesion value of 0.1 MPa and ignoring friction. Thus, the stress-strain behaviour of masonry prism in shear is shown in Fig. 5.

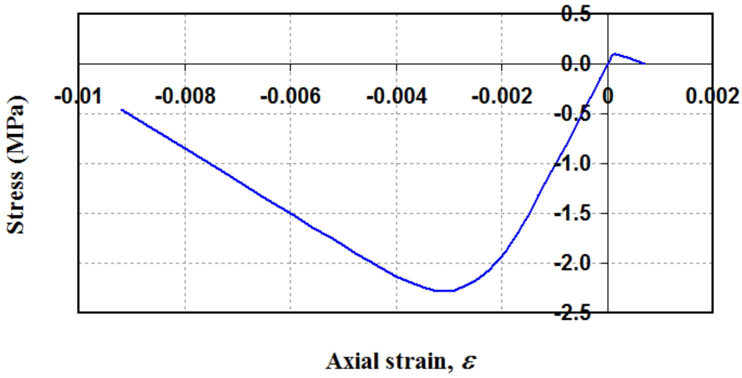


Figure 4. Compressive and tensile behaviour of masonry prism used in the numerical simulation.

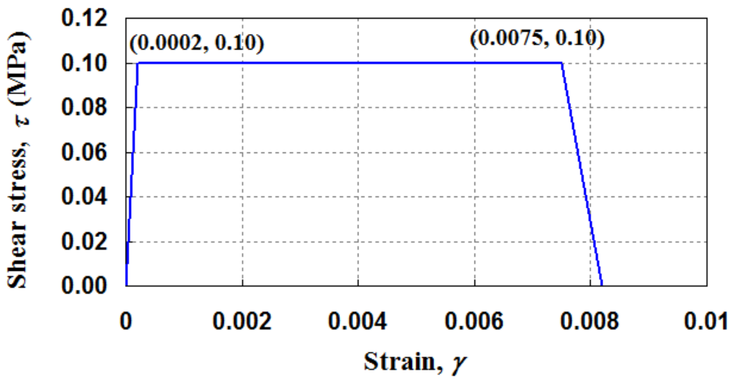


Figure 5. Stress-strain plot for shear of masonry prism.

Boundary condition. The simulation of the building is performed for both FB and BI conditions. For FB building, all nodes at ground level are fixed in all the directions, while for BI building, fourteen isolators placed at locations as per Fig. 2b are modelled by rubber isolator element defined under link type of elements. For simulation of a U-FREI, backbone curves obtained from force-displacement hysteresis loops of typical U-FREIs under horizontal cyclic loading are used to represent the properties of isolator along *X* and *Y*-axis. The force-displacement hysteresis loops of all U-FREIs in this study obtained from experimental and numerical analyses can be found in [13, 17]. For modelling of a U-FREI in SAP2000, the nonlinear force-deformation behaviour of its horizontal response is modelled through the bilinear hysteresis loop characterized (Fig. 6, a) by three parameters namely (i) The effective stiffness, K_{eff}, (ii) Initial stiffness K_1 and the post yield to pre-yield stiffness ratio, n (= K_2/K_1), where K_2 is post yield stiffness, and (iii) Yield strength F_y. An idealized bilinear hysteresis loop and idealised as well as actual force-displacement relationship of U-FREI are shown in Fig. 6b. The input parameters for the mechanical properties of the horizontal response of these U-FREIs supported on the prototype building for modelling are presented in Table 1.

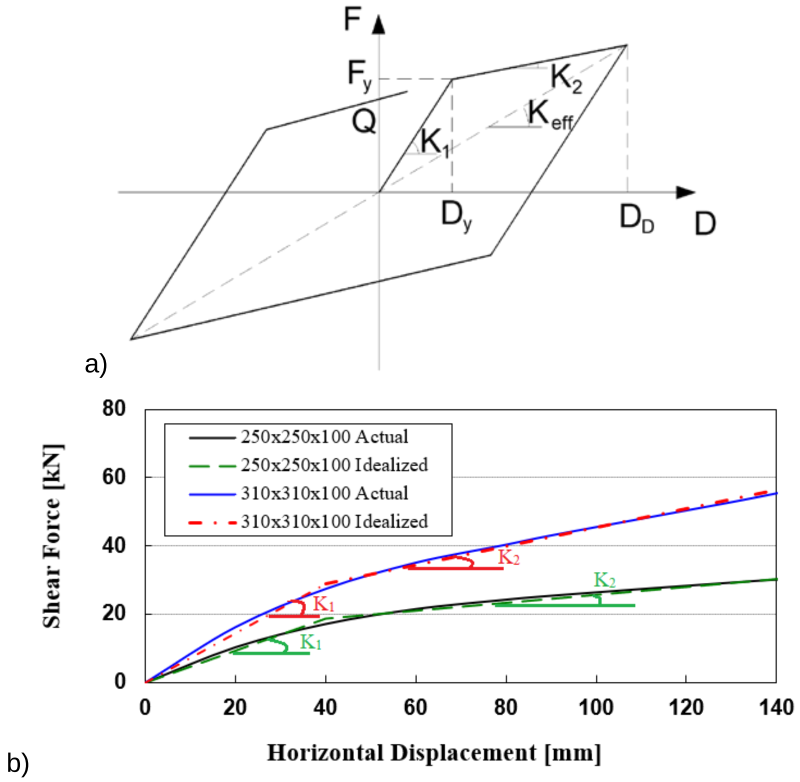


Figure 6. Idealised and actual force-displacement relationship of U-FREIs:
a – Idealised bi-linear force-displacement relationship of isolator;
b – Actual load-displacement curves of U-FREIs with superimposed idealized bi-linear curves.

Table 1. Input mechanical properties of the horizontal response of these U-FREIs for modelling.

Description	250×250×100 mm	310×310×100 mm
K_{eff} (kN/m)	210	395
K_1 (kN/m)	465	725
F_y (kN)	18.5	29.0
n	0.26	0.38

Vertical stiffness (K_V) of a laminated elastomeric isolator is given by [26]

$$K_V = \frac{E_c A}{t_r}, \quad (2)$$

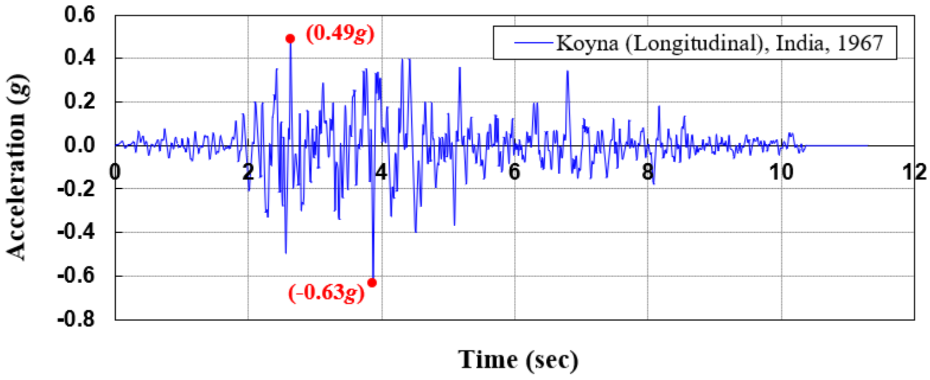
where E_c is the compression modulus of the isolator; A is the full cross-sectional area of the isolator and t_r is the total thickness of elastomer / rubber layers in the isolator. According to [27], the compression modulus, E_c, for a square isolator is E_c = 6.748 GS^2, where S is the shape factor of the isolator which is defined as the ratio of the loaded area to load free area of an elastomer / rubber layer. The vertical stiffness of these isolators supported on the building are furnished in Table 2.

Table 2. Vertical stiffness of these U-FREIs for modelling.

Description	250×250×100 mm	310×310×100 mm
Compression modulus, E_c, (MPa)	948.94	1459.09
Vertical stiffness, K_V, (kN/m)	658984.4	1557979.9

Input ground motions of earthquakes. The building is located at Tawang in north-eastern part of India even in the highest seismic zone (zone V). The actual time history data has been carried out specifying closest distance to a known fault that is capable of producing large magnitude events and that has high rate of seismic activity. The recording stations are just near to an active fault, it is likely to be subjected to the near-fault effects. In this study, three time history ground motions with different stations, peak accelerations, frequency contents and durations from actual record earthquakes as Koyna (India, 1967, Comp – Longitudinal), El-Centro (US, 1940, Comp – N-S) and Victoria (Mexico, 1980, Comp – CPE045) as shown in Fig. 7, are selected. Time history analyses of both FB and BI buildings are carried out along the weaker axis, i.e. *Y*-axis (Fig. 2).

Numerical analysis. The dynamic response of both FB and BI buildings under the action of various recorded real earthquake time history ground motions above are investigated. Comparison of floor acceleration and inter-storey drift responses of both FB and BI buildings is carried out to evaluate the effectiveness of the BI building. In addition, the hysteresis loops of the U-FREIs under these earthquakes are also investigated.



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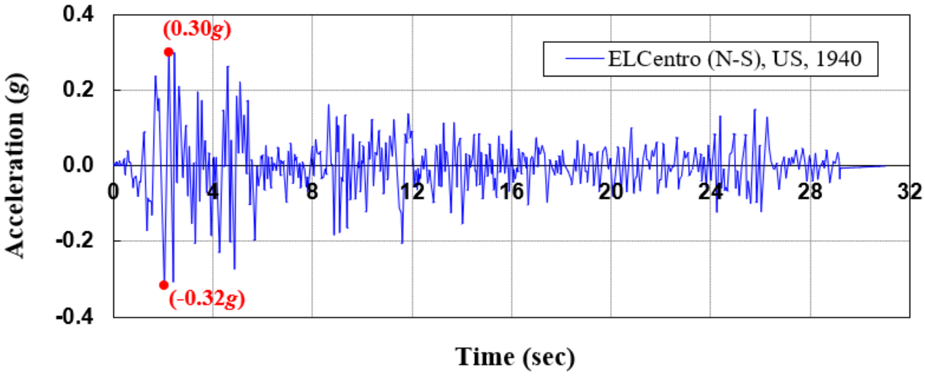

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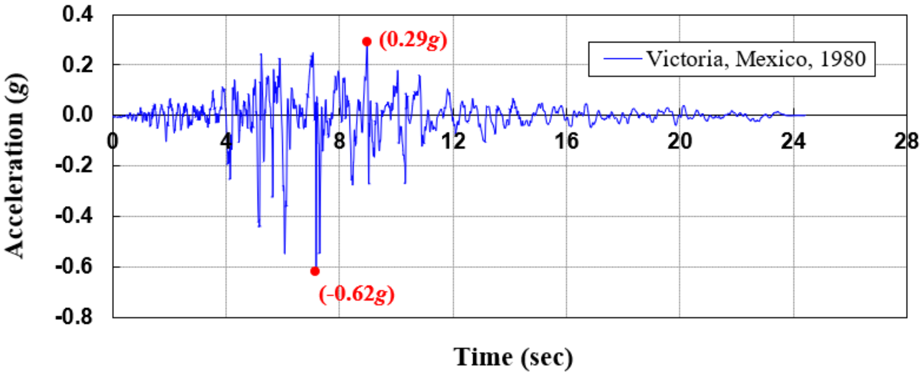

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Figure 7. Real time-history record of selected earthquake motions:
a – Koyna earthquake; b – ElCentro earthquake; c – Victoria earthquake.

3. Results and Discussion

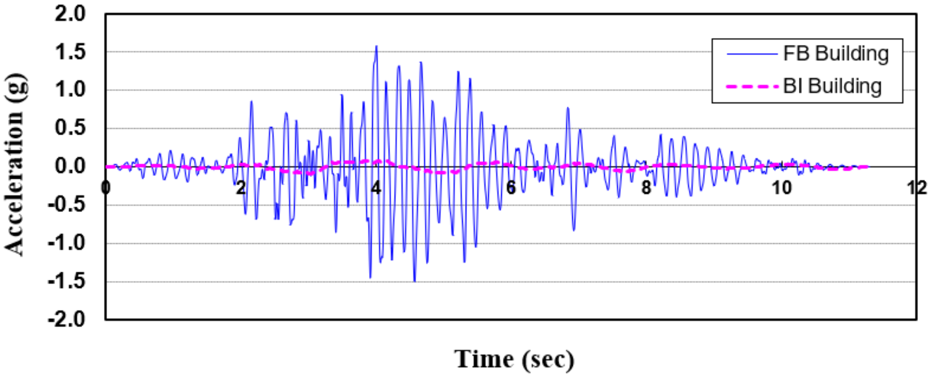
From results of FE analysis, it is found that the dynamic responses (acceleration, inter-storey drift) of BI building are significantly lower than those of FB building. Peak absolute values of floor accelerations and inter-storey drifts of both buildings under various earthquakes are presented in Table 3.

Table 3. Peak values of floor accelerations and inter-storey drifts under various earthquakes.

Parameter	FB building			BI building		
	Koyna	ElCentro	Victoria	Koyna	ElCentro	Victoria
Peak acceleration at 1st floor level (m/s^2)	1.34*g*	0.65*g*	0.76*g*	0.08*g*	0.09*g*	0.12*g*
Peak acceleration at roof level (m/s^2)	1.57*g*	1.05*g*	1.37*g*	0.09*g*	0.10*g*	0.12*g*
Peak drift at 1st storey (mm)	8.6	5.0	5.5	0.7	0.7	0.9
Peak drift at 2nd storey (mm)	4.8	3.0	3.7	0.4	0.4	0.5

g is the acceleration of gravity (*g* = 9.81 m/s^2).

It may be seen from Table 3 that significant reduction in magnitude of peak floor accelerations of BI building has taken place as compared to FB building for the sample excitations. Specifically, reduction of peak floor acceleration between FB building and BI building under Koyna earthquake is found from 1.34 *g* to 0.08 *g* (94.0 %) at the 1st floor level and 1.57 *g* to 0.09 *g* (94.3 %) at roof level. Further, the magnitudes of peak acceleration at different floor levels of BI building are almost same under each excitation, which indicates the absence of any noticeable acceleration amplification along the height of the BI building model. Unlike the BI building, the magnitude of peak acceleration of FB building at roof level is significantly higher than that at the 1st floor level as expected. This finding is in agreement with the observation made by [15] based on the shake table testing results of a scaled model of BI un-reinforced brick masonry building supported on U-FREIs. Similar to the acceleration, magnitudes of peak inter-storey drifts of BI building are significantly lesser than that of FB building, thus clearly indicating the lesser possibility of any damage in the superstructure of the BI building. The detailed time history of floor acceleration at roof level (the level has the maximum magnitude of peak acceleration) and the inter-storey drifts at the 1st floor level (the level has the maximum magnitude of peak drift) of both FB and BI buildings under each earthquake excitations are shown in Fig. 8 and 9 respectively.



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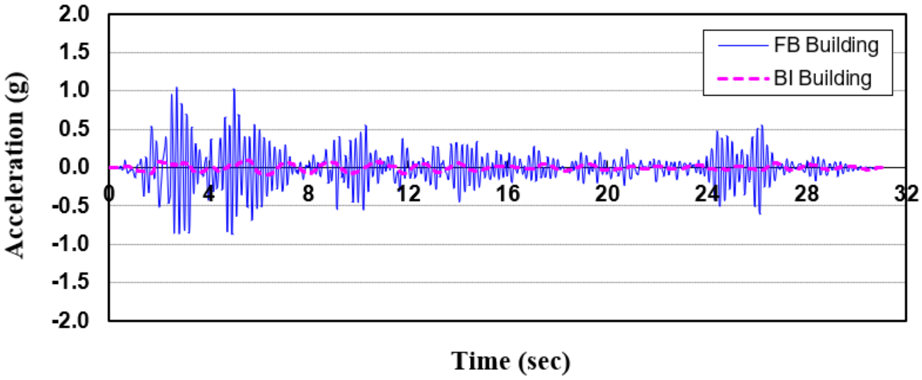

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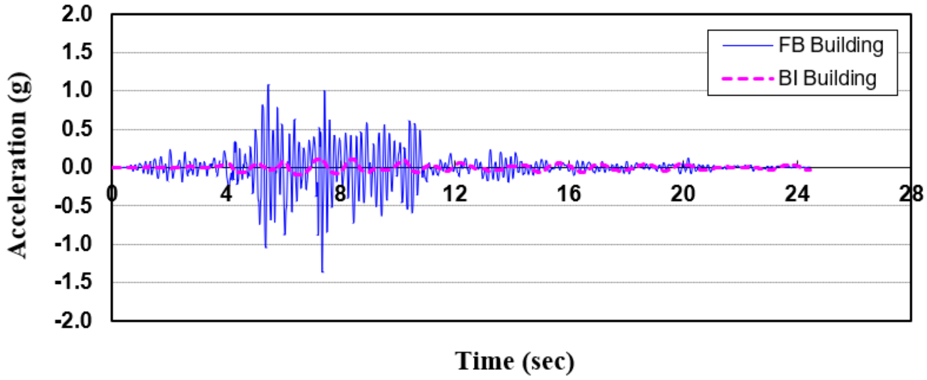

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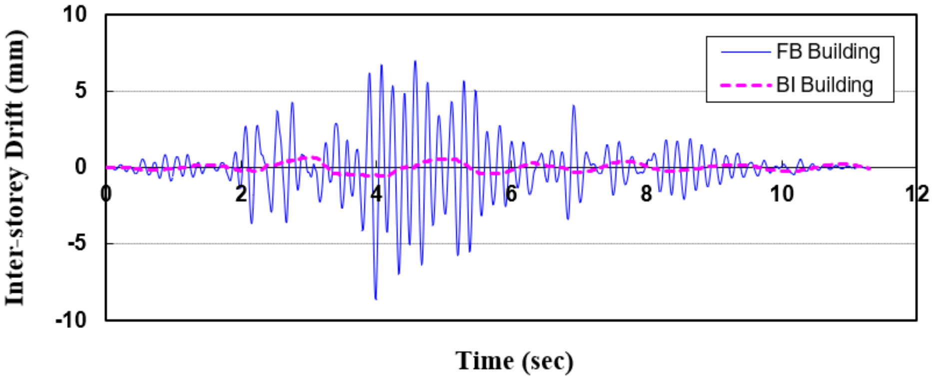
Figure 8. Floor acceleration responses at the roof level of the building under different earthquakes: a – Koyna earthquake; b – ElCentro earthquake; c – Victoria earthquake.



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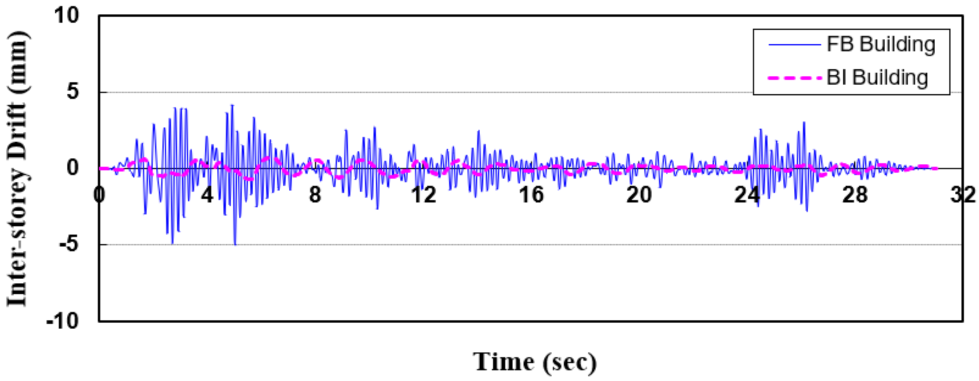

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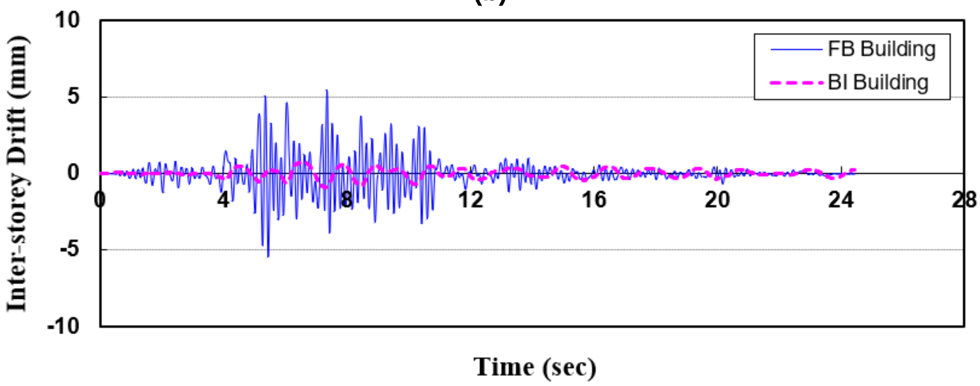

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Figure 9. Time history of inter-storey drift at the 1st floor level of the building under various earthquakes: a – Koyna earthquake; b – ElCentro earthquake; c – Victoria earthquake.

Horizontal displacement responses of U-FREIs of the base isolation system under different earthquakes are shown in Fig. 10. It can be seen from the figure that the peak values of horizontal displacement of U-FREIs under the action of Koyna, ElCentro and Victoria accelerograms are found to be 58, 66 and 104 mm respectively.

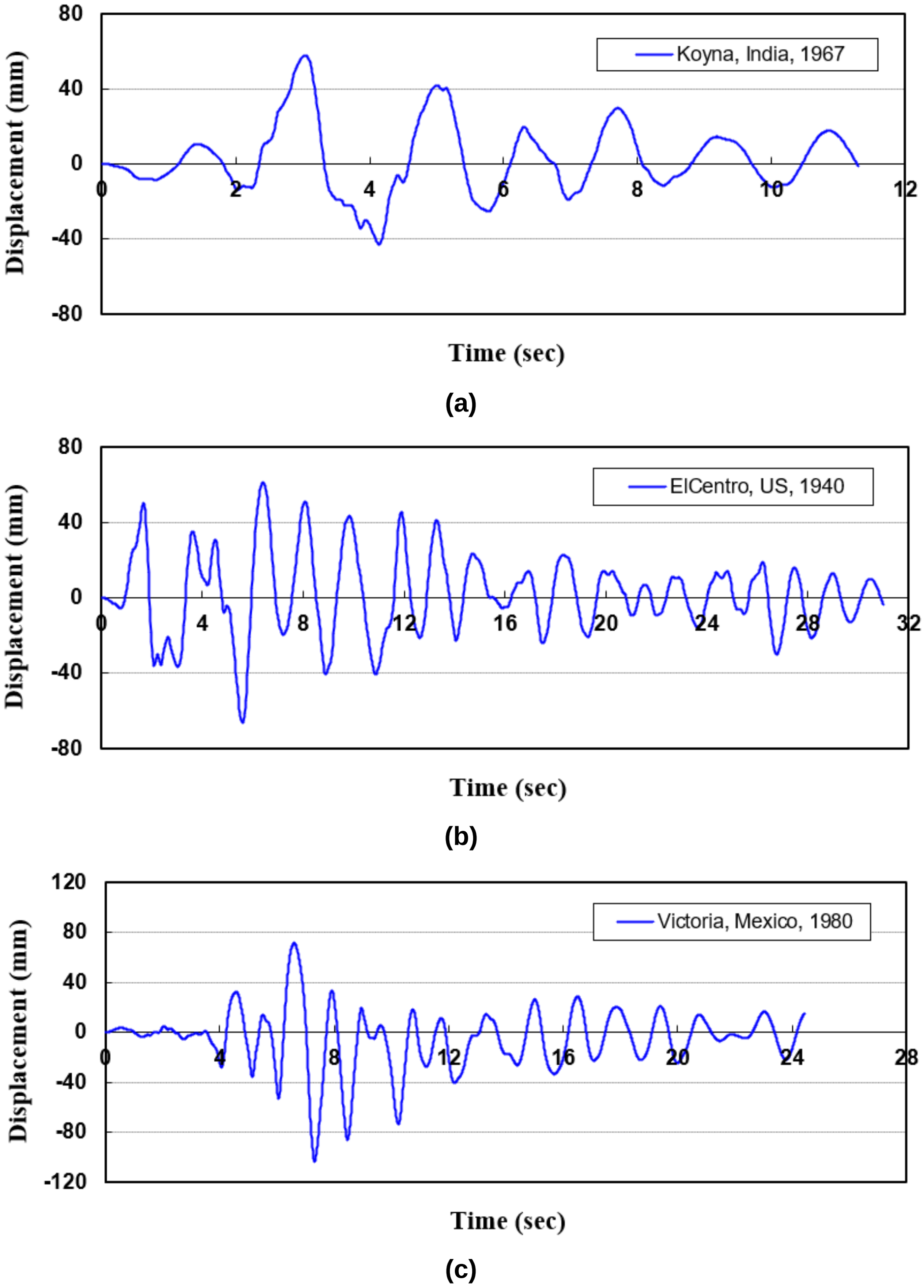
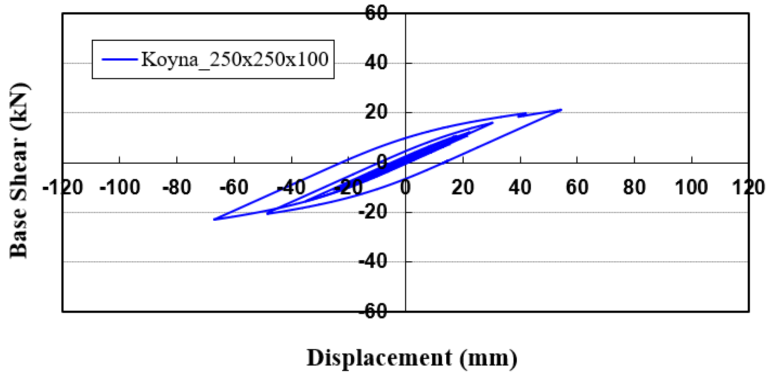


Figure 10. Horizontal displacement responses of U-FREIs under different earthquakes: a – Koyna earthquake; b – ElCentro earthquake; c – Victoria earthquake.

It may further be noted that some standard codes such as [28, 29] specify the performance evaluation of an elastomeric isolator up to a maximum of 1.50 t_r (135 mm). According to [9, 17], these U-FREIs in the building are able to maintain stability up to maximum horizontal displacement of 1.70 t_r (155 mm). These values are larger than the peak values of horizontal displacement of U-FREIs under the action of Koyna, ElCentro and Victoria accelerograms (Fig. 10). Thus, the adopted base isolation system is capable of ensuring overall safety and stability of the structure under the considered earthquakes induced vibration.

The nonlinear behaviour of any isolator is generally reflected in hysteresis loop. The hysteresis loop of an isolator represents the relationship between shear forces and cyclic horizontal displacements. The hysteresis loops of the U-FREIs supported the prototype BI masonry building under various recorded real earthquake time history ground motions are shown in Fig. 11 and 12 for size of 250×250×100 mm and 310×310×100 mm respectively.



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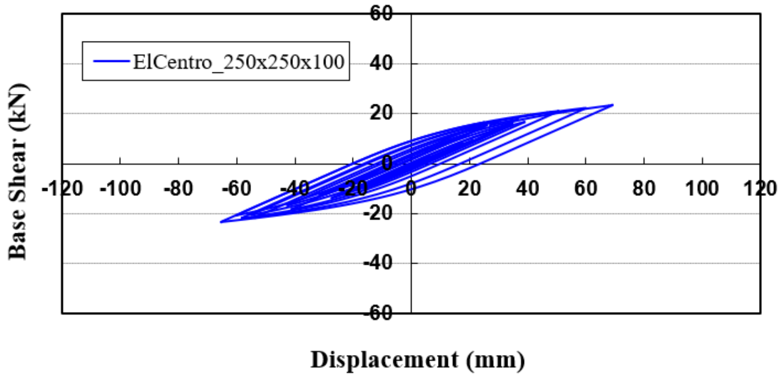

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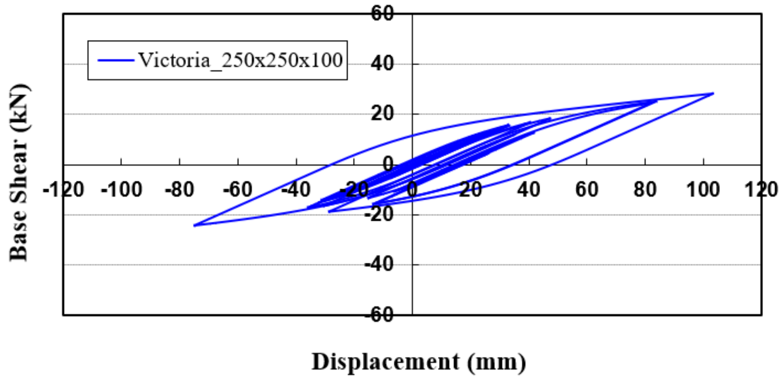

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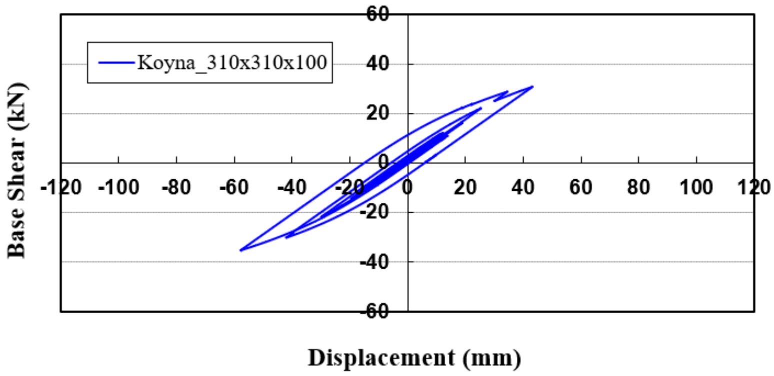
Figure 11. Hysteresis loop behaviour of U-FREIs size 250×250×100 mm supported the prototype masonry building under various earthquakes: a – Koyna earthquake; b – ElCentro earthquake; c – Victoria earthquake.



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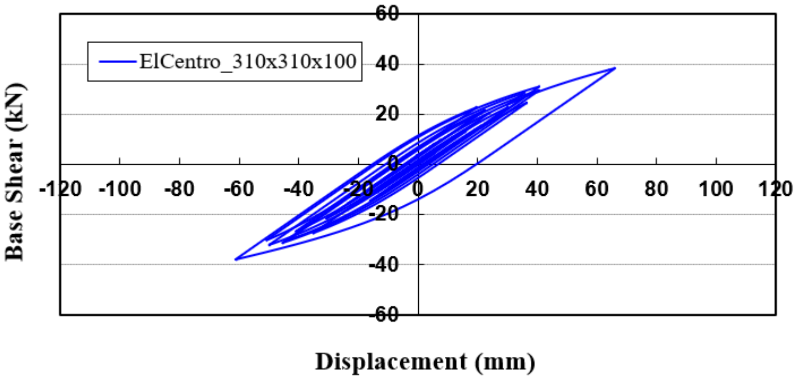

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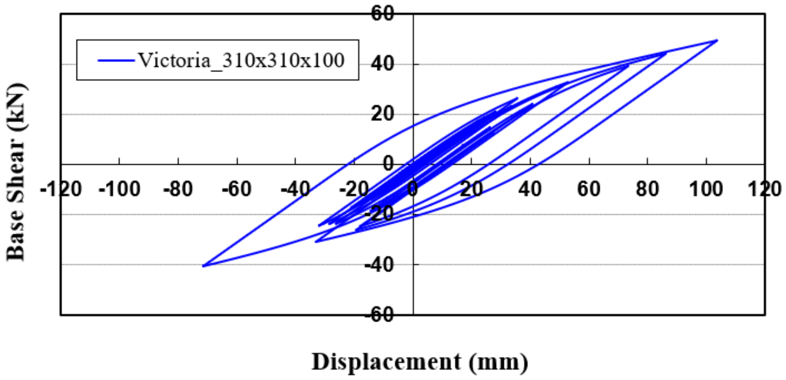

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Figure 12. Hysteresis loop behaviour of U-FREIs size 310×310×100 mm supported the prototype masonry building under various earthquakes: a – Koyna earthquake; b – ElCentro earthquake; c – Victoria earthquake.

It can be seen from Fig. 11 and 12, the values of shear forces corresponding to the peak value of horizontal displacement of the U-FREIs under various earthquakes are appropriate with the values of input bi-linear behaviour of the U-FREIs in Fig. 6b. A close inspection of the curve shows that the characteristic forces, yield displacement, initial stiffness and post yield stiffness for the U-FREIs appear as modelled. Thus, the results obtained by FE analysis for the BI masonry building supported on square U-FREIs under various recorded real earthquake time history ground motions are be considered as accurate.

4. Conclusion

This study investigates the effectiveness of U-FREIs in controlling seismic response of low-rise masonry building under the action of ground motions of earthquakes. A two-storey stone masonry building supported on fourteen U-FREIs located at Tawang, Arunachal Pradesh State, representative of a common building typology in many parts of north-eastern zone of India is selected to evaluate the effectiveness of the base isolation system using U-FREIs under various ground motions as compared to the corresponding fixed base building. Three-dimensional nonlinear models are simulated for the building in both FB and BI conditions. Dynamic response of both FB and BI buildings subjected to various recorded real earthquake time history ground motions are investigated. The concluding remarks are as follows:

1. Floor acceleration and inter-storey drift responses of BI building under excitations from earthquakes are significantly lesser than those of FB building.

2. While the magnitudes of peak acceleration are amplified along the height of the FB building model under each excitation, those of the BI building are almost same at different floor levels.

3. U-FREIs maintain a stable rollover configuration within the estimated displacement limit.

4. U-FREIs are found to be very effective in reduction of seismic vulnerability of low-rise masonry buildings. U-FREIs are introduced to be use for seismic isolation of low-rise building in remote areas as there are light weight, less expensive and easy to install prototype isolation system.

References

1. Kelly, J.M. Analysis of fiber-reinforced elastomeric isolators. Journal of Seismology and Earthquake Engineering. 1999. 2 (1). Pp. 19–34.
2. Zhang, J., Huo, Y. Evaluating effectiveness and optimum design of isolation devices for highway bridges using the fragility function method. Engineering Structures. 2009. 31 (8). Pp. 1648–1660. DOI: 10.1016/j.engstruct.2009.02.017
3. Arutunyan, A.R. Modern methods of buildings seismic isolation. Magazine of Civil Engineering. 2010. 13 (3). Pp. 56–60. (rus). DOI: 10.18720/MCE.13.1
4. Tavares, D.H., Padgett, J.E., Paultre, P. Fragility curves of typical as-built highway bridges in eastern Canada. Engineering Structures. 2012. No. 40. Pp. 107–118. DOI: 10.1016/j.engstruct.2012.02.019
5. Kovaleva, N.V., Rutman, Yu.L., Davydova, G.V. Determination of optimal damping parameters for seismic isolation systems. Magazine of Civil Engineering. 2013. 40 (5). Pp. 107–115. (rus). DOI: 10.5862/MCE.40.12
6. Siqueira, G.H., Sanda, A.S., Paultre, P., Padgett J.E. Fragility curves for isolated bridges in eastern Canada using experimental results. Engineering Structures. 2014. No. 74. Pp. 311–324. DOI: 10.1016/j.engstruct.2014.04.053
7. Kumar, P., Petwal, S. Seismic performance of secondary systems housed in isolated and non-isolated building. Earthquakes and Structures, An International journal. 2019. 16(4). Pp. 401–413. DOI: 10.12989/eas.2019.16.4.401
8. Artar, M., Coban, K., Yurdakul, M., Canb, O., Yilmaz, F., Yildiz, M. Investigation on seismic isolation retrofit of a historical masonry structure. Earthquakes and Structures, An International journal. 2019. 16(4). Pp. 501–512. DOI: 10.12989/eas.20-19.16.4.501
9. Toopchi-Nezhad, H., Tait, M.J., Drysdale, R.G. Testing and modeling of square carbon fiber-reinforced elastomeric seismic isolators. Structural Control and Health Monitoring. 2008. 15(6). Pp. 876–900. DOI: 10.1002/stc.225
10. Toopchi-Nezhad, H., Tait, M.J., Drysdale, R.G. Lateral response evaluation of fiber-reinforced neoprene seismic isolator utilized in an unbonded application. Journal of Structural Engineering, ASCE. 2008. 134 (10). Pp. 1627–1637. DOI: 10.1061/(ASCE)0733-9445(2008)134:10(1627)
11. Toopchi-Nezhad, H., Tait, M.J., Drysdale, R.G. Parametric study on the response of stable unbonded-fiber reinforced elastomeric isolator (SU-FREIs). Journal of Composite Materials, SAGE. 2009. 43(15). Pp. 1569–1587. DOI: 10.11-77/0021998308106322
12. Dezfuli, F.H., Alam, M.S. Performance of carbon fiber-reinforced elastomeric isolators manufactured in a simplified process: experimental investigations. Structural Control and Health Monitoring. 2014. No. 21. Pp. 1347–1359. DOI: 10.1002/stc.1653
13. Ngo, V.T., Dutta, A., Deb, S.K. Evaluation of horizontal stiffness of fibre reinforced elastomeric isolators. Earthquake Engineering and Structural Dynamics. 2017. 46(11). Pp. 1747–1767. DOI: 10.1002/eqe.2879
14. Toopchi-Nezhad, H., Tait, M.J., Drysdale, R.G. Shake table study on an ordinary low-rise building seismically isolated with SU-FREIs (Stable Unbonded-Fiber Reinforced Elastomeric Isolators). Earthquake Engineering and Structural Dynamics. 2009. 38(11). Pp. 1335–1357. DOI: 10.1002/eqe.923
15. Das, A., Deb, S.K., Dutta, A. Shake table testing of un-reinforced brick masonry building test model isolated by U-FREI. Earthquake Engineering and Structural Dynamics. 2016. No. 45. Pp. 253–272. DOI: 10.1002/eqe.2626
16. 16. Losanno, D., Spizzuoco, M., Calabrese, A. Bidirectional shaking table tests of unbonded recycled rubber fiber-reinforced bearings (RR-FRBs). Structural Control and Health Monitoring. 2019. 26(9). DOI: 10.1002/stc.2386
17. Ngo, V.T., Deb, S.K., Dutta, A. Mitigation of seismic vulnerability of a prototype low-rise masonry building using U-FREIs. Journal of Performance of Constructed Facilities, ASCE. 2018. 32(2). Pp. 04017136-1-13. DOI: 10.1061/(ASCE)CF.1943-5509.0001136
18. Calabrese, A., Losanno, D., Spizzuoco, M., Strano, S., Terzo, M. Recycled rubber fiber-reinforced bearings (RR-FRBs) as base isolators for residential buildings in developing countries: The demonstration building of Pasir Badak, Indonesia. Engineering Structures. 2019. No. 192. Pp. 126–144. DOI: 10.1016/j.engstruct.2019.04.076
19. IS 1893 Part 1. Criteria for earthquake resistant design of structures. Bureau of Indian Standard. New Delhi, India. 2002. 45 p.
20. SAP2000 v.15. Computers and Structures Inc., CSI Analysis Reference Manual. Berkeley, California, USA. 2014.
21. Bilgin, H., Korini, O. Seismic capacity evaluation of un-reinforced masonry residential buildings in Albania. Natural Hazards and Earth System Sciences. 2012. No. 12. Pp. 3753–3764. DOI: 10.5194/nhess-12-3753-2012
22. Kaushik, H.B., Rai, D.C., Jain, S.K. Stress-strain characteristics of clay brick masonry under uniaxial compression. Journal of Materials in Civil Engineering, ASCE. 2007. 19(9). Pp. 728–739. DOI: 10.1061/(ASCE)0899-1561(2007)19:9(728)
23. Akhaveissy, A.H., Milani, G. Pushover analysis of large scale unreinforced masonry structures by means of a fully 2D non-linear model. Construction and Building Materials. 2013. No. 41. Pp. 276–295. DOI: 10.1016/j.conbuildmat.2012.12.006
24. Milani, G., Lourenco, P.B., Tralli, A. Homogenised limit analysis of masonry walls, Part I: Failure surfaces. Computers and Structures. 2006. No. 84. Pp. 166–180. DOI: 10.1016/j.compstruc.2005.09.005
25. Milani, G., Lourenco, P.B., Tralli, A. 3D homogenized limit analysis of masonry buildings under horizontal loads. Engineering Structures. 2007. 29(11). Pp. 3134–3148. DOI: 10.1016/j.engstruct.2007.03.003
26. Naeim, F., Kelly, J.M. Design of Seismic Isolated Structures: From Theory to Practice. John Wiley & Sons, Inc. New York, USA. 1999. DOI: 10.1002/9780470172742
27. Kelly, J.M., Konstantinidis, D.A. Mechanics of Rubber Bearings for Seismic and Vibration Isolation. John Wiley & Sons, Ltd, Publication. New Delhi, India. 2011. 222 p.
28. ASCE/SEI 7-10. Minimum Design Load for Buildings and Other Structure. American Society of Civil Engineers. Reston, Virginia, USA. 2013.
29. EN 1337-3. Structural bearings, Part 3: Elastomeric bearings. European Committee for Standardization. CEN/TC250. Brussels. 2005. 94 p.

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