International Research Journal of Engineering and Technology (IRJET) e-ISSN: 2395-0056
Volume: 07 Issue: 07 | July 2020 www.irjet.net p-ISSN: 2395-0072

Study of Hybrid Seismic Base Isolation System using Unbonded Fiber Reinforced Elastomeric Isolators and SMA Wires for Masonry Buildings

Merin S Raju[1], Dr. Alice Mathai[2]

[1]M. Tech Structural Engineering and Construction Management, Mar Athanasius College of Engineering, Kothamangalam, Ernakulam, Kerala, India
[2]Professor, Dept. of Civil Engineering, Mar Athanasius College of Engineering, Kothamangalam P.O, Ernakulam, Kerala, India

***

Abstract - *Seismic isolation is a seismic design philosophy that aims to reduce the seismic demand on structures as opposed to increasing their capacity to endure forces. One of the most promising devices for seismic base isolation of structures is the unbonded fiber reinforced elastomeric isolator (UFREI) due to its low manufacturing cost and horizontal stiffness. This low horizontal stiffness increases the structural period, shifting the structure into a period range of low seismic energy content. The objectives of this research were to investigate the possibility of combining UFREIs and shape memory alloy (SMA) wires to increase the energy dissipation capacity of the isolation system. With the purpose of evaluating the performance of UFREI – SMA isolation system in structural applications, non-linear dynamic time history analyses of the two storeyed masonry building located in Tawang was conducted in the fixed model and model equipped with hybrid base isolation systems. Numerical results show that the utilization of SMA wires significantly increases the energy dissipation capacity of the base isolation system and decreases the horizontal displacements of the masonry building. Thus UFREI-SMA base isolation are found to be very effective in reduction of the seismic vulnerability of low-rise masonry buildings.*

***Key Words*: Base Isolation, UFREI, SMA wire, ABAQUS, Nonlinear Time History Analysis**

1. INTRODUCTION

Fiber reinforced elastomeric isolators comprise of alternating bonded layers of elastomer and fiber reinforcement. The elastomeric layers provide lateral flexibility and the primary role of fiber reinforcement is to constrain lateral bulging of the elastomer when the isolator is subjected to vertical compressive loads. FREI have been introduced as a potential low-cost alternative to conventional steel reinforced elastomeric ones. They can be unbonded (UFREI) or bonded (BFREI) to both the superstructure and substructure. The effective horizontal stiffness of UFREI is considerably lower than that of BFREI, thus decreasing the seismic demand. Additional benefits are obtained in the form of considerable reduction in the manufacturing costs resulting from a lesser labour – intensive process.

Kelly et al. (1999) [1] presented method of evaluation of the mechanical characteristics of fiber reinforced elastomeric isolator in which steel plant of conventional elastomeric isolators were replaced by fiber reinforced. The influence of fibre flexibility on the mechanical properties of FREI, such as vertical and horizontal stiffness was studied.

Moon et al. (2002) [2] carried out experiments to evaluate and compare the performances of fiber reinforcement with performance of steel reinforcement, and the differences in performance among different kinds of fiber reinforcement. Experiments showed that performance of the carbon FREI was even superior to that of SREI in view of vertical stiffness and effective damping.

Hamid Toopchi-Nezhad et al. (2011) [3] developed finite element model for the analysis of strip fiber reinforced elastomeric isolators that are subjected to any given combination of static vertical and lateral loads. The model is able to simulate both bonded and unbonded boundary conditions at the top and bottom contact surfaces of the isolator. Using the proposed FE- model, the lateral responses of a B-FREI and a SU-FREI were evaluated.

Habieb, Milani et al. (2017) [4] in this research go through the detailed 3D finite element analysis to predict the behaviour of the low cost rubber isolator undergoing moderate deformations. An isolation system is implemented to structure of two story masonry house prototype, identifying the 3D model with a damped nonlinear spring model. The results reveal that the isolation system proposed can improve the seismic performance of the masonry building effectively, with an excellent applicability of the low-cost rubber isolator.

Van Ngo Thuyet et al. (2018) [5] has done the seismic vulnerability of a two storied stone masonry building supported on U-FREIs located in Tawang, India. Fragility curves corresponding to different damage states indicated a significant reduction in seismic vulnerability of the base isolated building on UFREIs as compared to that of the fixed base building.

E. Choi et al. (2005) [6] proposes a new concept of an isolation device in which shape memory alloy wires are incorporated in an elastomeric bearing. A three-span continuous steel bridge was used for seismic analyses to compare the performance of lead-rubber and the proposed bearings. The proposed bearings limit the deck relative displacement effectively with strong ground motions and recover almost original undeformed shape.

The objective of this paper was to

•To study the behaviour of a hybrid base isolation system by combining UFREIs and shape memory alloy (SMA) wires for the application in masonry buildings

•To investigate the response of a two storied masonry building isolated with the hybrid isolation system

2. NUMERICAL MODELLING OF UNBONDED FIBER REINFORCED ELASTOMERIC ISOLATORS

Detailed 3D Finite element models are developed and cyclic shear FE analyses are performed through the software code ABAQUS to investigate the behaviour of UFREI. In the software code ABAQUS, different types of hyperelastic material models are available and each model defines the strain energy function in a different way. In this study the Ogden hyperelastic material model is used to represent the properties of rubber due to its simplicity. Table 1 shows the values of the coefficients adopted for the Ogden hyperelastic material model [7].

To characterize the damping behavior of rubber, the Prony-series model is used. It is a time-domain viscoelasticity available in ABAQUS to determine the time-dependent stress-strain relation. Table 2 shows the coefficients values of the Prony-series viscosity model [7]. The isolator investigated in this study uses bidirectional woven glass fibers as vertical reinforcement. The fibers are bonded to the rubber pads simply by using a polyurethane adhesive. The glass fiber is assumed isotropic-elastic with Young modulus equal to 40 GPa and Poisson's ratio equal to 0.25 [9].

Table -1: Coefficients of the Ogden hyperelastic model

μ_1	α_1	μ_2	α_2	$\mu 3$	α_3	K_1	K_2	K_3
1.89	1.3	0.0036	5	-0.03	-2	0	0	0

Table -2: Coefficients of the Prony-series model

α	t
0.3333	0.04
0.3333	100

Fig-1 illustrates the FE model of the UFREI investigated in this study, with an indication of the main geometrical characteristics. It consists of 18 square rubber pads that are 5 mm thick and 265 mm long. The thickness of the fiber reinforcement is equal to 0.55 mm. The total height of UFREI is 99.35 mm.

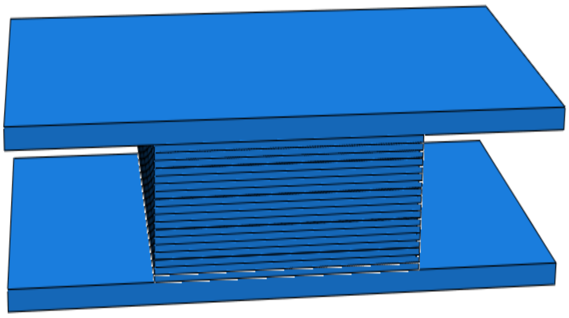


Fig-1: Geometry of the FE model of the UFREI

Since rubber is a nearly incompressible material, the 8-node 3D solid elements with hybrid formulation C3D8H are used for meshing. The glass fabric layers are modelled with the 4-node membrane elements M3D4 sharing their nodes with the rubber elements.

To obtain an unbonded condition, no bonding is introduced between the rubber and the support. A penalty friction with coefficient $\mu = 0.85$, which corresponds to the friction between dry concrete and rubber, is adopted [8].

Cyclic shear analyses are conducted on the detailed 3D FE models of UFREI up to lateral displacements equal to about 1.5 times thickness of isolator. A constant vertical pressure equal to 2.5 MPa is applied at top of the isolator such a pressure approximately corresponds to the vertical force experienced by a single isolator when placed under a masonry building.

3. MECHANICAL PROPERTIES OF UFREI

3.1 Vertical Stiffness

Obtaining adequately high vertical compression stiffness is an important consideration in the design of an isolation system. Intuitively, the isolator must support the vertical compressive load of the structure without excessive deformations or failure. In order to determine the vertical stiffness as well as the maximum vertical deflection, changes of vertical force are plotted versus vertical deflection. Chart- 1 depicts the corresponding results of vertical load vs vertical displacement. The maximum vertical displacement occurred is 0.34mm.The vertical stiffness, K_v of the isolator was evaluated at 9.5MPa vertical pressure as 2180kN/mm. Results show that required vertical stiffness was developed.

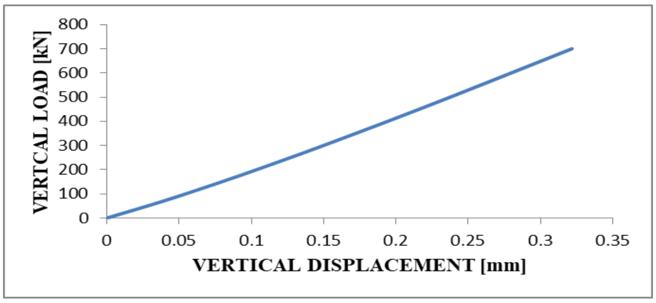


Chart -1: Vertical load vs vertical displacement

3.2 Rollover Deformation

In UFREIs, a unique rollover deformation occurs with lateral displacement. As lateral load is applied to a UFREI bearing, the bearing begins to roll over. Rollover occurs as the top and bottom horizontal layers of elastomer lose contact with the upper and lower supports and begin to rotate with lateral displacement as shown in Fig-2. This occurs because of the combined unbonded application and lack of flexural rigidity of the fiber reinforcement.

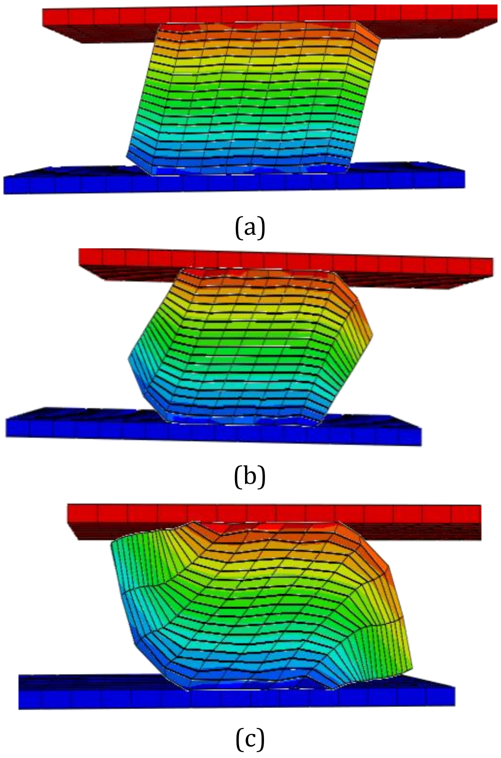


Fig-2: Deformed shapes of UFREI subjected to horizontal displacements of (a) 50mm, (b) 100mm and (c) 150mm

3.3 Horizontal Characteristics

The operational characteristics of UFREI are obtained from the lateral force-deflection hysteresis curves plotted at different amplitudes. Shear forces are plotted against the horizontal displacement to obtain the hysteresis loop for the isolator. Chart-2 depicts the hysteretic shear behaviour of UFREI.

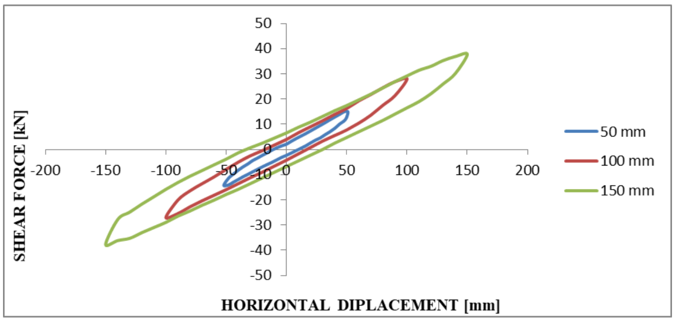


Chart-2: Shear force – horizontal displacement curves of UFREI subjected to horizontal displacements of (a) 50mm, (b) 100mm and (c) 150mm

Two important parameters such as effective horizontal stiffness and effective damping factor are obtained from the hysteresis loops. The effective horizontal stiffness (K^h_{eff}) of an isolator at any amplitude of horizontal displacement is defined as in Equation 3.1 and equivalent viscous damping of isolator (β) is computed by Equation 3.2 [8].

$$K^h_{eff} = \frac{F_{max} - F_{min}}{u_{max} - u_{min}} \qquad \text{Equation 3.1}$$

Where,
F_{max} is maximum value of shear force
F_{min} is minimum value of shear force
U_{max} is maximum value of displacement
U_{min} is minimum value of displacement

$$\beta = \frac{W_d}{2\pi K^h_{eff} \Delta^2_{max}} \qquad \text{Equation 3.2}$$

Where,
β is the equivalent viscous damping of isolator
W_d is the energy dissipated in each cycle
K^h_{eff} is the effective horizontal stiffness
Δ_{max} is the average of the positive and negative maximum displacements

Table-3 shows the results of horizontal stiffness and damping ratio of UFREI. The results show that, under the same vertical stress, the horizontal stiffness of the isolator has decreased and equivalent damping of the isolator increased with the increase in shear strain.

Table -3: Results of horizontal stiffness and damping ratio of UFREI

Displacement (mm)	Effective Horizontal stiffness (K^h_{eff}) (kN/m)	Equivalent Viscous Damping Ratio (%)
50	463.4	8
100	351.02	9.6
150	296.62	10.2

4. MODELING OF SHAPE MEMORY ALLOY WIRE

In the present work, a combination of unbonded fiber reinforced elastomeric isolators and SMA wires are proposed to seismically isolate masonry building. A straight wire configuration with frictionless steel hooks is adopted in the proposed system. In addition, flange supports are required to facilitate the deformation of the SMA wire in the two orthogonal directions without being in contact with the support beam or foundation, which may lead to a failure of the SMA wire as shown in Fig-3 [9].

Detailed 3D FE models are developed and cyclic shear FE analyses are performed through the software code ABAQUS to investigate the behaviour of the SMA wire. NiTi-SMA wire was used. Length equal to 300mm and diameter of 4.5mm was used [9]. The FEA model of SMA wire is shown in Fig-4.

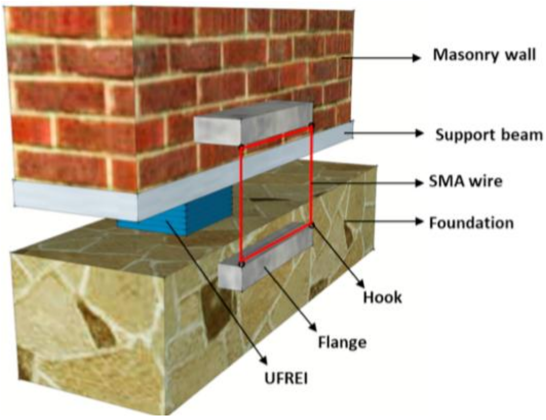


Fig-3: Arrangement of the combination of UFREI and SMA wire in the isolation system

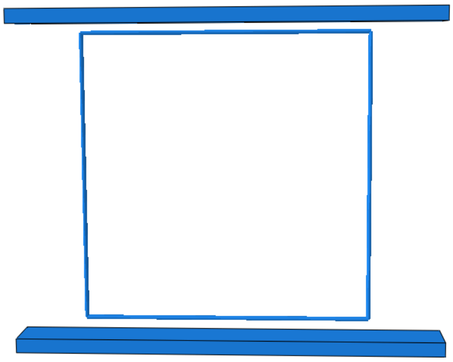


Fig -4: FEA model of SMA wire

In this study, the behaviour of the NiTi SMA is evaluated using the Auricchio's constitutive model [10]. Such a model is implemented in the user-defined material (UMAT) subroutine for SMA that available in ABAQUS environment. T3D2, a 2 noded linear 3-D truss element is used for structural discretization of SMA wire. Cyclic shear analysis is conducted on the SMA wire placed between the two supports. The shear force-displacement curves of the SMA wire device presented in Chart-3.

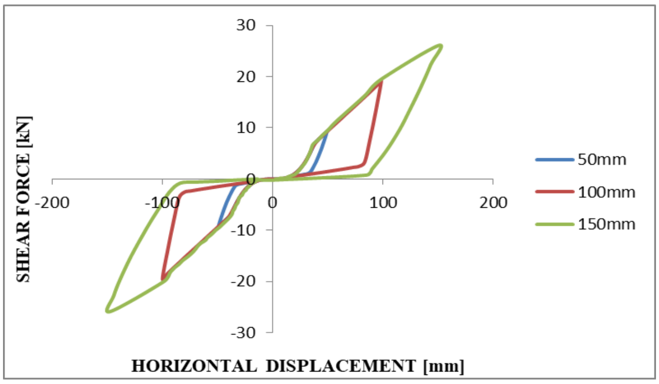


Chart-3: Shear force-displacement curves of the SMA wire subjected to horizontal displacements

By evaluating the responses of decoupled models of UFREI and SMA, the hysteresis of UFREI-SMA hybrid system can be determined based on the superposition method. The method of superposition is implemented in order to simplify the system by decoupling the rubber bearing and SMA wires. The shear force-displacement curves of the SMA wire device are combined with the shear force-displacement curve of the UFREI obtained through the 3D FE model. The combined curve is shown in Chart-4.

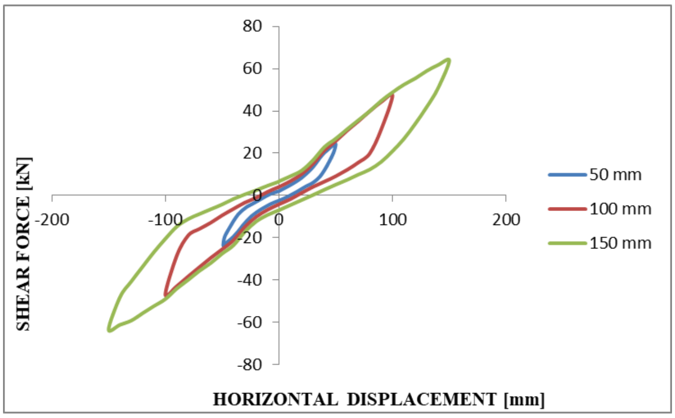


Chart-4: Shear force–horizontal displacement curves of Hybrid isolation system

By computing the hysteretic behaviour of UFREI-SMA, operational characteristics of the base isolator including the horizontal stiffness (K^h_{eff}) and the equivalent viscous damping (β) are calculated in order to compare the performances of UFREI with those of UFREI-SMA. Table-4 shows the results of horizontal stiffness and damping ratio of hybrid isolation system.

Table-4: Results of horizontal stiffness and damping ratio of UFREI-SMA System

Displacement (mm)	Effective Horizontal stiffness (K^h_{eff}) (kN/m)	Equivalent Viscous Damping Ratio (%)
50	485	9.5
100	450	11.14
150	400	12.4

5. SEISMIC ISOLATION OF A MASONRY BUILDING

Masonry buildings are one of the most commonly adopted structural types for low-rise buildings in developing countries. These buildings can be built rapidly and economically using traditional technology and locally available materials like stone, clay brick. These buildings can sustain gravity loads very easily because of their high compressive strength of masonry, but are highly susceptible to ground shaking because of their low tensile as well as shear strength, making them often susceptible to damage.
In order to check the effectiveness of hybrid isolation system dynamic response characteristic of base isolated masonry building with UFREI-SMA hybrid system subjected to input earthquakes and is compared with the response of the same building without base isolation system. This investigation is undertaken considering seismic vulnerability of low-rise masonry building.

5.1 Description of Base Isolated Masonry Building

A two storied base isolated stone masonry building is constructed in Tawang, India, supported on U-FREIs for seismic isolation[5]. This prototype building represents a class of similar low rise masonry buildings in parts of the north eastern part of India. The material characteristics and construction practices are generally similar. This is the first U-FREI-supported prototype low rise masonry building constructed anywhere in the world. A view of the prototype building supported on U-FREIs is shown in Fig-5. Such low-rise masonry buildings are representative of the common building types in the northeastern part of India.

Fig-5: Prototype base-isolated masonry building located in Tawang, India

Reinforced concrete basement beams (A and B) are provided at two different levels, as indicated in Fig-5. UFREIs are placed between the two beams without any connections. The beam layout with the positioning of isolators is shown in Fig-6. The building is composed of two main components, namely stone masonry walls and reinforced concrete floors. The roof is covered by galvanized iron sheets, which are supported on truss structures [5].

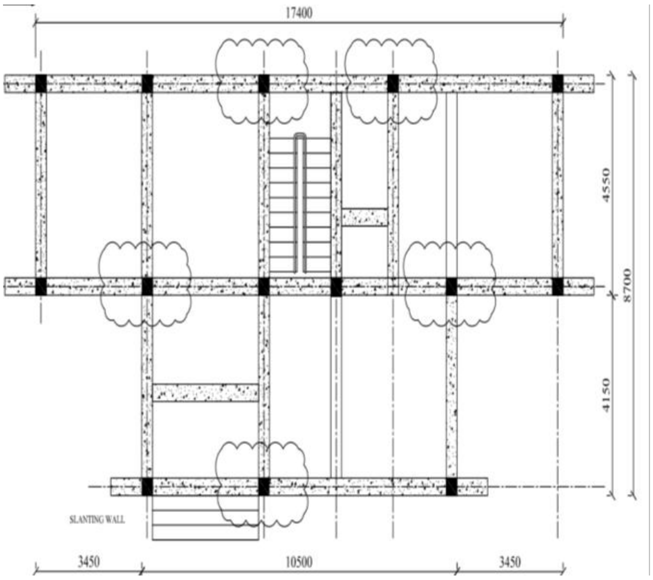


Fig-6: Beam layout of base isolated masonry building

5.2 Numerical Modeling of Masonry Building

A three-dimensional FE model of fixed base masonry building as shown in Fig-7. is simulated in ETABS 15 software package. Masonry walls are modelled using membrane shell elements. The shell elements are appropriately discretized for obtaining a reliable finite element solution. An isotropic material model is adopted for the masonry. The mechanical properties of the stone masonry used in the simulation are given in Table-5. The floors are modelled by introducing the rigid diaphragm constraint at each story level. The foundation beam is assumed made by reinforced concrete with compressive strength of 25 MPa.

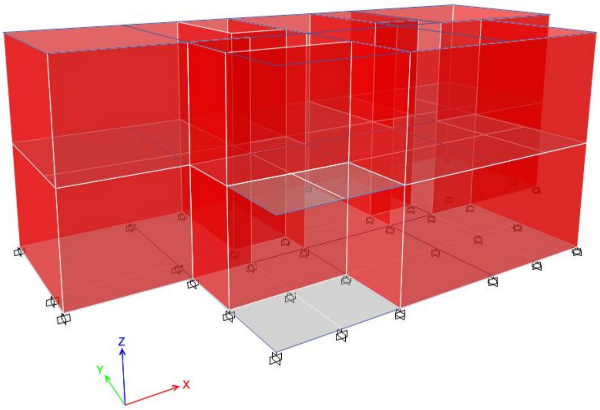


Fig-7: FE model of the masonry building with fixed base

Table-5: Material properties of stone masonry

Material properties	Value (MPa)
Young's modulus, E_m	1,247
Shear modulus, G_m	499
Compressive strength, f'_m	2.27
Tensile strength, f_t	0.1

The prototype masonry building is analysed for gravity load and horizontal load from earthquake induced ground motion. The gravity load includes the weight of building and superimposed dead load put on floors. Earthquake time history data of El Centro is used to define ground acceleration as shown in Fig-8. The seismic assessment of the isolated building is performed through non-linear dynamic time history analyses.

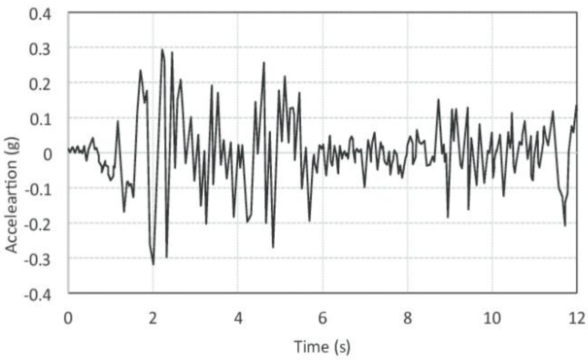


Fig-8: Time history data of El Centro earthquake

In order to evaluate the effectiveness of base isolation, simulation of the building is performed for fixed base and base isolated conditions. For the fixed base building, all nodes at ground level are fixed in all directions. However, for the base isolated building, 14 isolators are placed at locations as per Fig-6. Isolators are modelled as equivalent multi-linear plastic link. Table-6. shows the input parameters of link element. For simulation of unbonded isolators, the nonlinear force deformation behaviour is modelled through the Degrading hysteresis loop. A three-dimensional FE model of masonry building with base isolators is shown in Fig-9.

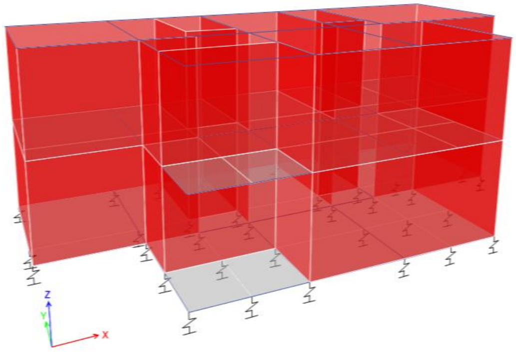


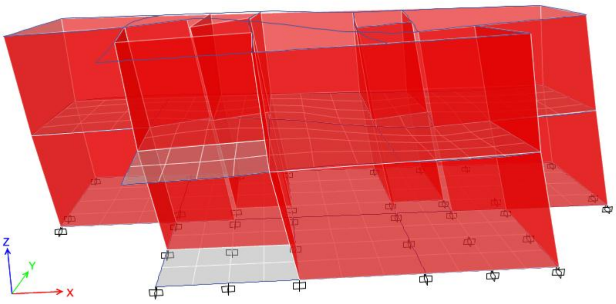
Fig-9: FE model of the base-isolated masonry building

Table-6: Properties of link element

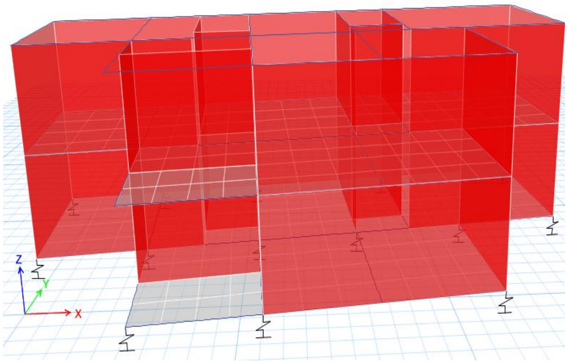
Vertical Stiffness = 2180 kN/mm	
Multilinear plastic link	
Force [kN]	Displacement [mm]
-64	-150
-48	-100
-24	-50
0	0
24	50
48	100
64	150

6. RESULTS AND DISCUSSIONS

To evaluate the performance of the proposed hybrid isolation system with a sufficient insight, time-history analyses have been performed on a real prototype of a two-storied masonry building in India. The first mode of vibration of the fixed base and base isolated buildings is shown in Fig-10.



(a)



(b)

Fig-10: First mode of vibration for FB and BI building models: (a) FB building; (b) BI building

Results show that superstructure of the model with UFREI-SMA hybrid base isolator is observed to have undergone rigid body motion and hence experiences insignificant inter-storey drift. The behaviour of base isolated building model under all the condition is observed to be stable with no distress in either building or in the isolators.

6.1 Time Period

The fundamental time period of the fixed base building is 0.121s and that of base isolated building is obtained as 2.328s. Increased time period reduces response of earthquake and at the same time it reduces base shear. Thus the application of UFREI and SMA system significantly increases the fundamental period considerably reducing the seismic demand on the building.

6.2 Base Shear

The base shear obtained is 762 kN for fixed base and 463 kN for base isolated building. Thus it is observed that base shear of fixed base building is more than base isolated building. Base isolation increases the flexibility of the building and hence less seismic energy is transmitted to the base of the building which results in decreased base shear.

6.3 Storey Displacement

Table-7. shows the storey displacement for fixed base and base isolated building. From the result, it is observed that the storey displacement for the building with fixed base increases linearly and displacement of base isolated building is more than the fixed base building. Chart-5 shows the variation of storey displacement for fixed base and base isolated building along X axis and Chart-6 shows the variation of storey displacement for fixed base and base isolated building along Y axis.

Table-7: Comparison of Storey displacement

Storey height (m)	Storey Displacement (mm)			
	Fixed base		Base isolated	
	X	Y	X	Y
0	0	0	12.8	45.6
3	12.29	32	12.8	50.2
6	24.93	45	12.8	56.4

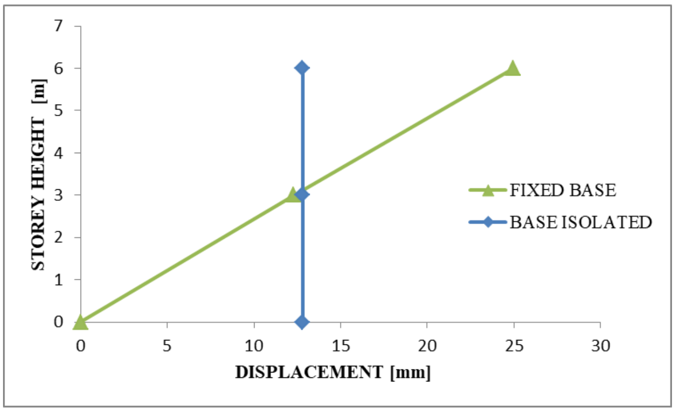


Chart-5: Variation of storey displacement for fixed base and base isolated building along X axis

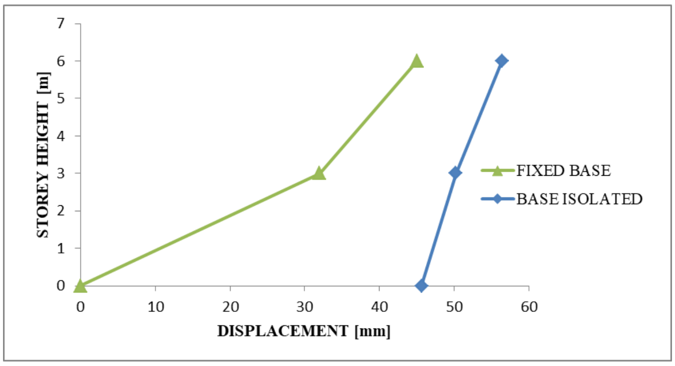


Chart-6: Variation of storey displacement for fixed base and base isolated building along Y axis

7. CONCLUSIONS

This study establishes the effectiveness of a hybrid isolation system consisting of unbonded fiber reinforced elastomeric isolators and shape memory alloy wires as additional dissipative device in controlling the seismic response of low-rise masonry buildings under seismic excitation. Detailed 3D FE model are developed and cyclic shear analyses are carried out to characterize the response of UFREI. The behaviour of SMA is described using Auricchio's constitutive model implemented in a user-defined material subroutine that is available in the software package ABAQUS. A two story masonry building supported on 14 U-FREIs located in Tawang and representative of a common building typology in many parts of the north eastern zone of India is selected to evaluate seismic vulnerability underground motions. Three dimensional FE models are simulated for both fixed base and base isolated building, and non linear time history analyses are carried out for both buildings. The results have clearly shown that a base isolation system using U-FREI and SMA can significantly decrease the damage caused by a seismic event to a masonry structure.

The concluding remarks are as follows:

- The unbonded isolators showed stable rollover deformed shape at higher displacement.
- UFREI-SMA hybrid isolation system has horizontal stiffness slightly greater than UFREI.
- Results show that addition of the SMA increased the energy dissipation capacity of the isolation system which is advantageous with respect to base isolation.
- Base isolated models showed reduced base shear compared to fixed base building.
- Time period of the structure is increased by the use of hybrid isolation system which reduces the transfer of lateral forces at the time of earthquake.
- Thus results show that the responses of structures can be reduced by the use of the hybrid isolator of UFREI and SMA system.
- It can be concluded that the proposed UFREI-SMA hybrid base isolation system is a promising and effective isolation system.

ACKNOWLEDGEMENT

I express my sincere gratitude to Dr. Alice Mathai, Professor Department of Civil Engineering, M.A. College of Engineering, Kothamangalam for her timely guidance and support for taking up this project work.

REFERENCES

[1] James M. Kelly. "Analysis of Fiber-Reinforced Elastomeric Isolators." Journal of Seismology and Earthquake Engineering, 1999: Vol 2.

[2] Moon BY. "Design and manufacturing of fiber reinforced elastomeric isolator for seismic isolation." Journal of Materials Processing Technology, 2002: pp 140-150.

[3] Nezhad HT. "Bonded versus unbonded strip fiber reinforced elastomeric isolators." Journal of Composite Structures, 2011: pp 850-859.

[4] Ahmad B. Habieb. "Seismic Performance Of a Masonry Building Isolated With Low-cost Rubber Isolators." Journal of Earthquake Resistant Engineering Structures, 2017: Vol 172.

[5] Van Ngo Thuyet." Mitigation of Seismic Vulnerability of Prototype Low-Rise Masonry Building Using U-FREIs." Journal of Performance of Constructed Facilities, 2018: Vol 32.

[6] E. Choi. "An isolation bearing for highway bridges using shape memory alloys." Journal of Materials Science and Engineering , 2005: pp 181-184.

[7]Animesh Das. "Modeling of Fiber-Reinforced ElastomericBase Isolators." Journal of Earthquake Engineering & Structural Dynamics, 2016: pp 1239-1262.

[8] Ahmad Basshofi Habieb." Base seismic isolation of a historical masonry church using fiber reinforced elastomeric isolators." Journal of Soil Dynamics and Earthquake Engineering, 2019: pp 127-145.

[9] Ahmad Basshofi Habieb." Hybrid seismic base isolation of a historical masonry church using unbonded fiber reinforced elastomeric isolators and shape memory alloy wires." Journal of Soil Dynamics and Earthquake Engineering, 2019.

[10] Auricchio F, "A robust integration-algorithm for a finite-strain shape-memoryalloy superelastic model," Int. J. Plast., vol. 17, no. 7, pp. 971–990, 2001.