

# EFFECT OF SHEAR MODULUS ON THE PERFORMANCE OF PROTOTYPE UN-BONDED FIBER REINFORCED ELASTOMERIC ISOLATORS

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## Abstract

Un-bonded fiber reinforced elastomeric isolator (U-FREI) is light weight and facilitates easier installation in comparison to conventional steel reinforced elastomeric isolators (SREI), in which fiber layers are used as reinforcement to replace steel shims as are normally used in conventional isolators. Shear modulus of elastomer has significant influence on the force-displacement relationship of U-FREI. However, a few studies investigated the effect of shear modulus on the horizontal behavior of prototype U-FREI in literature. In this study, effect of shear modulus on performance of prototype U-FREIs is investigated by both experiment and finite element (FE) analysis. It is observed that reduction in horizontal stiffness of U-FREI with increasing horizontal displacement is due to both rollover deformation (or reduction in contact area of isolator with supports) and shear modulus of elastomer. Reasonable agreement is observed between the findings from experiment and FE analysis.

*Keywords:* base isolator; prototype un-bonded fiber reinforced elastomeric isolator; rollover deformation; shear modulus; cyclic test.

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## 1. Introduction

Base isolation is an efficient and viable method to reduce the vulnerability of structure in high seismic risk zone. Earthquake energy transmitted to the structure can be reduced by lengthening the fundamental horizontal period of structure. Base isolators are installed in between substructure and superstructure to achieve the desired horizontal period of structure. Conventional steel reinforced elastomeric isolators (SREIs) consist of alternating layers of rubber bonded to intermediate steel shims with two steel end plates at top and bottom. In general, SREIs are often applied for large, important buildings like hospitals and emergency centers, in developed countries such as United States, Japan, New Zealand, Italy, etc. This limited use is largely due to high material, manufacturing and installation costs. It is expected that the use of seismic isolators can be extended to ordinary low-rise and medium-rise buildings if the weight and cost of the isolators are reduced. In view of this, fiber reinforced elastomeric isolators (FREIs) are proposed by replacing steel shims in conventional isolators by multi-layer of fiber fabric as reinforcement sheets to reduce their weight and cost. An un-bonded fiber reinforced elastomeric isolator (U-FREI) is a significant effort to improve FREI by removing two steel end plates and installing directly between the substructure and superstructure without any connection

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to these boundaries. Using U-FREI would reduce the weight and cost, easier installation, and can be made as a long strip and then easily cut to the required size. It means that the U-FREIs can be used for low-rise and medium-rise buildings subjected to earthquake loading in the developing countries like Vietnam, Indonesia, Taiwan, Nepal, etc.

Some studies were conducted in recent time for obtaining the mechanical characteristics of FREIs leading to better understanding of their behavior. Kelly and Takhirov [1] studied the mechanical properties of U-FREIs by theoretical and experimental analysis. Toopchi-Nezhad et al. [2] carried out experimental study to investigate the lateral behavior of U-FREI. Strauss et al. [3] presented experimental tests to evaluate shear modulus and damping coefficient of elastomeric bearings with various reinforcing materials and under various loadings, support conditions. Dezfuli and Alam [4] prepared scaled U-FREIs with different initial shear moduli, number of elastomer layers, number of fiber layers, thickness of elastomer layers and experimentally evaluated the vertical and horizontal response of U-FREIs. Ngo et al. [5, 6] studied the horizontal stiffness and the effect of horizontal loading direction on performance of square U-FREI by both experiment and finite element (FE) analysis.

These studies indicate that the behavior of elastomeric isolators is affected by some factors such as material properties, sizes and shapes, loadings and directions of loading, friction between the surfaces of U-FREI and support areas, etc. An effort to study the effect of shear modulus on the behavior of elastomeric isolators was conducted by Strauss et al. [3]. They conducted laboratory tests to study the effect of shear modulus of scaled bonded FREI as well as SREI of various dimensions, under good combinations of vertical load and cyclic horizontal displacement up to  $1.0t_r$  ( $t_r$  is the total thickness of elastomer/rubber layers of isolator). Dezfuli and Alam [4] evaluated experimentally the reduction in effective shear modulus of scaled U-FREIs with increasing horizontal displacement up to  $1.0t_r$ . The effect of shear modulus on horizontal response of U-FREI specimens in [4] is not clear because of different sizes and shape factors of these specimens. It is necessary to study the effect of shear modulus on the response of U-FREIs with the same sizes and shape factors under the action of larger horizontal displacement. Further, most of previous studies were carried out on scaled models of U-FREIs with relatively low shape factor (less than 10). According to Naeim and Kelly [7], shape factor ( $S$ ) is defined as the ratio of the loaded area to load free area of an elastomer layer. Range of shape factor values of typical isolators for seismic isolation is from 10 to 20 [7]. Thus, the effect of shear modulus on horizontal response of prototype U-FREIs with high shape factors should be studied. This will have huge significance in design and production of prototype isolators for field application.

This study investigates the performance of prototype U-FREIs under cyclic loading by both experiments and FE analysis. In experiments, four prototype specimens with the same sizes in plan and two different values of shear modulus are produced, and then the characteristic properties including the horizontal stiffness as well as the energy dissipation capacity and the equivalent viscous damping are assessed. These specimens are tested under the same constant vertical pressure and cyclic horizontal displacement up to  $0.89t_r$ . In addition, the investigation of the behavior of isolators could be done up to very large applied horizontal displacements of  $1.50t_r$  using FE method. Numerical results are validated with experimental findings for cyclic horizontal displacement up to  $0.89t_r$ , a limit considered from the requirement of safety of the test set up during actual experiment. From experimental and numerical results, effects of shear modulus on the behavior of prototype U-FREIs are evaluated.

## 2. Details of test specimens

Specimens are produced to use in an actual building in India with the support of METCO Pvt. Ltd., Kolkata, India. Four specimens are manufactured by vulcanizing elastomer layers and bi-directional

(0°/90°) carbon fiber fabric. Two long strips of laminated pads with two different values of initial shear modulus are made from eighteen elastomer layers interleaved with seventeen carbon fiber fabric layers. Strip with initial shear modulus,  $G$  as 0.78 MPa is designated as type  $A$ , while similar such strip with value of  $G$  as 0.90 MPa is designated as type  $B$ . The thickness of each elastomer layer is 5 mm, while that of each fiber layer is 0.55 mm and total height of each bearing is 100 mm. Subsequently, four specimens (including of two specimens from sheet type  $A$ , denoted as isolator  $A_{(1,2)}$  and two specimens from sheet type  $B$ , denoted as isolator  $B_{(1,2)}$ ) are cut to squared size of  $250 \times 250 \times 100$  mm. A typical view of a prototype isolator with layer details is shown in Fig. 1. The shape factor of these isolators are  $S = 12.5$ , which is significantly higher than those of model FREIs used in most of the previous investigations. Geometrical details and material properties of the isolators are shown in Table 1.

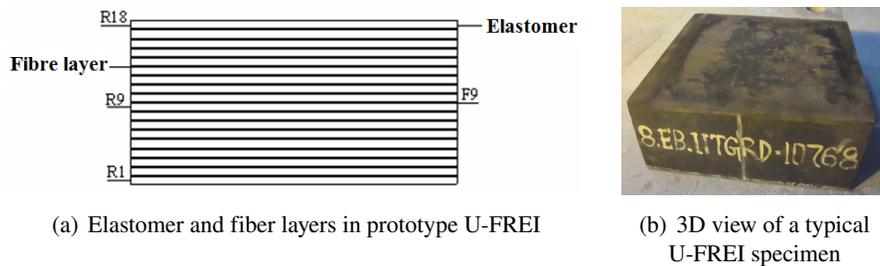


Figure 1. Details of prototype U-FREI specimen

Table 1. Geometrical details and material properties of prototype U-FREI

Description Isolator	$A_{(1,2)}$	Isolator $B_{(1,2)}$
Size of specimen, (mm)	$250 \times 250 \times 100$	$250 \times 250 \times 100$
Number of elastomer layer, $n_e$	18	18
Thickness of single elastomer layer, $t_e$ , (mm)	5.0	5.0
Total height of elastomer, $t_r$ , (mm)	90	90
Number of carbon fiber layer, $n_f$	17	17
Thickness of single fiber layer, $t_f$ , (mm)	0.55	0.55
Shape factor, $S$	12.5	12.5
Shear modulus of elastomer, $G$ , (MPa)	0.78	0.90
Elastic modulus of carbon fiber laminate, $E$ , (GPa)	40	40
Poisson's ratio of carbon fiber laminate, $\mu$	0.20	0.20

### 3. Experimental investigations

#### 3.1. Experimental set-up

All specimens are tested at Structural Engineering Laboratory, Indian Institute of Technology (IIT) Guwahati, India under simultaneous action of a constant vertical load and horizontal varying cyclic displacement. The experimental test setup is shown in Fig. 2. A couple specimen is put one above the other and separated by a steel spacer block. The bearing specimens are in contact with the

upper and lower surfaces of the steel block. However, these bearings are without any physical connection to the surfaces of the steel block and hence mimic the un-bonded condition. A horizontally placed servo-hydraulic actuator (make: MTS USA) is connected to the steel block for the application of cyclic displacements to the assembly. A constant design vertical load of 350 kN (or a constant vertical pressure of 5.6 MPa) is applied using hydraulic jack from a compression testing machine, where the assemblage of bearings and steel block is housed. The magnitudes of vertical loads correspond to factored column loads and the values are obtained from the analysis of the actual building.

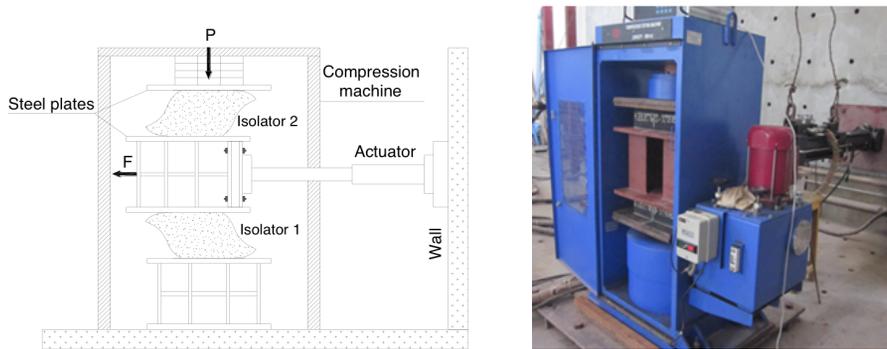


Figure 2. Schematic representation and actual experimental set-up

### 3.2. Details of input displacement history

The experimental investigations are carried out by subjecting the isolator under cyclic displacement, while maintaining a constant vertical pressure on the isolator. Three cycles of sinusoidal displacement of frequency  $f = 0.025$  Hz are applied continuously for four levels of displacement amplitudes as 20 mm ( $0.22t_r$ ), 40 mm ( $0.44t_r$ ), 60 mm ( $0.67t_r$ ) and 80 mm ( $0.89t_r$ ) as shown in Fig. 3. The experimental investigation of the behavior of U-FREIs is performed up to the applied horizontal displacement of 80 mm, considering the overall safety of test set-up. All specimens in this study are used in an actual building in India after being tested. Thus, specimens are tested with the maximum value of applied horizontal displacement of 80 mm to keep specimens from any damage. Horizontal displacement and corresponding horizontal forces are measured using in-built linear variable differential transformer (LVDT) and load cell of the actuator.

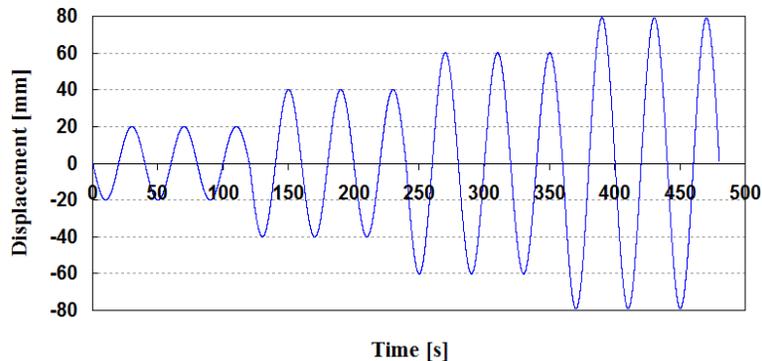


Figure 3. Applied horizontal displacement history

### 3.3. Experimental results

#### a. Deformed shape

Deformed shape of a typical specimen as obtained from experimental tests at 80 mm amplitude of horizontal displacement is shown in Fig. 4. The top and bottom surfaces of U-FREI exhibit stable roll off the contact surfaces without any damage. The reduction in contact area due to rollover deformation leads to the reduction in effective horizontal stiffness of isolators and results nonlinear behavior of elastomer at large displacement.



Figure 4. Deformed shape of U-FREI specimen at applied horizontal displacement of 80 mm

#### b. Hysteresis loops

The hysteresis loop of an isolator represents the relationship between shear forces and cyclic horizontal displacements. The horizontal displacements and shear forces experienced by the U-FREIs are measured by LVDT and load cells respectively, which are built-in the servo-hydraulic actuator. Further, the recorded shear forces actually represent the applied forces on two specimens tested simultaneously and hence, the hysteresis plot is obtained by dividing these measured forces by two to evaluate the shear forces on one specimen in average sense. Fig. 5 shows such hysteresis loops of different tested specimens considered in this study.

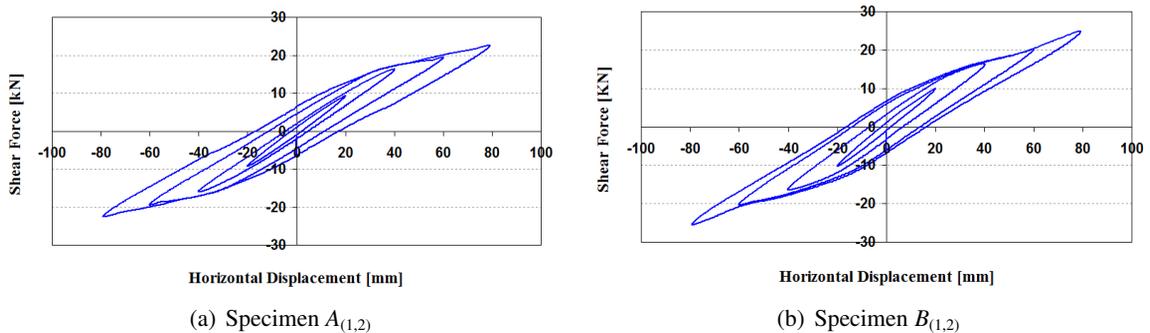


Figure 5. Hysteresis loops of different specimens from experimentally observed data

#### c. Mechanical properties of the U-FREIs

Two important parameters such as effective horizontal stiffness and equivalent viscous damping (or damping factor) are obtained from the hysteresis loops. The effective horizontal stiffness of an isolator at any amplitude of horizontal displacement is defined as International Building Code [8]:

$$K_{eff}^h = \frac{F_{max} - F_{min}}{u_{max} - u_{min}} \quad (1)$$

where  $F_{max}$ ,  $F_{min}$  are maximum and minimum values of the shear force;  $u_{max}$ ,  $u_{min}$  are maximum and minimum values of the horizontal displacement.

The equivalent viscous damping of isolator ( $\beta$ ) is computed by measuring the energy dissipated in each cycle ( $W_d$ ), which is the area enclosed by the hysteresis loop. The magnitude of  $\beta$  is computed as:

$$\beta = \frac{W_d}{2\pi K_{eff}^h \Delta_{max}^2} \quad (2)$$

where  $\Delta_{max}$  is the average of the positive and negative maximum displacements,  $\Delta_{max} = (|u_{max}| + |u_{min}|) / 2$ .

Effective horizontal stiffness and equivalent viscous damping of these isolators at different horizontal displacement amplitudes are furnished in Table 2. It can be seen from Table 2 that the effective horizontal stiffness of an U-FREI decreases, while the equivalent viscous damping increases with the increase in horizontal displacement. The decreases in effective stiffness corresponding to increase in amplitude of horizontal displacement from 20 to 80 mm are found to be 39.1%, 37.2% for specimen  $A_{(1,2)}$ ,  $B_{(1,2)}$ , respectively. These reductions are due to rollover deformation, which will result in an increase in time period of the base isolated structure leading to increase in their seismic response control efficiency.

Table 2. Experimentally evaluated mechanical properties of U-FREIs

Amplitude (mm)	$u/t_r$	Isolator $A_{(1,2)}$		Isolator $B_{(1,2)}$	
		$K_{eff}^h$ (kN/m)	$\beta$ (%)	$K_{eff}^h$ (kN/m)	$\beta$ (%)
20	0.22	464.26	5.18	507.26	5.00
40	0.44	403.41	6.94	410.21	9.67
60	0.67	324.22	11.15	339.01	12.02
80	0.89	282.60	11.83	318.68	10.02

#### 4. FE analysis

FE analyses of these isolators are also conducted under simultaneous action of constant vertical pressure and cyclic horizontal displacement by ANSYS v.14.0. FE analysis is used to simulate the behavior of these isolators up to very large horizontal displacement amplitude of  $1.50t_r$ , although experimental investigation is carried out for horizontal displacement amplitude up to  $0.89t_r$  because of practical constraint. Loading protocol considered in FE analysis is similar to that considered in experimental investigation. The comparison of results from numerically simulated model and experimental observations is performed to assess the accuracy of FE analysis.

##### 4.1. Element type for FE model

In the FE model of U-FREIs, the elastomer and fiber reinforcement are modeled using SOLID185, SOLID46 respectively. Two rigid horizontal plates are considered at the top and bottom of the isolator to represent the superstructure and substructure. Vertical load and horizontal displacement are applied at the top plate, while all degrees of freedom of bottom plate are constrained.

In order to study U-FREI, contact element CONTA173 is used to define the exterior elastomer surfaces and target element TARGE170 is used to define the interior surface of top and bottom rigid plates. The model is meshed with hexagonal volume sweep.

#### 4.2. Material model

Material properties of U-FREI as shown in Table 1 are used in FE model. Elastomer is modeled with hyper-elastic and visco-elastic parameters. Ogden 3-terms model has been adopted to model the hyper-elastic behavior of the elastomer and the visco-elastic behavior is modeled by Prony Viscoelastic Shear Response parameter.

Ogden (3-term):  $\mu_1 = 1.89 \times 106 \text{ (N/m}^2\text{)}$ ;  $\mu_2 = 3600 \text{ (N/m}^2\text{)}$ ;  $\mu_3 = -30000 \text{ (N/m}^2\text{)}$ ;  $\alpha_1 = 1.3$ ;  $\alpha_2 = 5$ ;  $\alpha_3 = -2$ ;

Prony Shear Response:  $a_1 = 0.3333$ ;  $t_1 = 0.04$ ;  $a_2 = 0.3333$ ;  $t_2 = 100$ .

#### 4.3. Input loading

Similar to experimental tests, analyses of all U-FREIs are carried out under cyclic horizontal displacement, while maintaining a constant vertical pressure of  $p = 5.6 \text{ MPa}$  distributed on the top steel plate of the simulated model. Three fully sinusoidal cycles with increasing displacement amplitudes up to  $1.50t_r$  (135 mm) as shown in Fig. 3 are applied on the top steel plate.

#### 4.4. FE analysis results

##### a. Validation of FE model of U-FREIs

Deformed shape of U-FREI under horizontal displacement amplitude of 80 mm as obtained from FE analysis is shown in Fig. 6. The upper and lower faces of the U-FREI roll off the contact supports. The pattern of deformed configuration of U-FREI as observed during actual test (Fig. 4) agrees very well with Fig. 6 obtained from FE analysis.

Fig. 7 shows the hysteresis loops of U-FREIs under displacement up to 80 mm for data obtained from both FE analysis and laboratory tests. Comparison of the hysteresis loops of U-FREIs as obtained from experiments and FE analysis for each type shows the discrepancy to be quite less.

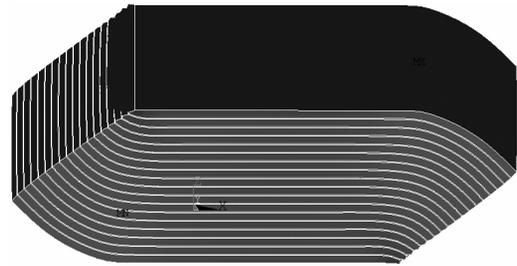


Figure 6. Numerically observed deformed shape of U-FREI under displacement amplitude of 80 mm

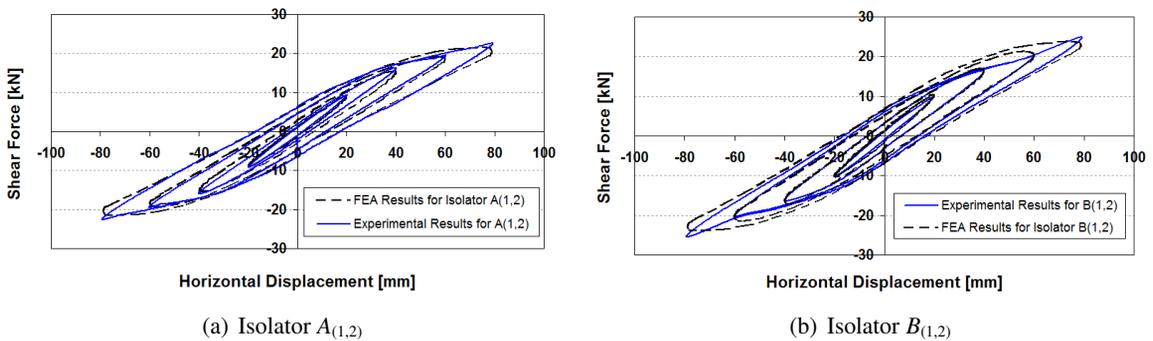


Figure 7. Comparison of hysteresis loops of different U-FREIs obtained from experiment and FE analysis

b. Mechanical properties of U-FREIs

Effective horizontal stiffness and equivalent viscous damping of all U-FREIs are calculated from Eqs. (1) and (2) and are presented in Table 3. The effective horizontal stiffness of U-FREIs obtained from FE analysis decreases with the increase in horizontal displacement. Specifically, the decreases in effective stiffness of U-FREIs  $A_{(1,2)}$ ,  $B_{(1,2)}$  are found to be 57.2%, 57.0% respectively in the displacement range of 20 mm to 135 mm. It can be observed from Tables 2 and 3 that reasonable agreement is observed in terms of mechanical properties of U-FREIs between the findings from experiment and FE analysis at displacements ranging from 20 mm to 80 mm. Hence, the results obtained by FE analysis for U-FREIs at even larger displacements (from 80 mm to 135 mm) will be considered as accurate. The accuracy of the FE analysis results are established for the considered problem.

Table 3. Mechanical properties of U-FREIs obtained from FE analysis

Amplitude (mm)	$u/t_r$	Isolator $A_{(1,2)}$		Isolator $B_{(1,2)}$	
		$K_{eff}^h$ (kN/m)	$\beta$ (%)	$K_{eff}^h$ (kN/m)	$\beta$ (%)
20.0	0.22	457.72	7.16	515.87	7.58
40.0	0.44	385.10	9.30	426.93	9.60
60.0	0.67	321.99	11.71	357.01	12.05
80.0	0.89	272.20	13.22	301.67	13.46
90.0	1.00	251.09	13.78	281.34	14.11
112.5	1.25	219.02	14.19	247.09	14.58
135.0	1.50	195.75	14.94	222.03	15.42

5. Effect of shear modulus on horizontal response of prototype U-FREIs

As discussed earlier, isolator  $A_{(1,2)}$  and  $B_{(1,2)}$  are made with same component layers and have same size of  $250 \times 250 \times 100$  mm. These U-FREIs are subjected to same vertical load of 350 kN and cyclic horizontal displacement. However, these isolators are having different shear moduli, where  $G = 0.78$  MPa for isolator A and  $G = 0.90$  MPa for isolator B. The response and characteristics of

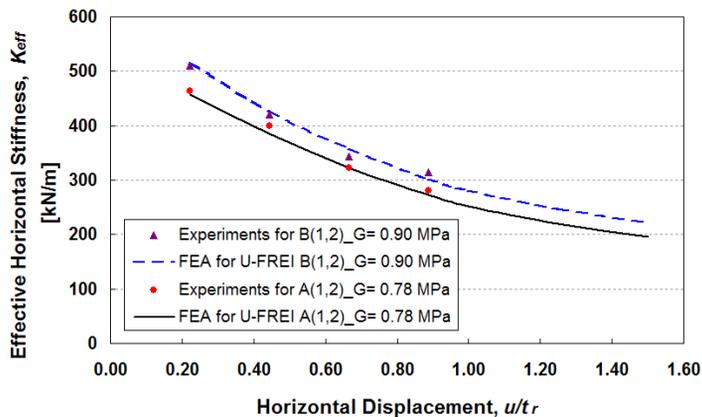


Figure 8. Effective horizontal stiffness versus displacement of different prototype U-FREIs

these isolators are compared to infer on the influence of shear modulus on isolators. Reduction in effective horizontal stiffness of U-FREI types *A* and *B* with increasing horizontal displacement as obtained from both experiments and FE analyses is shown in Fig. 8.

Due to rollover deformation, the area of these specimens in contact with the support surfaces decrease with the increase in horizontal displacement, thus resulting in the reduction in effective horizontal stiffness. It can be seen from Fig. 8 that at a given displacement, whereas the U-FREI types *A* and *B* are likely to have same area in contact with the supports, the horizontal stiffness of U-FREI decreases with the decrease in shear modulus. Thus, the decrease in horizontal stiffness of U-FREI with increasing horizontal displacement is not only due to rollover deformation through the decrease in area in contact with the supports, but also due shear modulus of isolator.

## 6. Conclusions

This paper presents experimental as well as numerical analysis of prototype U-FREIs under cyclic load. Experimental investigations are done up to a displacement limit and finding from FE analysis are validated. Evaluation of influence of shear modulus on the behavior of U-FREIs are studied. The concluding remarks are as follows:

- Due to rollover deformation, the effective horizontal stiffness of U-FREIs decreases with the increase in horizontal displacement, while the equivalent viscous damping increases. The decreases in effective horizontal stiffness of U-FREIs  $A_{(1,2)}$ ,  $B_{(1,2)}$  as obtained from experimental study are found to be 39.1%, 37.2% respectively in the displacement range of 20 mm to 80 mm; while those of U-FREIs  $A_{(1,2)}$ ,  $B_{(1,2)}$  as obtained from FE analysis are found to be 57.2%, 57.0% respectively in the displacement range of 20 mm to 135 mm.

- Reasonable agreement is found between the findings from experimental and FE analysis at displacements ranging from 20 mm to 80 mm. FE analysis can be adopted effectively to a very large range of displacement (135 mm), which may be otherwise difficult in experimental study.

- Reduction in horizontal stiffness of U-FREI with increasing horizontal displacement is due to both shear modulus and the contact area of the isolator with support surfaces.

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