North East Regional Conference on Earthquake and Landslide Mitigation-Building Disaster Resilience in North East India

Seismic Performance Evaluation of Un-bonded Fibre Reinforced Elastomeric Isolator (U-FREI)

Anjan Dutta

DEPARTMENT OF CIVIL ENGINEERING
IIT GUWAHATI

Other Members of the Research Group

1. Prof. S.K. Deb, IITG
2. Dr. Ngo Van Thuyet, Univ. of Hanoi (Former, R/S)
3. Dr. Animesh Das, BHEL, New Delhi (Former R/S)
4. Mr. A. Hazarika, Atkins, B'luru (Former PG Student)
5. Mr. K. Reddy, Former Undergraduate student

Supporting Staffs

1. Dr. Arun C. Borsaikia, SeniorTechnical Officer
2. Mr. Biswajit Debnath, Junior Tech. Supdt.

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Outline of the presentation

- Basic Concept of Base Isolation
- Design issues
- FE Simulation of Isolator
- Comparison of Experimental and FE Results
- Shake Table Testing of unreinforced masonry test model
- Prototype Implementation

Limitations of Conventional Design

- Conventional fixed base structures can not be realistically designed to remain elastic in large seismic events (more so in regions of high seismicity)
- Common practice is to design them so that they experience damage in a controlled manner and can undergo large inelastic displacements

Structural control devices: classification

- Base isolation systems
- Energy dissipation systems
- Tuned Systems

Passive System

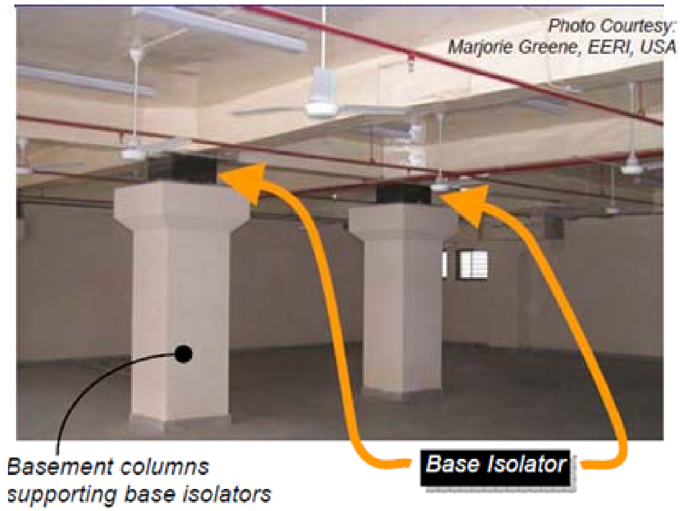
- Active control systems
- Semi-active systems
- Hybrid control systems

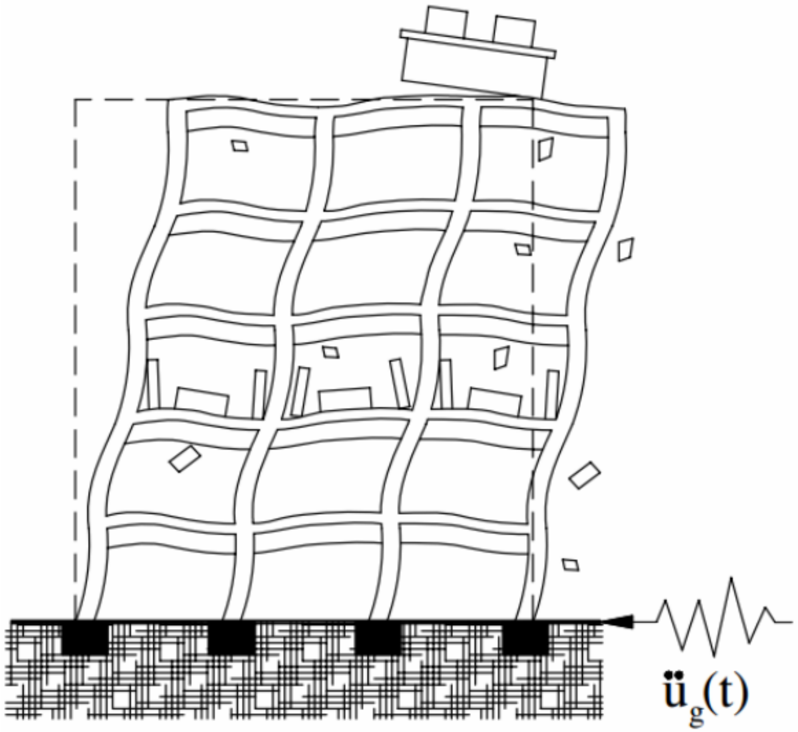
Active System

Seismic Base Isolation

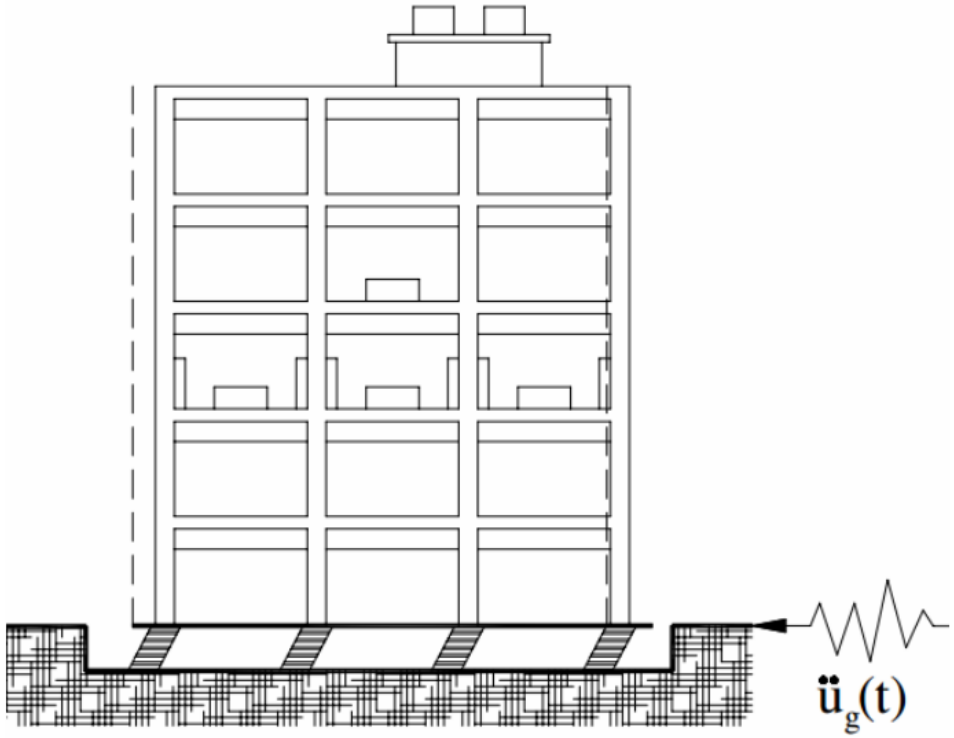
The objective of seismic isolation systems is to decouple the building structure from the damaging components of the earthquake input motion, i.e., to prevent the superstructure of the building from absorbing the earthquake energy.

The entire superstructure must be supported on discrete isolators whose dynamic characteristics are chosen to uncouple the ground motion





(a) Conventional structure



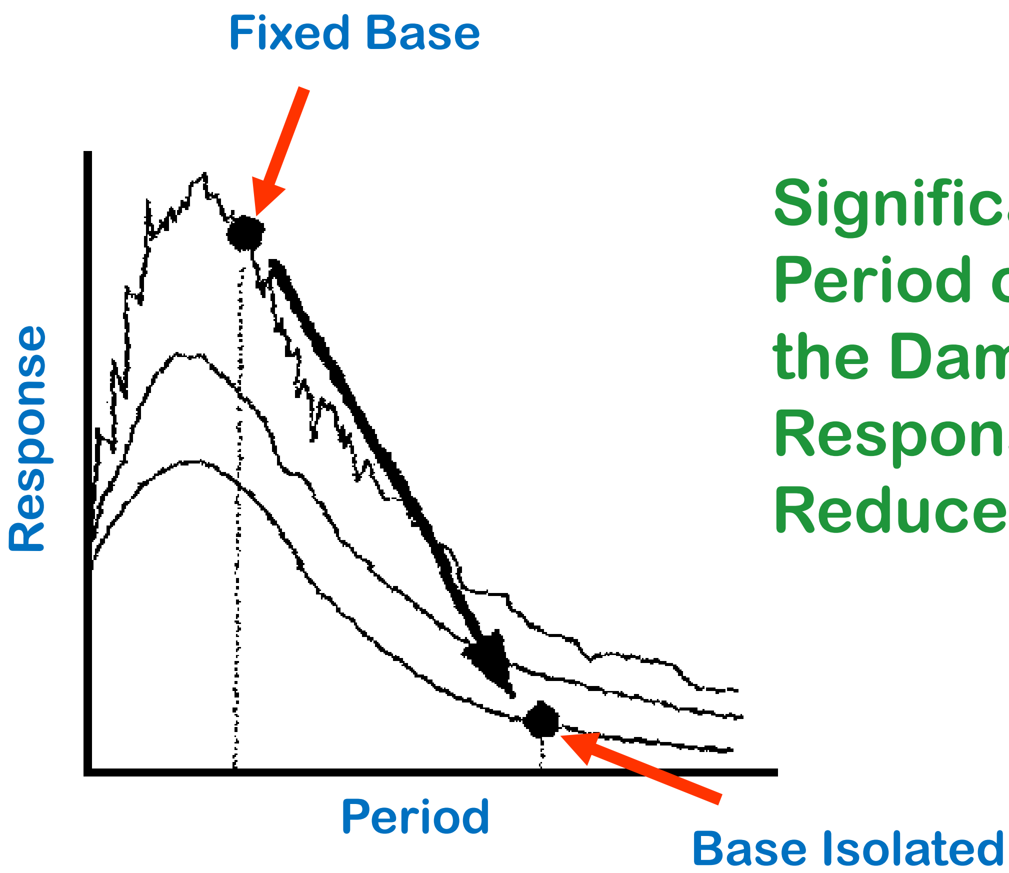
(b) Base-isolated structure

Suitability of Base Isolation Systems

Earthquake protection of structures using base isolation technique is generally suitable if following conditions are fulfilled:

- **The subsoil does not produce a predominance of long period ground motion**
- **The structure is fairly squat with sufficiently high column load**
- **The site permits large horizontal displacements at the base**
- **Lateral loads due to wind are less than approximately 10% of the weight of the structure**

Concept of Base Isolation



Significantly Increase the Period of the Structure and the Damping so that the Response is Significantly Reduced

Designs of Seismic Isolator

Natural frequency (f_n) of the base isolated model structure is given by:

$$f_n = \frac{1}{2\pi}\sqrt{\frac{K_H}{m_t}}$$

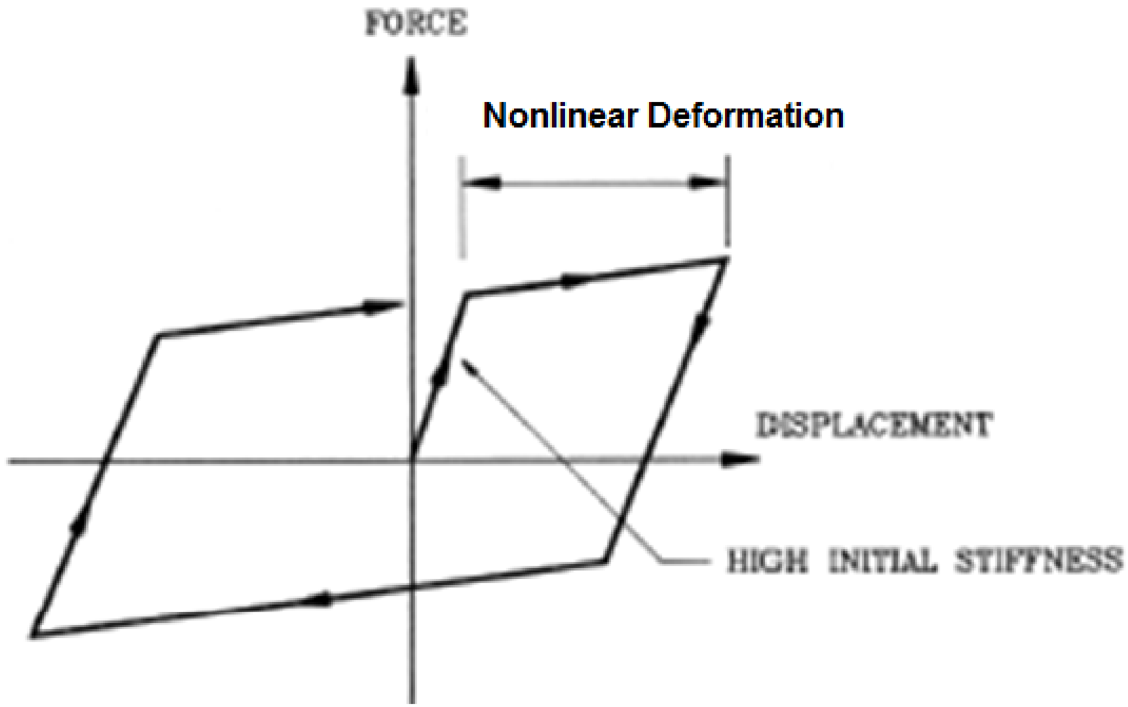
Horizontal stiffness of bearing:

$$K_h = \frac{K_H}{\text{Number of bearings}}$$

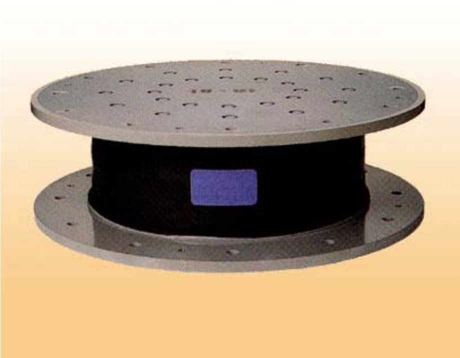
For (SREI), the horizontal stiffness is given by:

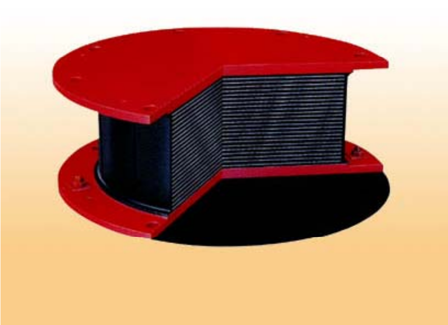
$$K_h = \frac{GA}{t_r}$$

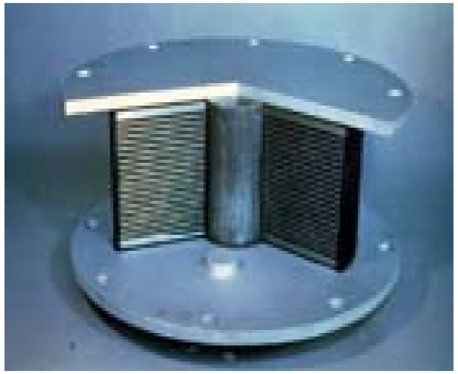
Idealized force-displacement hysteretic behavior of isolation system

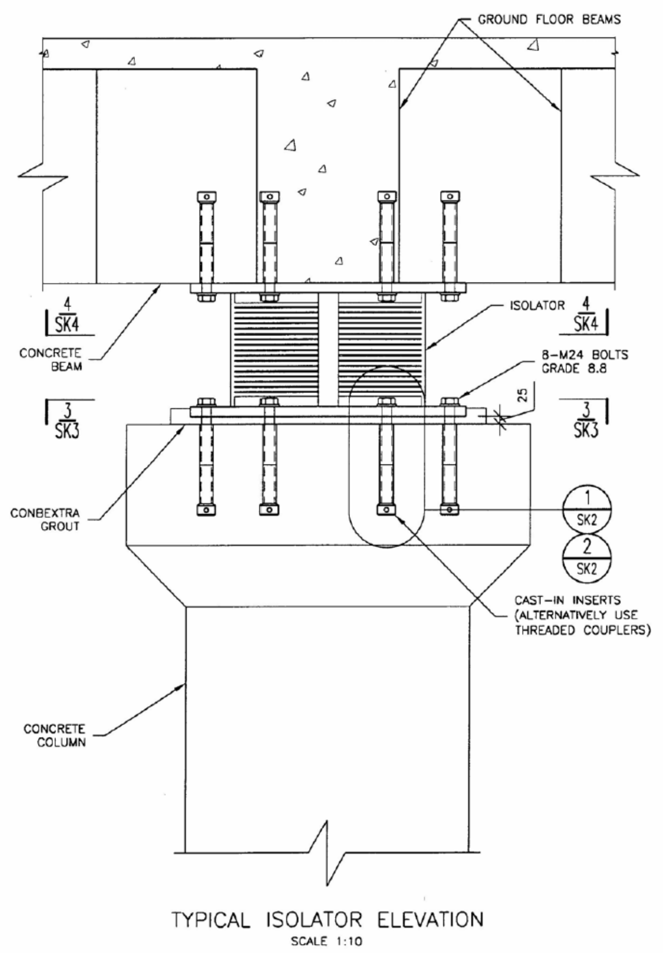


Conventional Laminated Rubber Seismic Isolation Bearings









Construction Details

Estimation of Displacement [ASCE / SEI: 7-10]

- **Minimum lateral displacement in each main horizontal direction**

$$D_D = \left[\frac{g}{4\pi^2}\right] S_{aD} T_{eD}^2 / B$$

$$\xi_{eD} = \frac{1}{2\pi}\left[\frac{A_{TD}}{K_{eD} D_D^2}\right]$$

$$T_{eD} = 2\pi\sqrt{\frac{W}{K_{eD}\, g}}$$

Design 5% damped elastic spectral acceleration parameter at T_{eD}

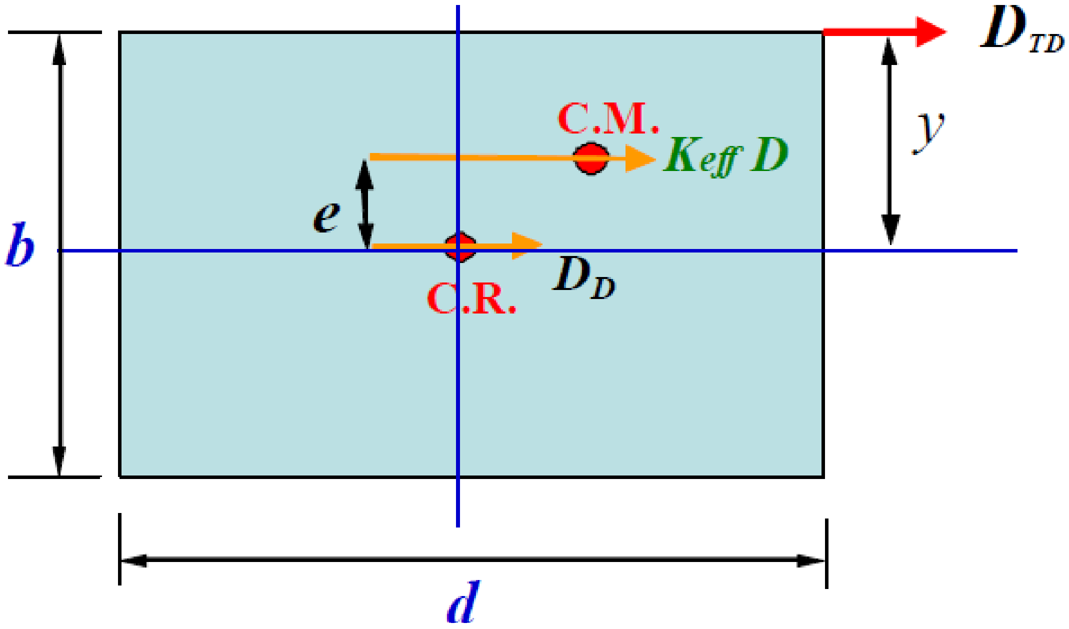
- **Maximum displacement in most critical direction**

$$D_M = \left[\frac{g}{4\pi^2}\right] S_{aM} T_{eM}^2 / B$$

$$\xi_{eM} = \frac{1}{2\pi}\left[\frac{A_{TM}}{K_{eM} D_M^2}\right]$$

$$T_{eM} = 2\pi\sqrt{\frac{W}{K_{eM}\, g}}$$

Maximum considered 5% damped elastic spectral acceleration parameter at T_{eM}



– **Total design displacement**

$$D_{TD} = D_D\left[1 + y\frac{12e}{b^2 + d^2}\right]$$

– **Total maximum displacement**

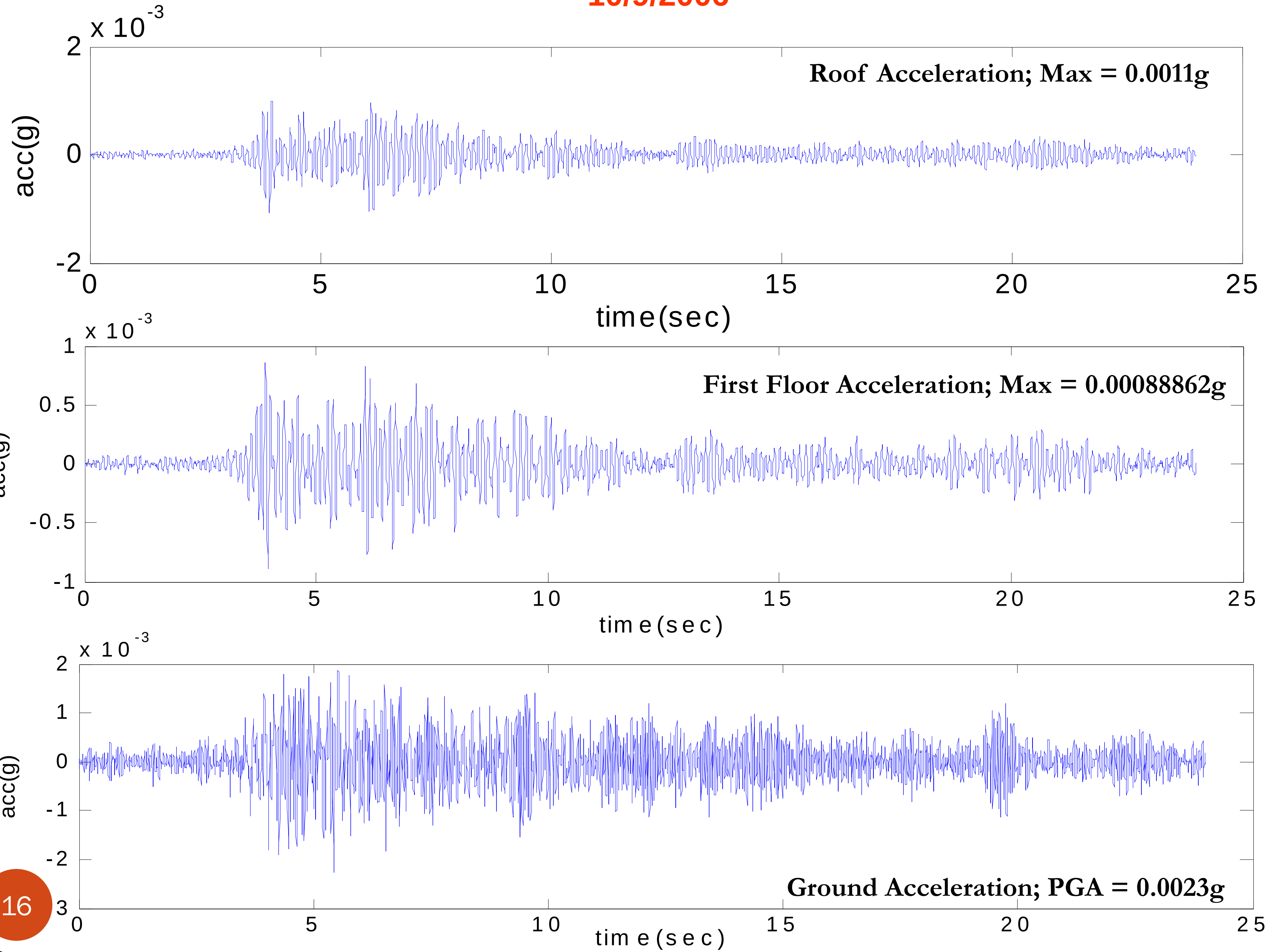
$$D_{TM} = D_M\left[1 + y\frac{12e}{b^2 + d^2}\right]$$

Constructed base isolated buildings

Non-Isolated Isolated

Sponsor of the project
BRNS, DAE, GOI

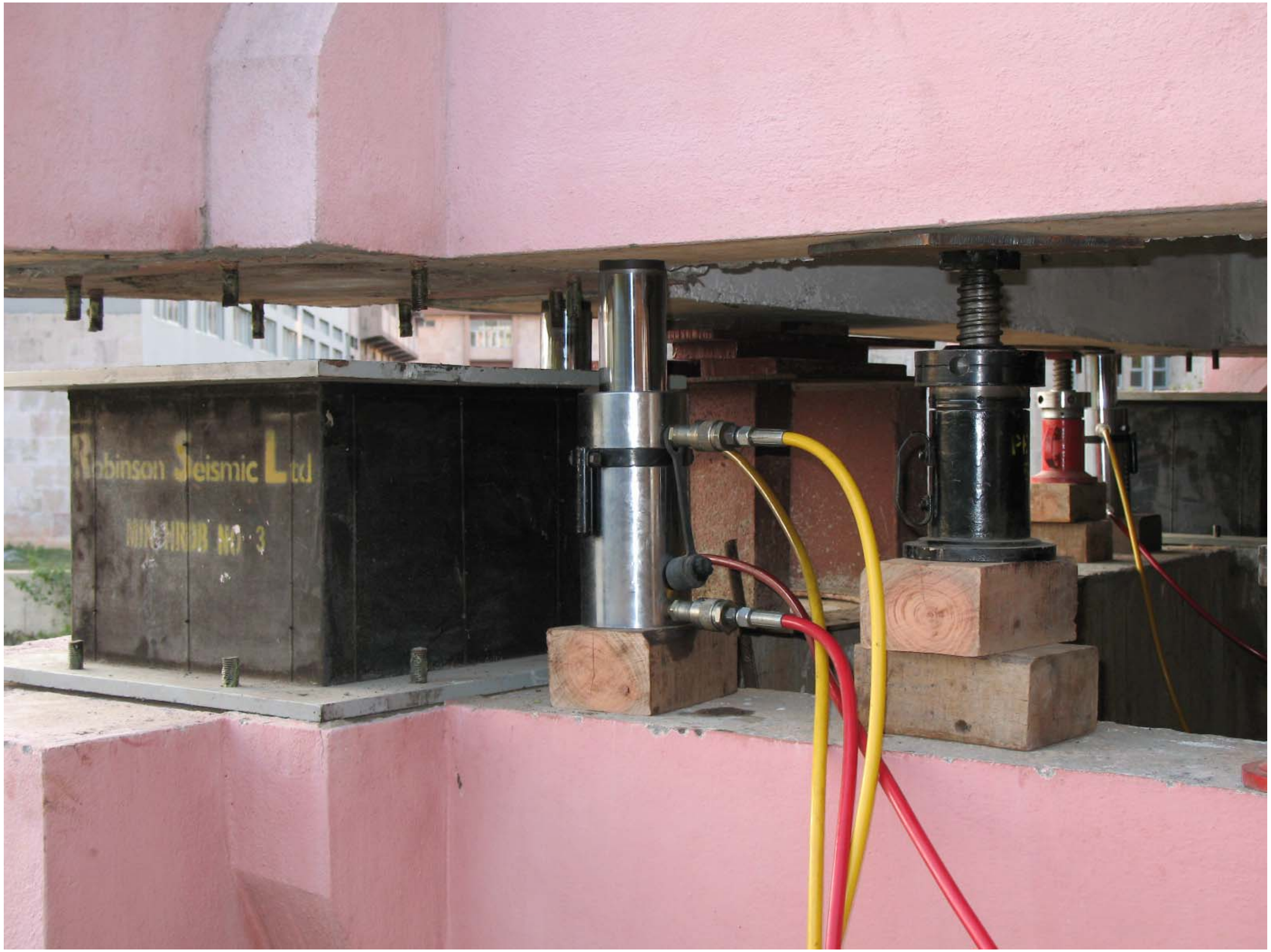
Base-Isolated Building: Time histories in X-direction recorded on 10/9/2006



Details of peak acceleration response reduction relative to PGA in base-isolated building (X-direction is longer direction of the building)

Event Date	PGA(g)		Percentage Reduction	
	X-direction	Y-direction	X-direction	Y-direction
10-09-2006	0.0023	0.0030	52	76
06-11-2006	0.0021	0.0030	20	53
10-11-2006	0.0037	0.0048	49	73

Nath, R.J., **Deb, S.K.** and Dutta, A. (2013), " Base isolated RC building – performance evaluation and numerical model updating using recorded earthquake response", ***Int. Journal of Earthquakes and Structures*** (Techno Press, Korea), Vol.4 (5), PP. 471-487.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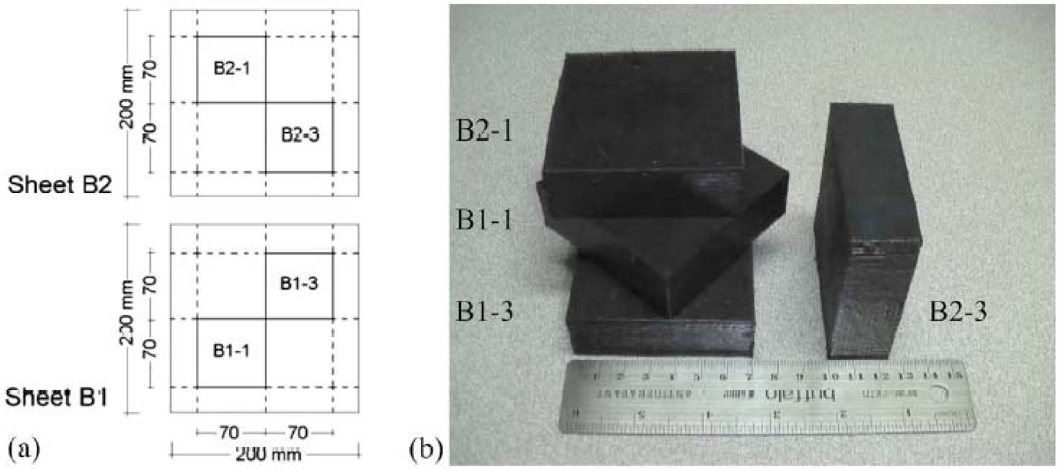
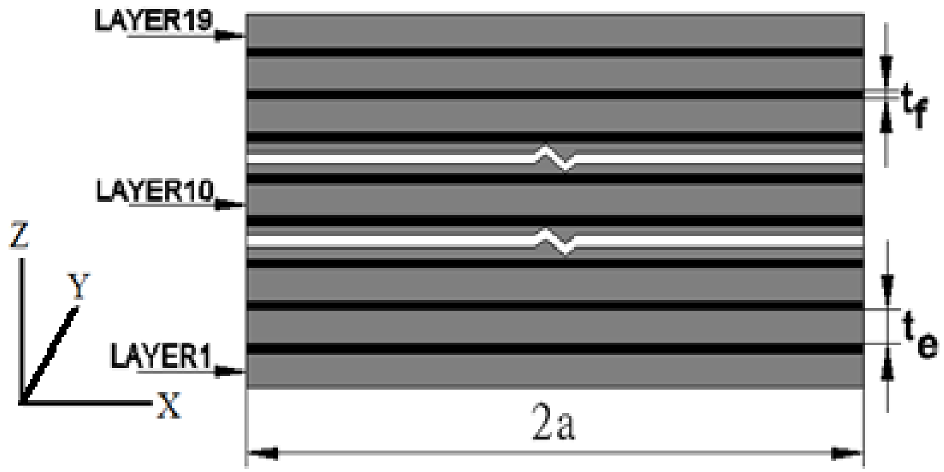
Fiber Reinforced Elastomeric Isolator (FREI)

Advantages:

- Use of fiber material reduces the weight
- Sand blasting, acid cleaning coating not required
- Manufacturing of long rectangular strip



Geometry of model FREI



Description		Square
Width (2a) of isolator	=	100 mm
Thickness of fiber layer (t_f)	=	0.55 mm
Number of layer	=	18
Thickness of single rubber layer (t_e)	=	5.0 mm
Number of rubber layer	=	19
Total Height (h)	=	104.90 mm

FE ANALYSIS OF FREI

- **Using ANSYS v.14.0**
- **Element type:**
  - Elastomer: SOLID185; Fibre: SOLID46;
  - Contact element: CONTA173; TARGE170;
- **Material model:**
  - Elastomer: hyper-elastic and visco-elastic behaviour.

    Hyper-elastic behaviour: Ogden 3-terms model

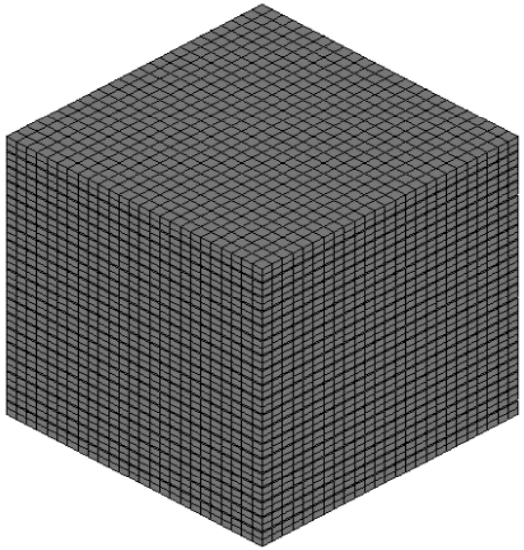
    $\mu_1 = 1.89\text{x}10^6$ (N/m^2); $\mu_2 = 3600$ (N/m^2);

    $\mu_3 = -30000$ (N/m^2);

    $\alpha_1 = 1.3$; $\alpha_2 = 5$; $\alpha_3 = -2$;

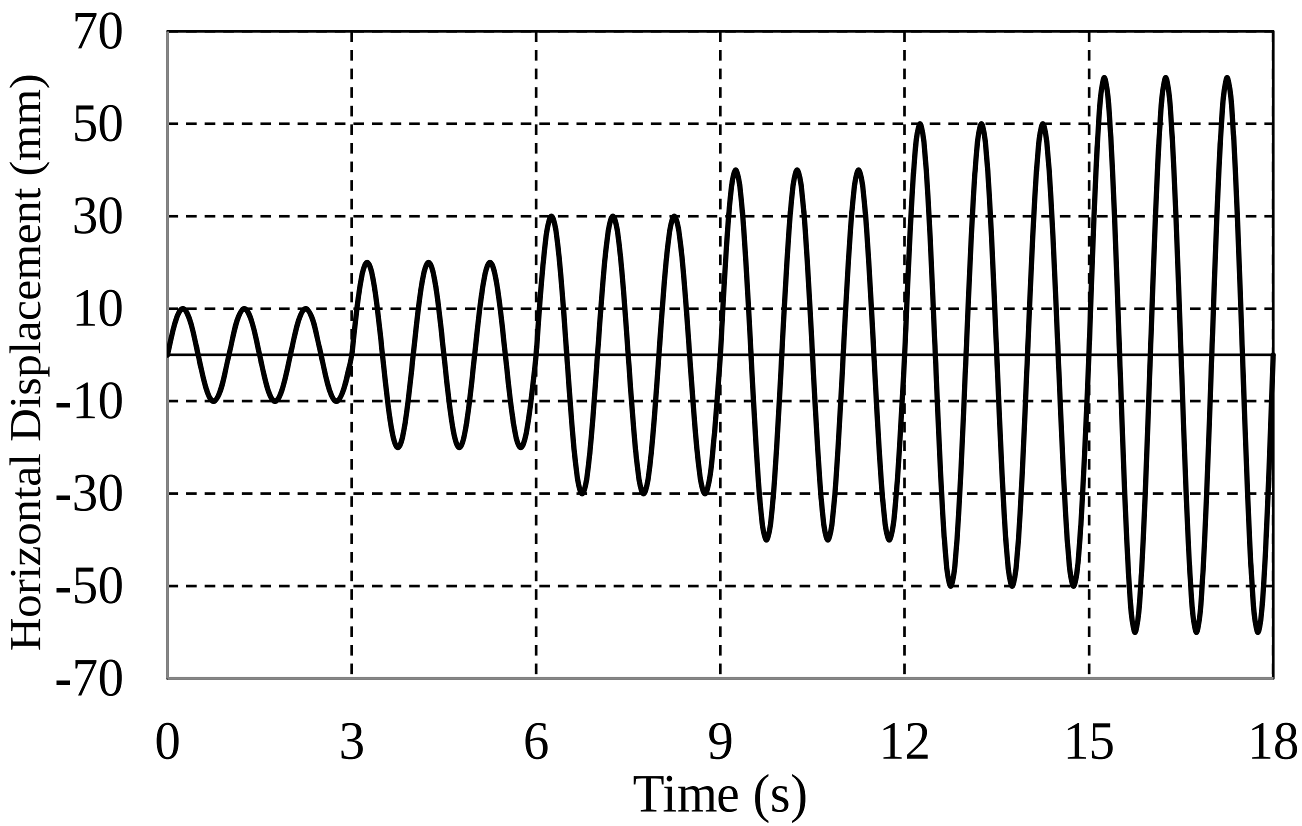
    Visco-elastic behaviour: Prony Visco-elastic Shear Response

    $a_1 = 0.3333$; $t_1 = 0.04$; $a_2 = 0.3333$; $t_2 = 100$.



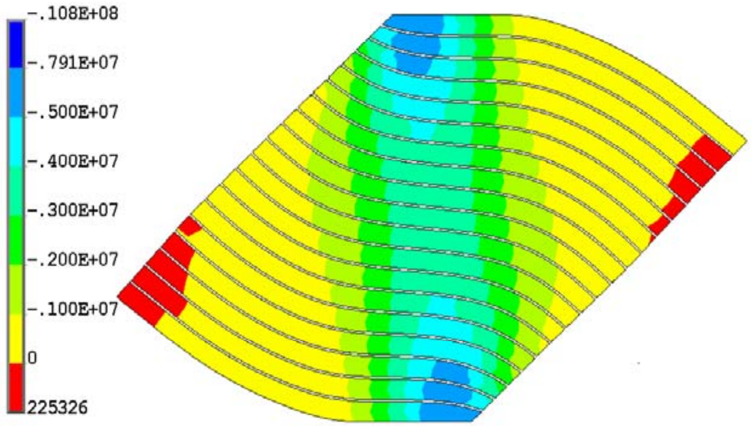
- Meshing

Imposed horizontal displacement history

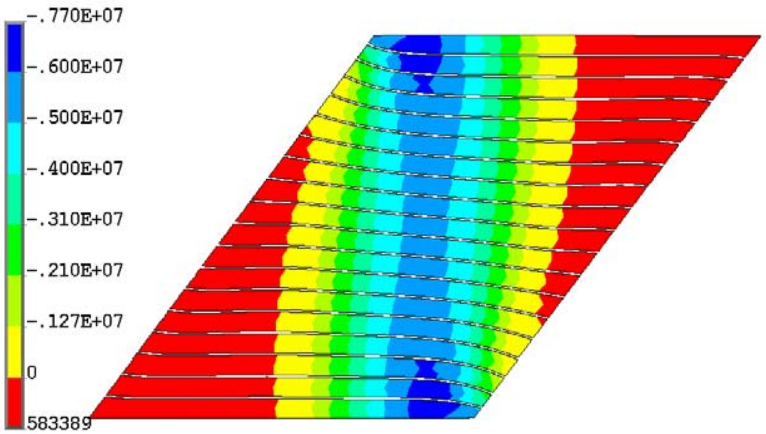


Stress Contour

❖ Square isolator with 0^0 loading direction



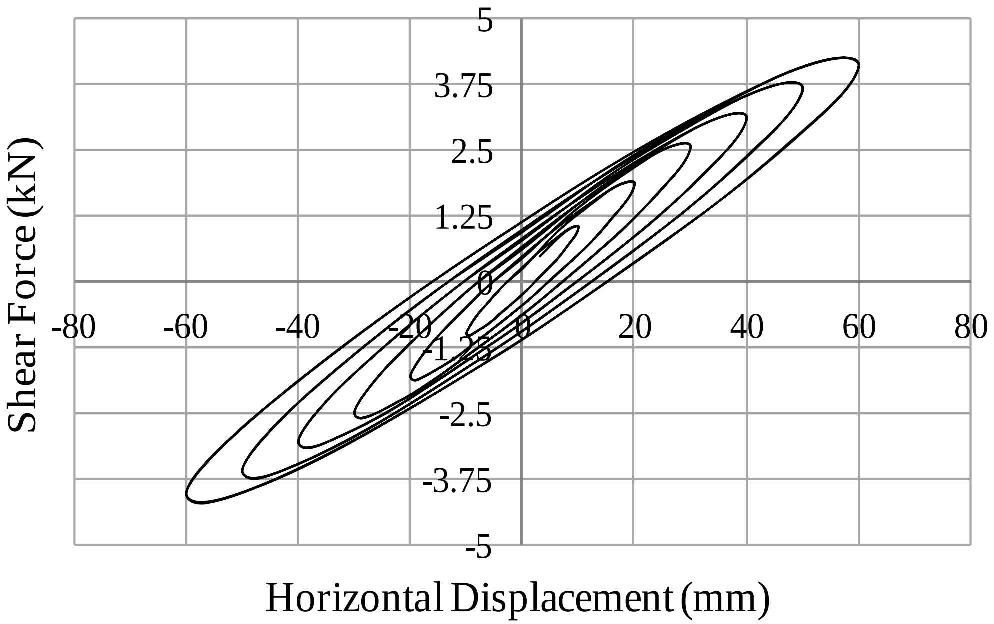
Unbonded square isolator

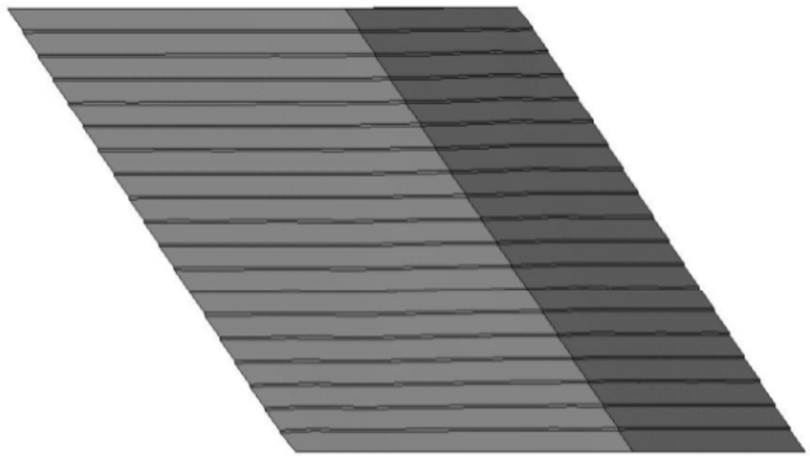


Bonded square isolator

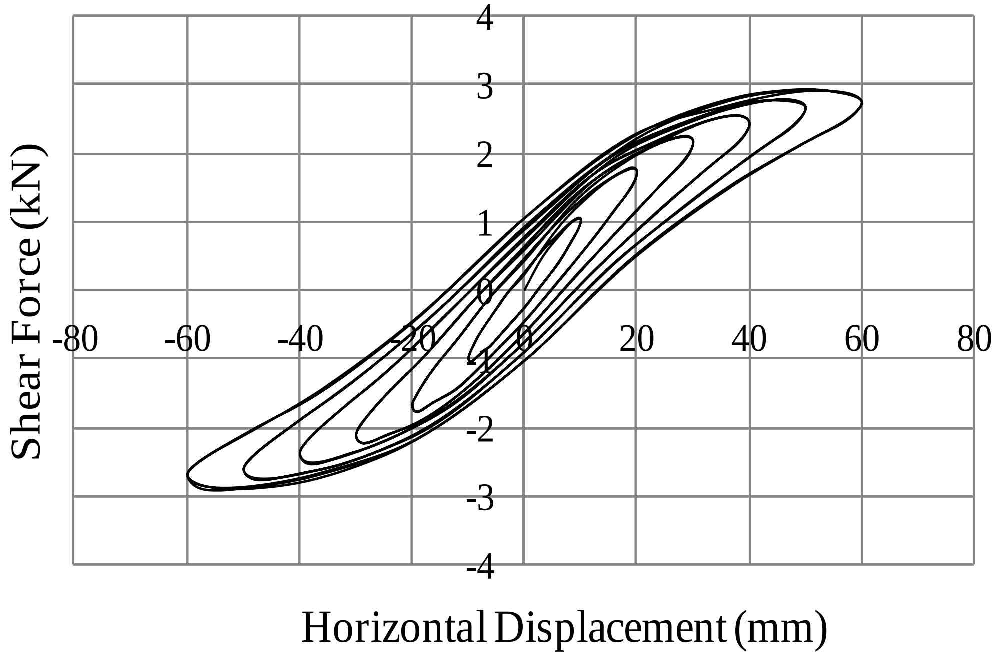
Contour of normal stress S_{33} (N/m^2) in rubber layer of isolator at horizontal displacement 60mm and 0^0 loading direction (Positive value indicate tension)

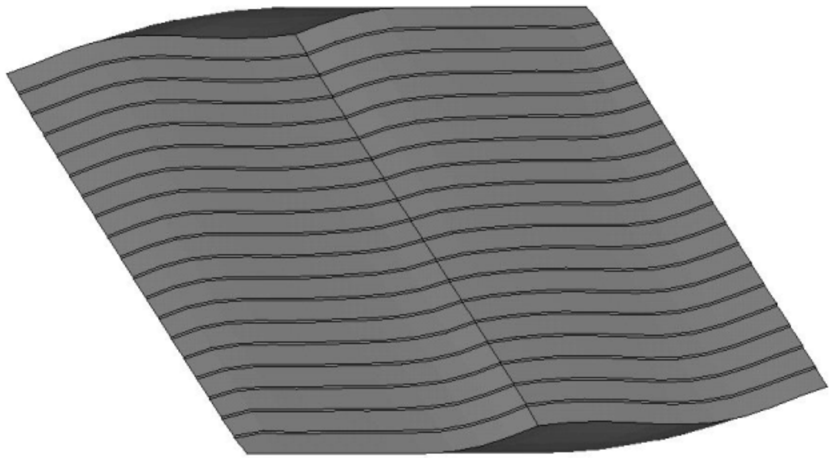
Hysteretic behaviour of square bonded isolator with 45^0 loading direction





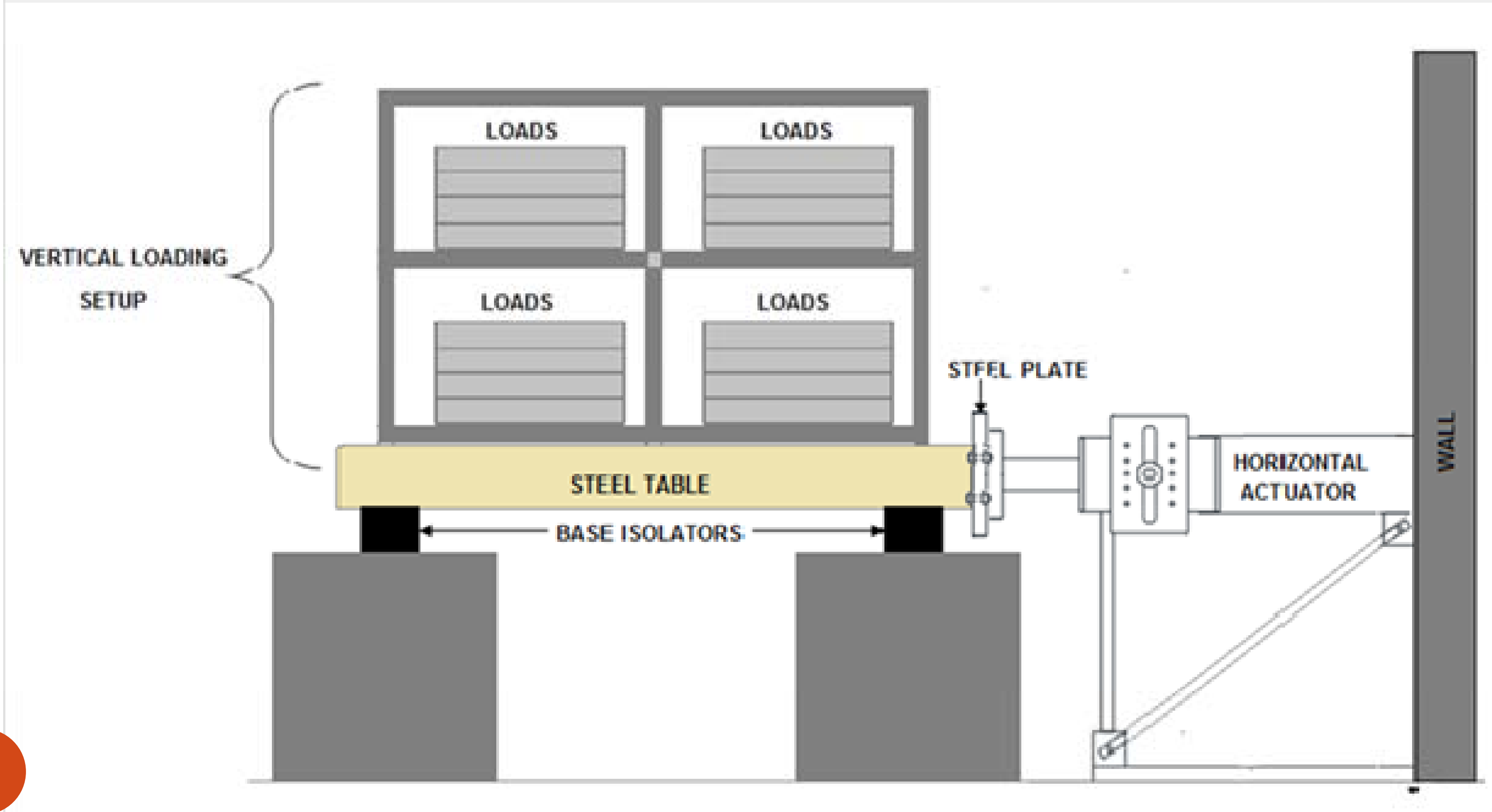
Hysteretic behaviour of square unbonded isolator with 45^0 loading direction



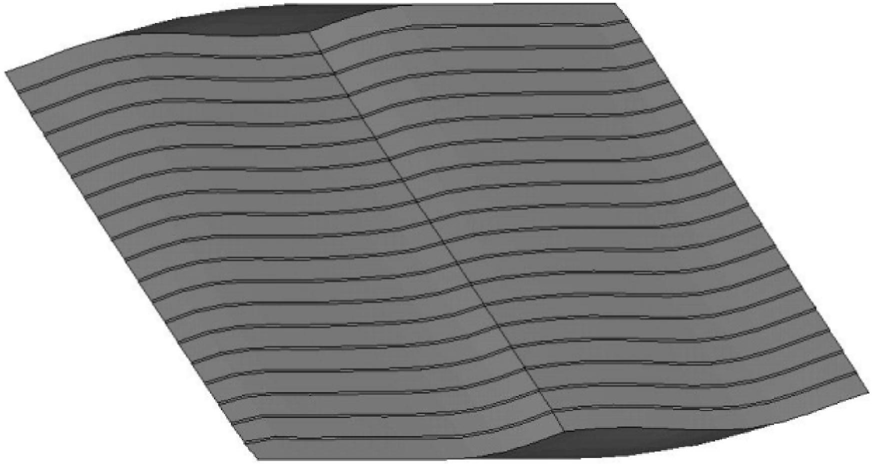


	Square unbonded 45°		Square bonded 45°	
Displacement (mm)	Effective Horizontal Stiffness (K_{eff}^{h}) (kN/m)	Damping (β) (%)	Effective Horizontal Stiffness (K_{eff}^{h}) (kN/m)	Damping (β) (%)
10	104.8	12.1	104.0	12.2
20	89.1	12.4	94.3	12.2
30	74.7	13.0	87.2	12.3
40	63.7	13.3	79.6	12.4
50	55.4	13.8	75.4	12.6
60	48.2	14.3	70.6	13.0

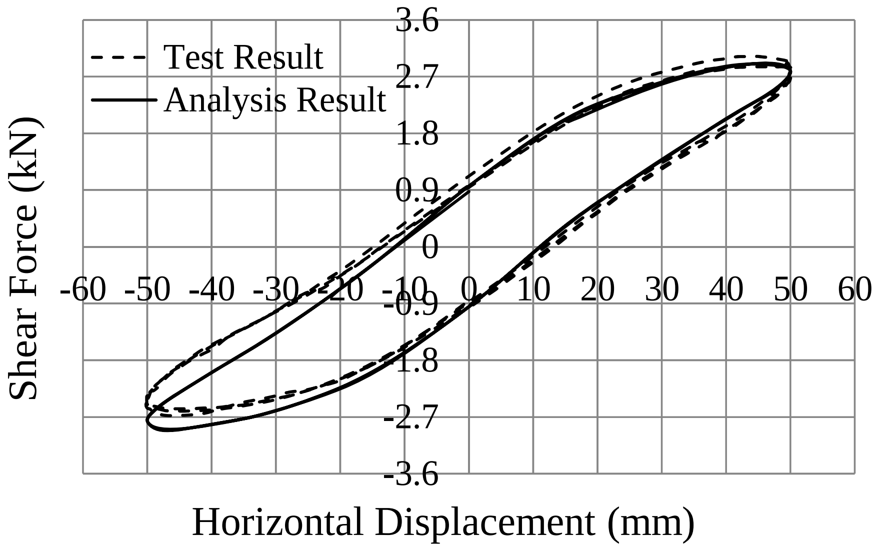
Experimental Set-up for Lateral Force-Displacement Behaviour



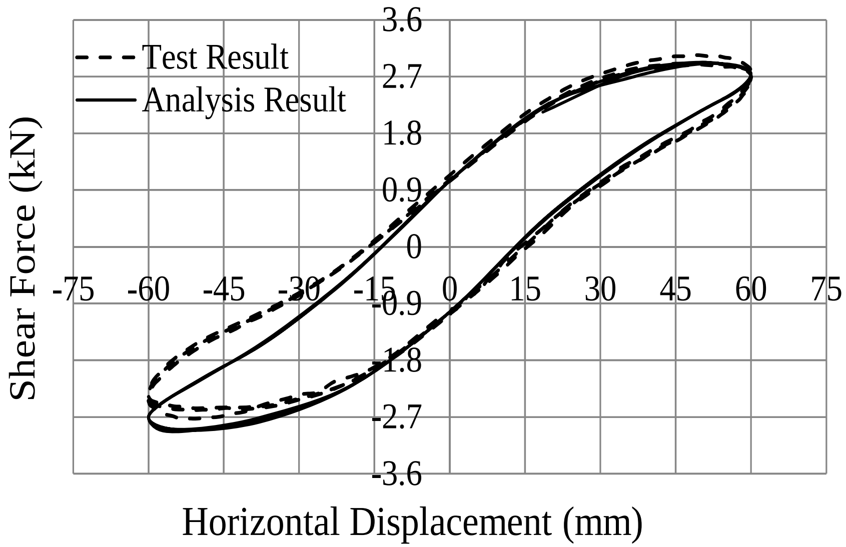
Displaced shape of isolator



Comparison of Numerical & Experimental Result



Shear force vs. horizontal displacement at 50mm displacement



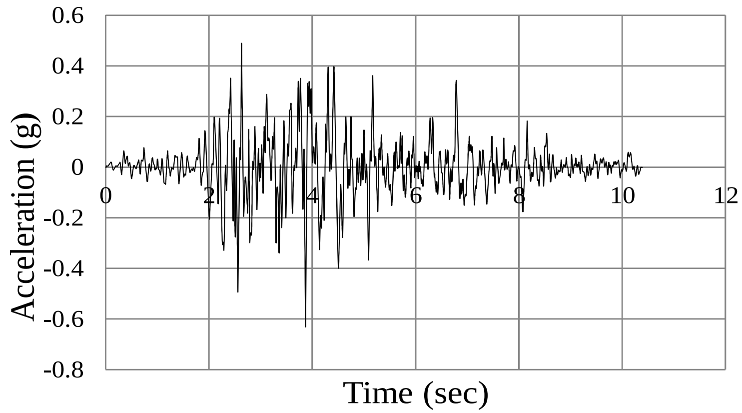
Shear force vs. horizontal displacement at 60mm displacement

Das, A., Dutta, A. and Deb, S.K. (2015), "Performance of fiber-reinforced elastomeric base isolators under cyclic excitation", Journal of *Structural Control and Health Monitoring,* (Wiley Inter-Science), Vol. 22(2), pp.197-220.

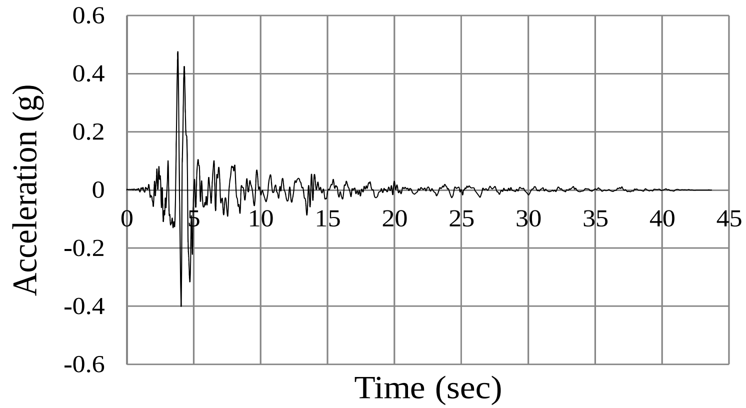
Shake Table Testing of Model Building Supported on FREI

Das, A., **Deb, S.K.** and Dutta, A. (2016), "Shake table testing of unreinforced brick masonry building test model isolated by U-FREI", ***Earthquake Engineering and Structural Dynamics*** (Wiley Inter-Science), Vol. 45, pp. 263-272.

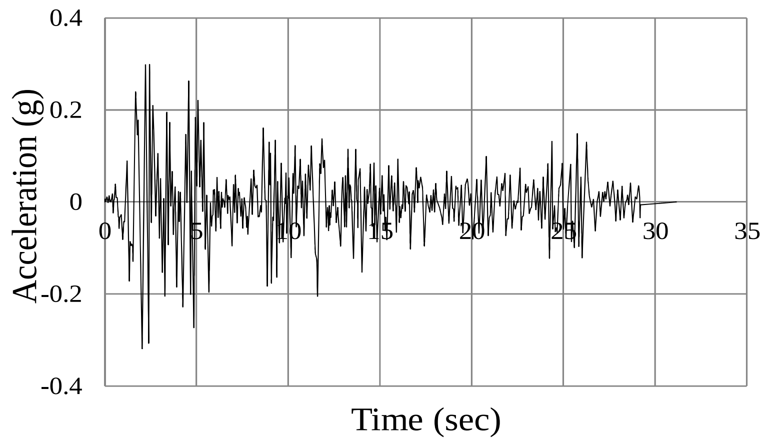
Acceleration time histories of four different earthquakes



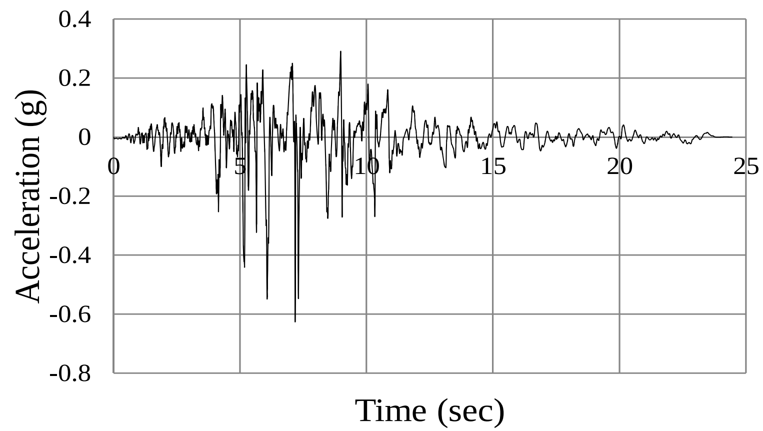
(a) Koyna (1967)



(b) Parkfield (1966)



(c) El Centro (1940)



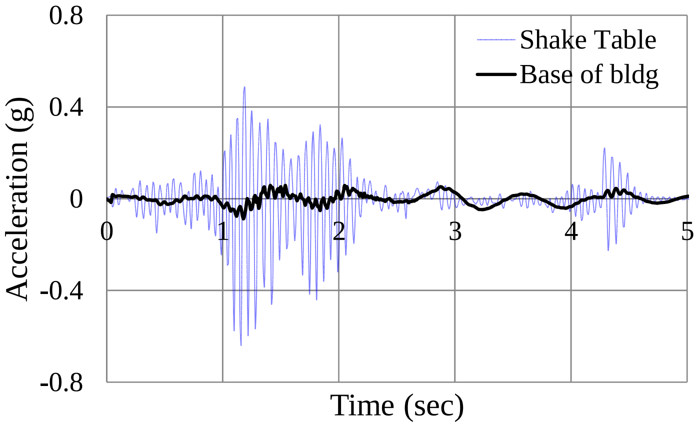
(d) Mexico (1980)

Displaced shape of isolator during shake table test for Park-Field input earthquake

(a) Park-field (for 100% acceleration amplitude of earthquakes along X-axis).

(b) Park-field (for 70% acceleration amplitude of earthquakes along 45^0 to X-axis.)

Acceleration response at shake table level and base level subjected to four earthquakes



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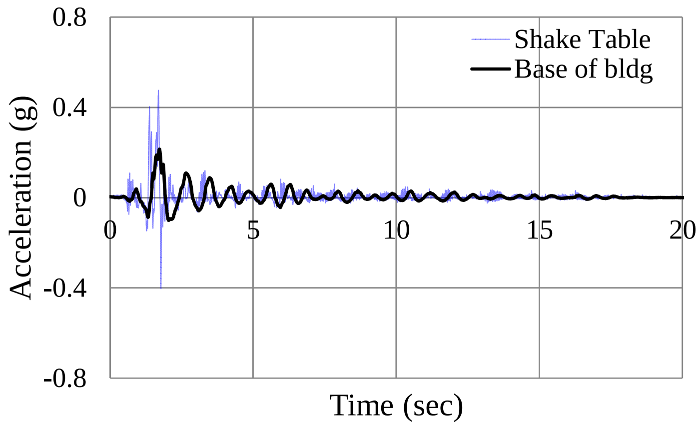
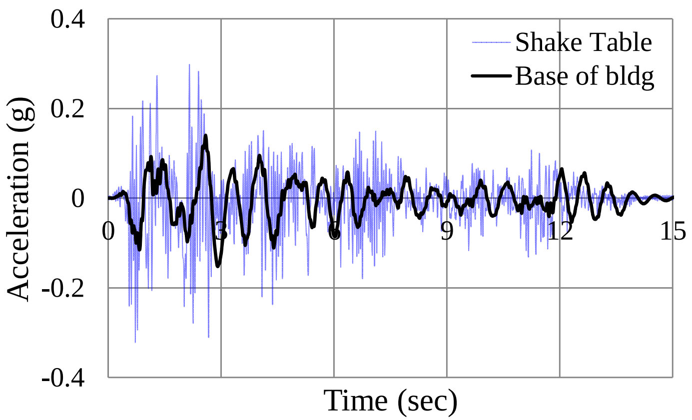
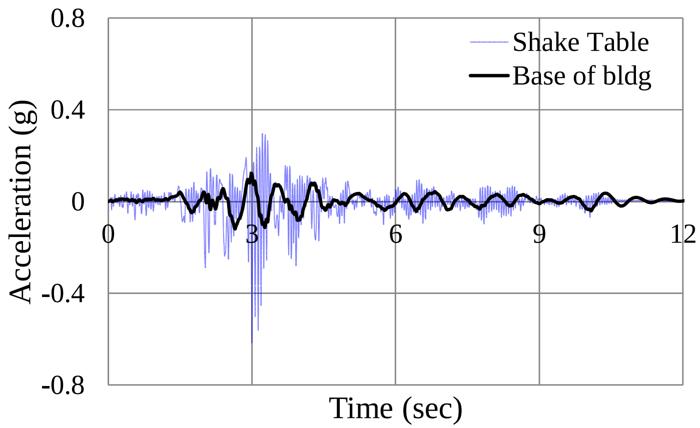


(b) Parkfield (1966)

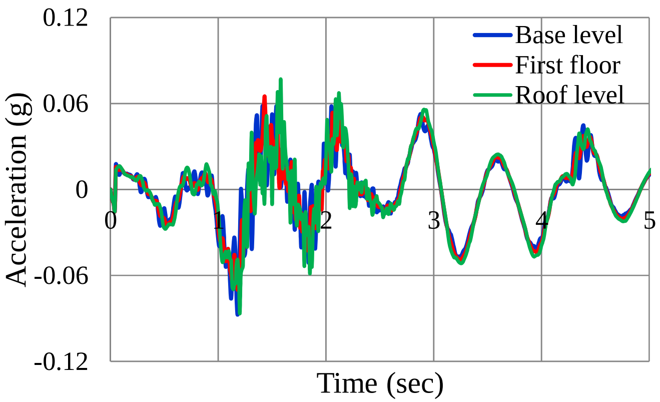


(c) El Centro (1940)



(d) Victoria (1980)

Comparison of acceleration responses at base level, first floor and roof level subjected to four earthquakes



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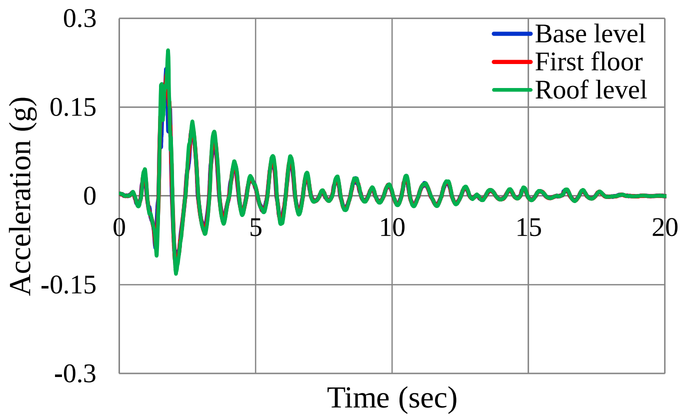
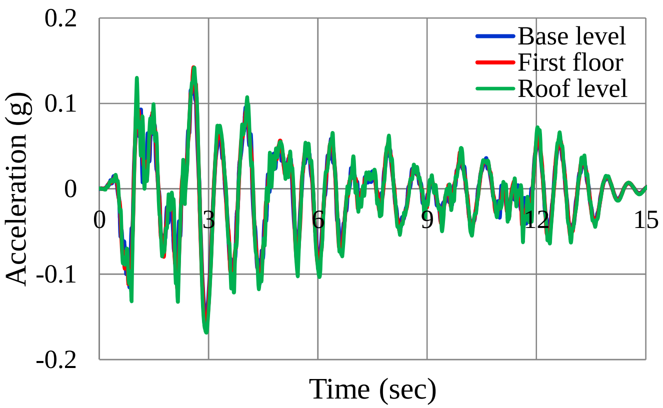
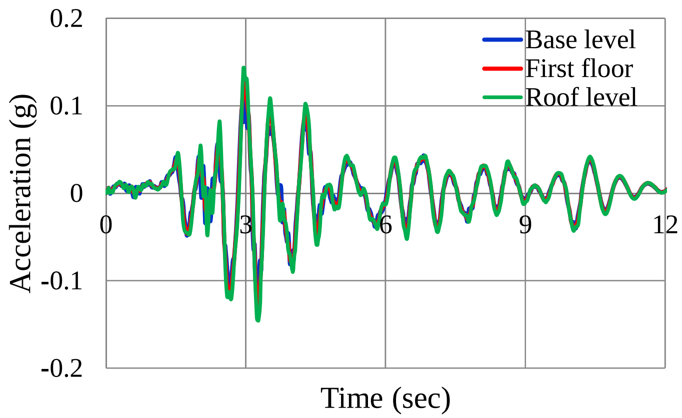


(b) Parkfield (1966)

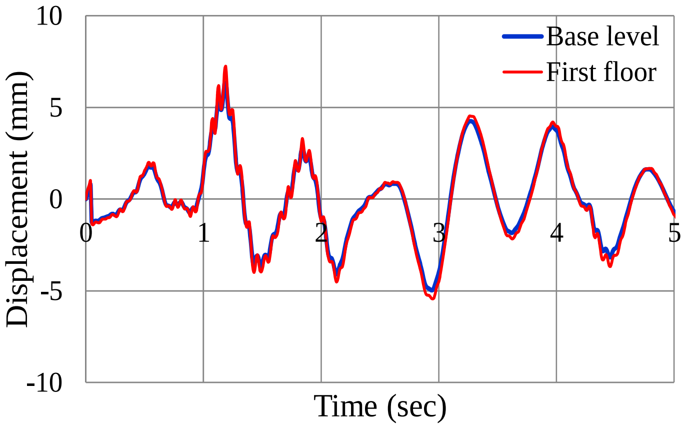


(c) El Centro (1940)



(d) Victoria (1980)

Displacement at base level and first floor level subjected to four earthquakes



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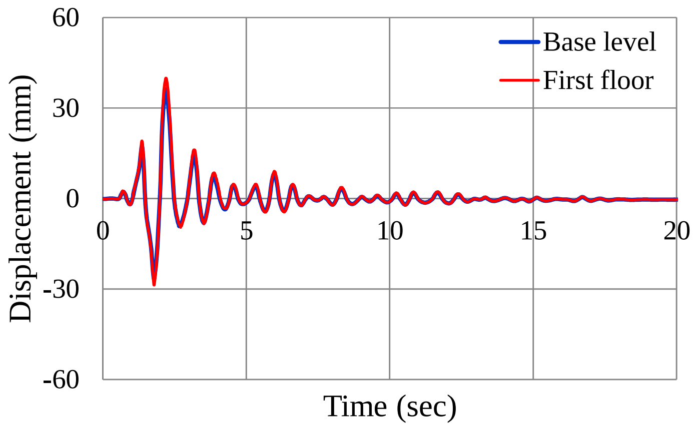

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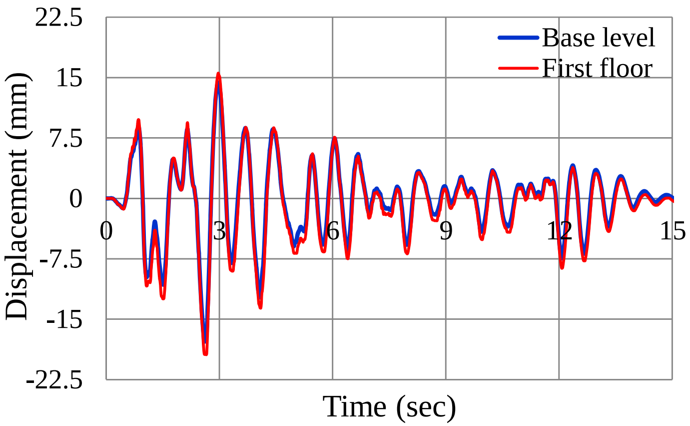

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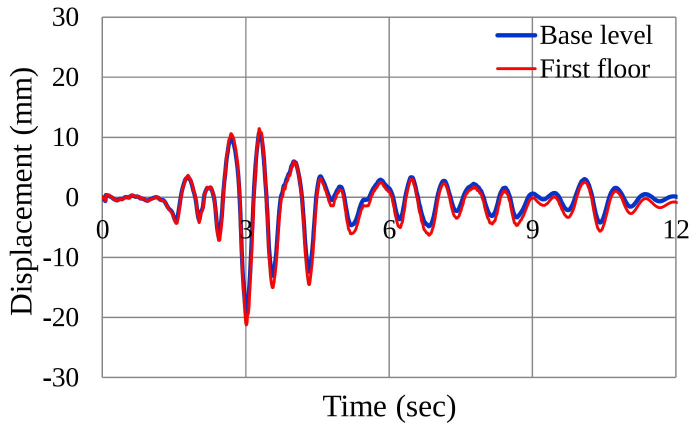
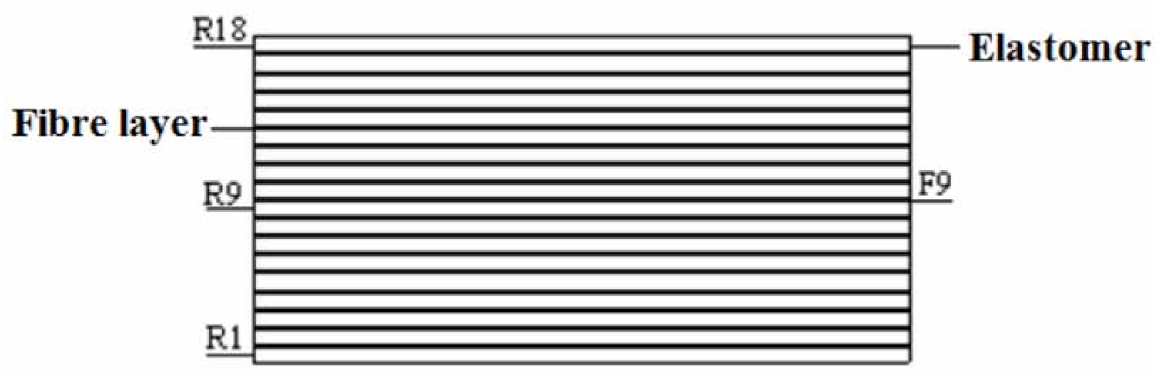


(d) Victoria (1980)

Peak acceleration and displacement at different levels of model subjected to four earthquakes along X-axis

Earthquake	Peak Accelerations (g)				Peak Displacement (mm)	
	At Shake Table	At Base	At First Floor	At Roof Level	At Base level	At First Floor
Koyna (1967)	0.632	0.0873	0.0700	0.0867	6.326	7.240
Parkfield (1966)	0.476	0.2145	0.2081	0.2463	36.199	39.920
El Centro (1940)	0.319	0.1524	0.1601	0.1686	17.789	19.409
Mexico (1980)	0.615	0.1230	0.1310	0.1459	19.452	21.251

EXPERIMENTAL STUDY ON HORIZONTAL-DISPLACEMENT BEHAVIOUR OF PROTOTYPE U-FREIs



(a) Details of different layers in an isolator

(b) 3-D view of a typical isolator

Prototype U-FREI

EXPERIMENTAL STUDY ON HORIZONTAL FORCE-DISPLACEMENT BEHAVIOUR OF PROTOTYPE U-FREIs

Details of prototype FREIs: (*support of METCO Pvt. Ltd., Kolkata, India*)

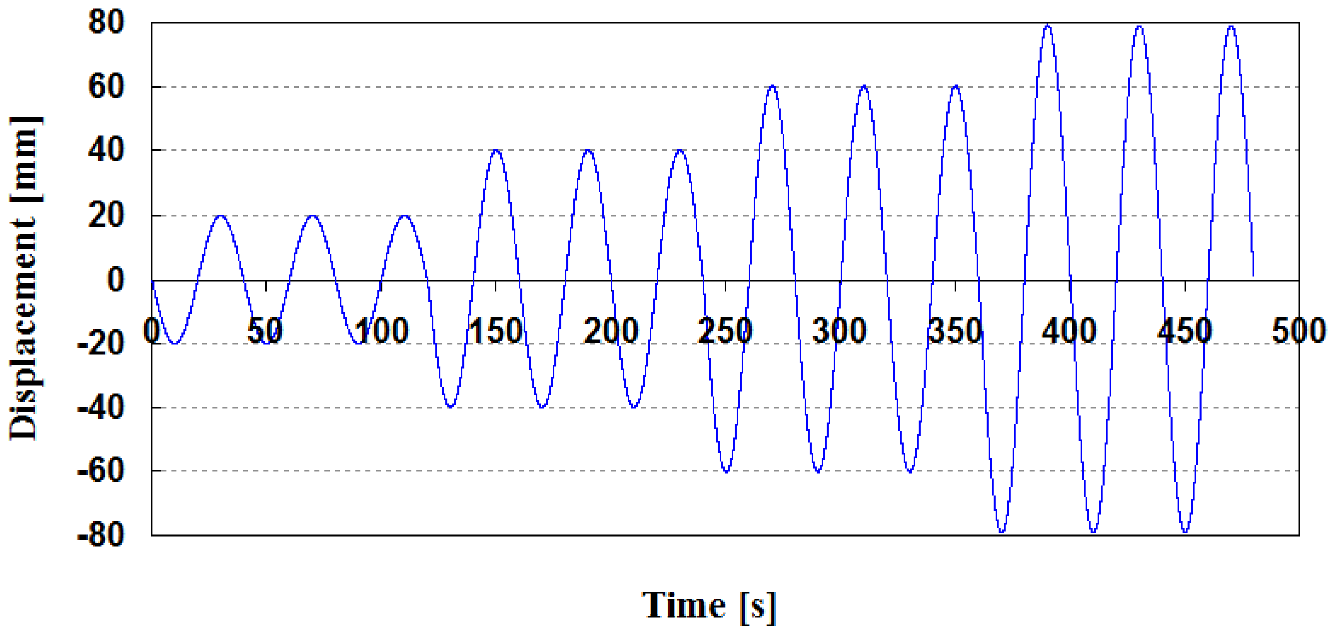
Description	Isolator *A1*	Isolator *B1*	Isolator *B2*
Size of specimen, mm	250x250x100	250x250x100	310x310x100
Number of isolators, N	2 - $A1_{(a,b)}$	4 - $B1_{(a,b,c,d)}$	2 - $B2_{(a,b)}$
Number of elastomeric layer, n_e	18	18	18
Thickness of single elastomeric layer, t_e	5 mm	5 mm	5 mm
Total height of elastomer, t_r	90 mm	90 mm	90 mm
Number of fibre layer, n_f	17	17	17
Thickness of single fibre layer, t_f	0.55 mm	0.55 mm	0.55 mm
Shape factor, S	12.5	12.5	15.5
Aspect ratio	2.50	2.50	3.10
Shear modulus of elastomer, G	0.78 MPa	0.90 MPa	0.90 MPa
Elastic modulus of carbon fibre laminate	40 GPa	40 GPa	40 GPa
Poisson's ratio of carbon fibre laminate	0.20	0.20	0.20

Evaluation of lateral load-displacement behaviour of prototype U-FREIs

Experimental set-up

Horizontal displacement history

All isolators are subjected to a constant vertical pressure of 5.6 MPa and cyclic horizontal displacement (f= 0.025 Hz) up to 0.89t_r



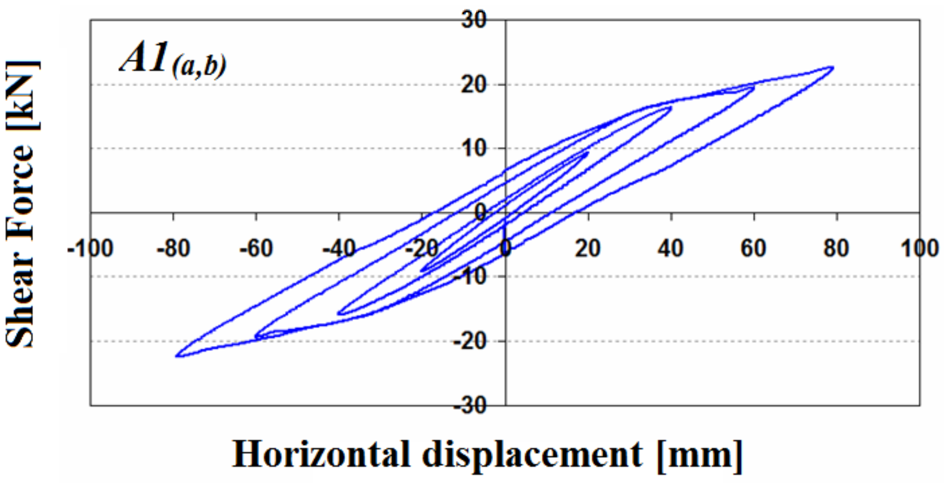
EXPERIMENTAL STUDY ON HORIZONTAL-DISPLACEMENT BEHAVIOUR OF PROTOTYPE U-FREIs

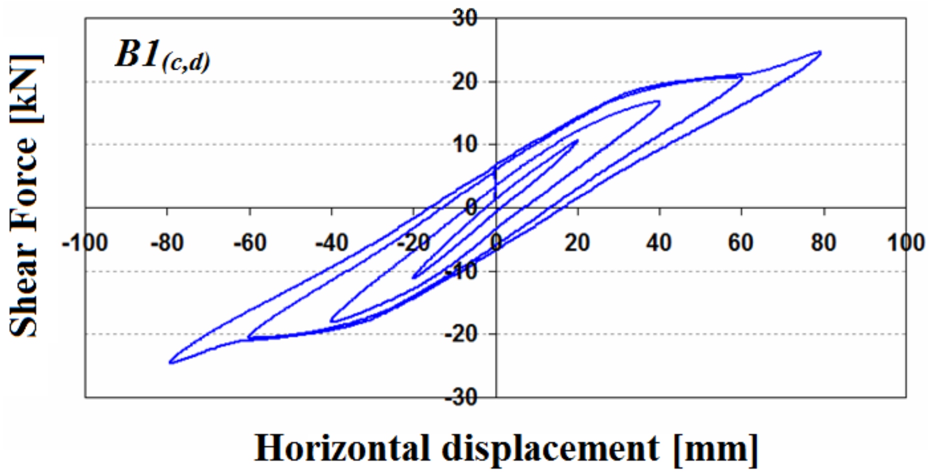
- **Deformed shapes:**

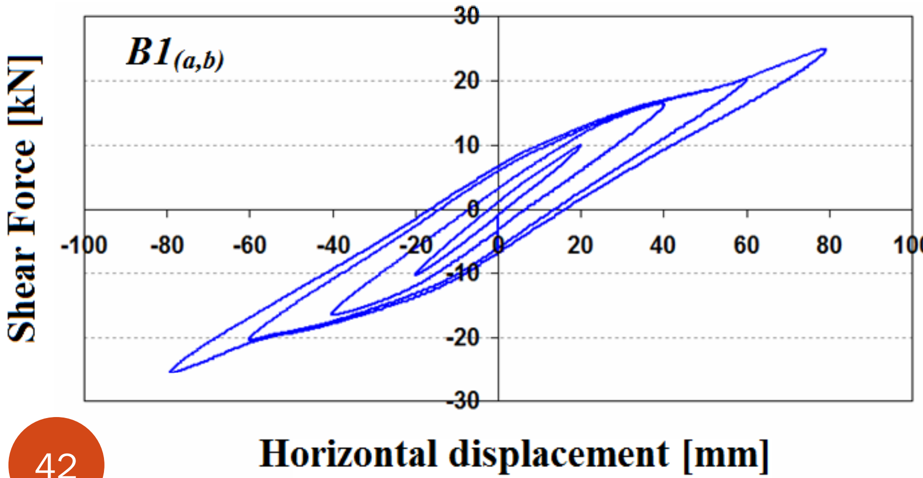
Experimental Deformed shapes of U-FREI at 80 mm amplitude of horizontal displacement

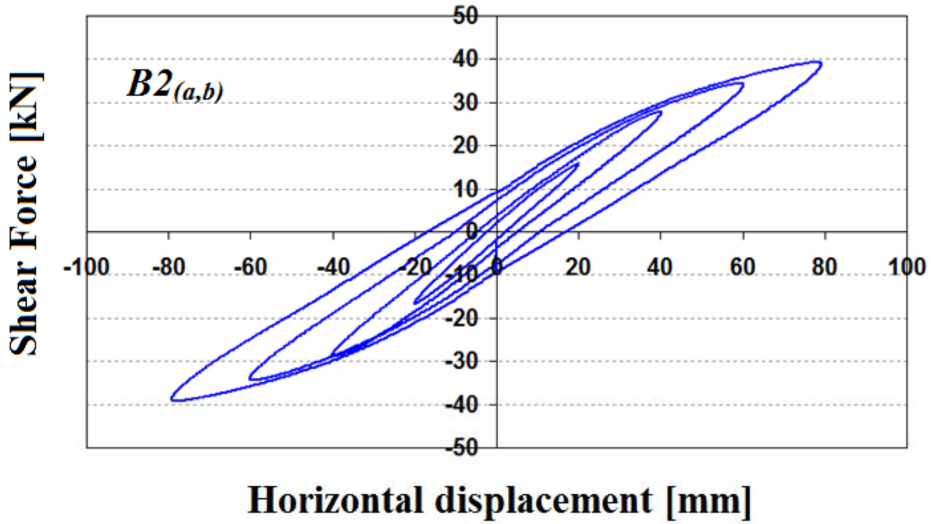
EXPERIMENTAL STUDY ON HORIZONTAL-DISPLACEMENT BEHAVIOUR OF PROTOTYPE U-FREIs

➢ Hysteresis loops:









EXPERIMENTAL STUDY ON HORIZONTAL-DISPLACEMENT BEHAVIOUR OF PROTOTYPE U-FREIs

- **Mechanical characteristic properties:**
  - The effective horizontal stiffness:

    [*Kelly and Takhirov*, 2001]

    $$K_{eff}^{h} = \frac{F_{\max} - F_{\min}}{u_{\max} - u_{\min}}$$

  - The equivalent viscous damping:

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

Amplitude (mm)	u/t_r	$A1_{(a,\,b)}$		$B1_{(a,\,b)}$		$B1_{(c,\,d)}$		$B2_{(a,\,b)}$	
		K_{eff}^{h} (kN/m)	β (%)	K_{eff}^{h} (kN/m)	β (%)	K_{eff}^{h} (kN/m)	β (%)	K_{eff}^{h} (kN/m)	β (%)
20	0.22	464.26	5.18	507.26	5.00	547.00	4.79	814.54	5.82
40	0.44	403.41	6.94	410.21	9.67	436.10	9.57	708.04	6.89
60	0.67	324.22	11.15	339.01	12.02	343.86	13.12	573.36	10.14
80	0.89	282.60	11.83	318.68	10.02	310.52	11.51	497.48	11.84

Effect of loading direction on horizontal response of square U-FREIs:

- Most previous studies for square U-FREIs were investigated under cyclic horizontal displacement in **0/90º and 45º directions**. Angle of incidence of earthquake to a structure may be from any directions.

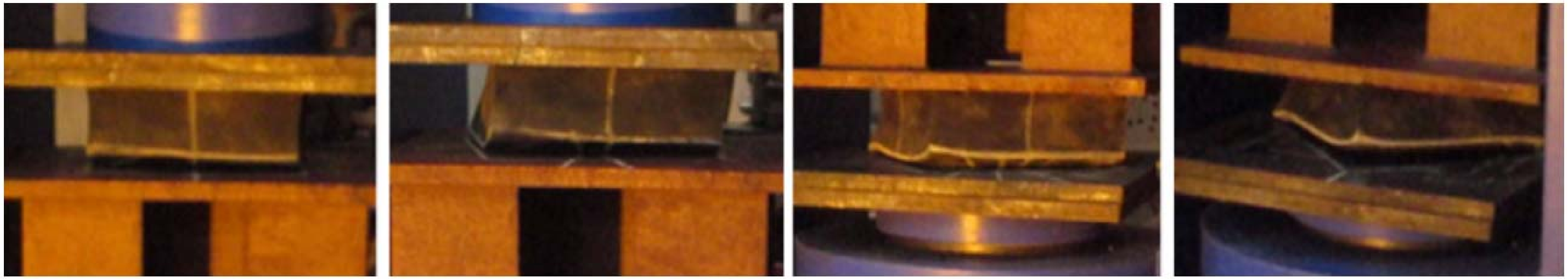
- However, **no experimental study** on effect of loading directions on horizontal response of square U-FREIs was performed.

Specimens undergoing tests under horizontal displacement in different directions (0º, 15º, 30º and 45º)

- **Experimental results:**
  - **Deformed shapes:**

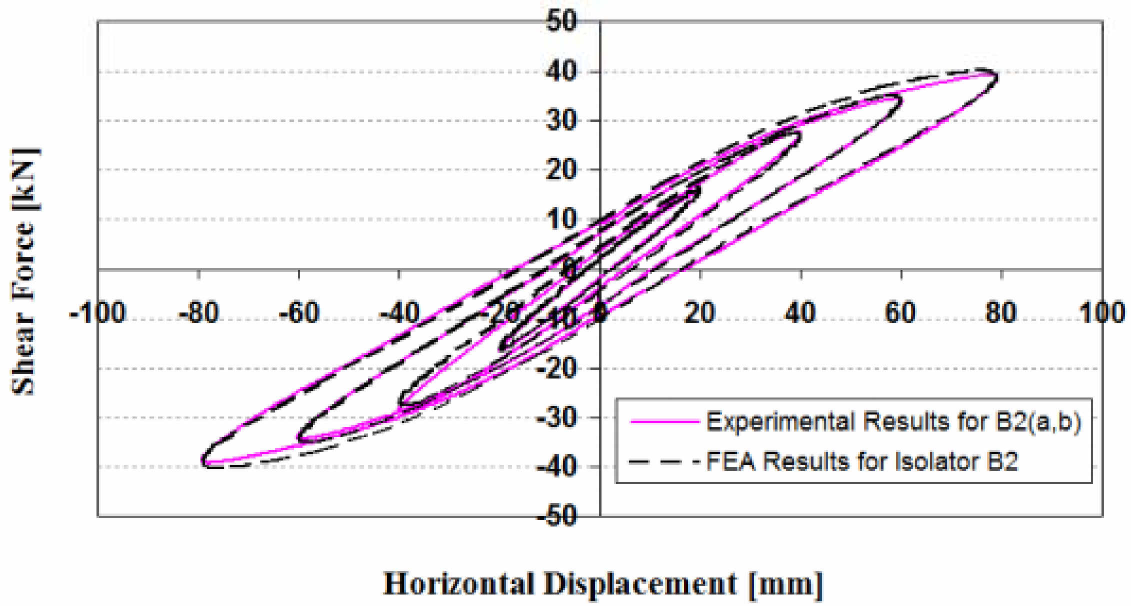
    As the loading direction changes from 0° to 45°, the **area of the isolator** in contact with the support surfaces **increases**. This results in **an increase in effective horizontal stiffness.**



Deformed shapes of U-FREI type *A1* corresponding to 0°, 15°, 30° and 45° loading directions at 80mm amplitude of horizontal displacement

FINITE ELEMENT SIMULATION OF FREI

- **Hysteresis loops:**



(c) Isolator *B2*

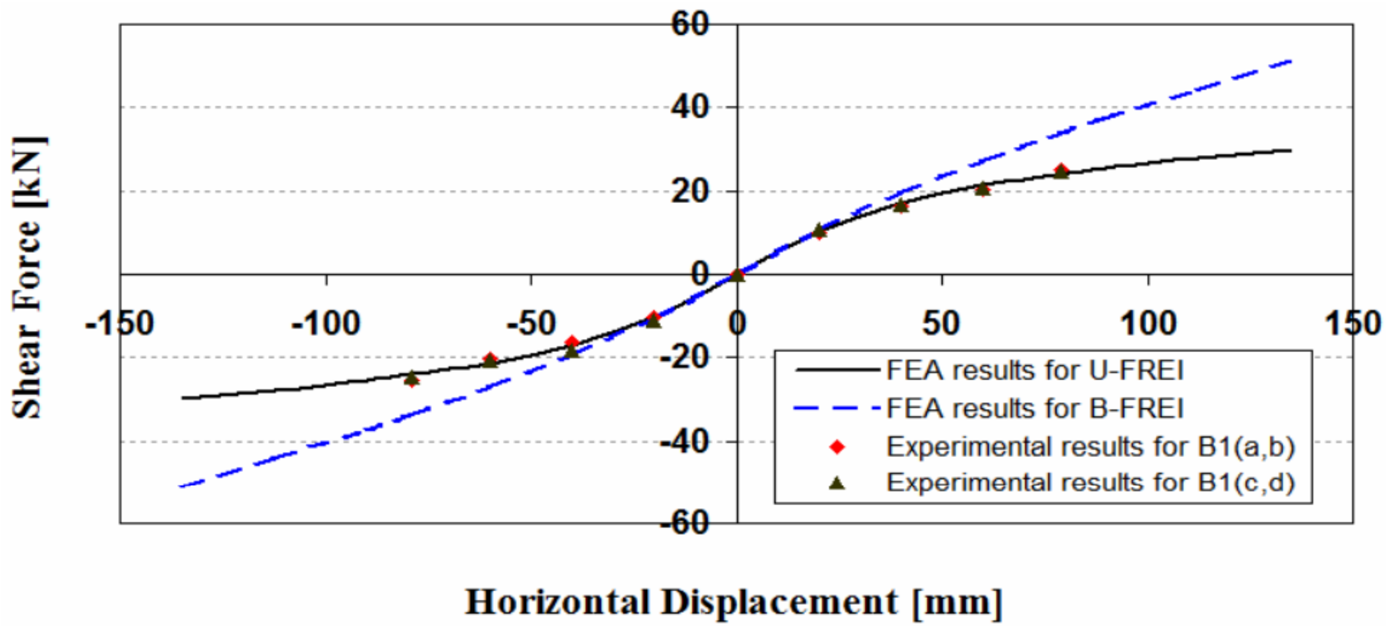
Comparison of hysteresis loops of different types of U-FREI as obtained from FE analysis and experimental results

Mechanical Properties of Prototype FREIs

Mechanical properties of U-FREI and B-FREI type *B1*

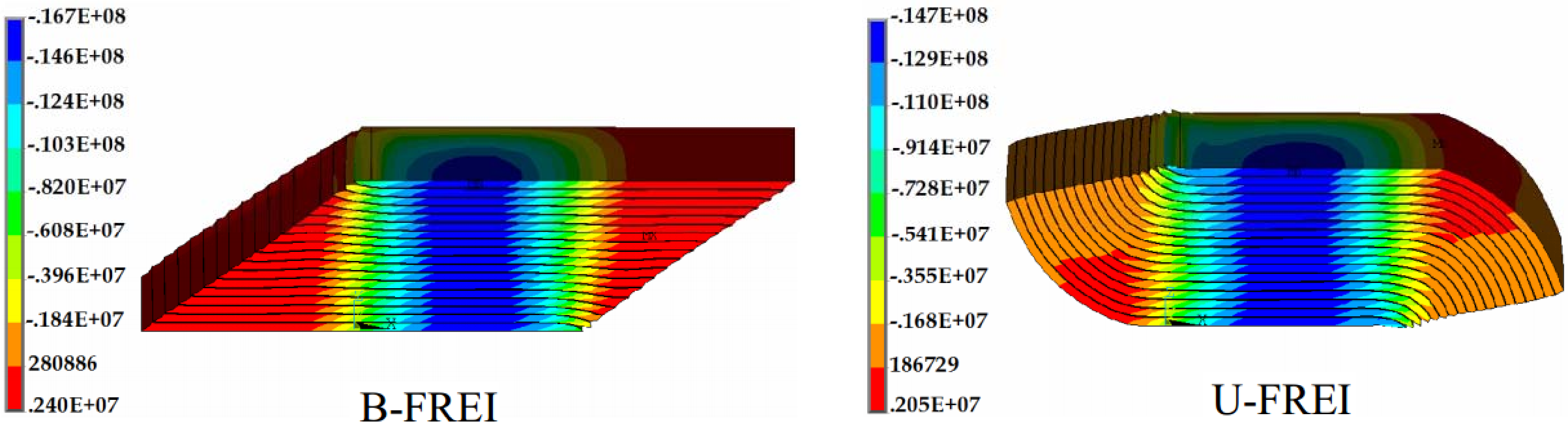
Amplitude (mm)	Experimental results				FEA results			
	$B1_{(a,b)}$		$B1_{(c,d)}$		Un-bonded		Bonded	
	K_{eff}^{h} (kN/m)	β (%)	K_{eff}^{h} (kN/m)	β (%)	K_{eff}^{h} (kN/m)	β (%)	K_{eff}^{h} (kN/m)	β (%)
20.0	507.26	5.00	547.00	4.79	515.87	7.58	528.12	7.51
40.0	410.21	9.67	436.10	9.57	426.93	9.60	486.13	9.03
60.0	339.01	12.02	343.86	13.12	357.01	12.05	452.65	10.52
80.0	318.68	10.02	310.52	11.51	301.67	13.46	425.54	11.10
90.0	-	-	-	-	281.34	14.11	414.90	11.42
112.5	-	-	-	-	247.09	14.58	393.10	11.91
135.0	-	-	-	-	222.03	15.42	379.09	12.27

Horizontal load – displacement relationships



(b) Isolator *B1*

FINITE ELEMENT SIMULATION OF Prototype FREI



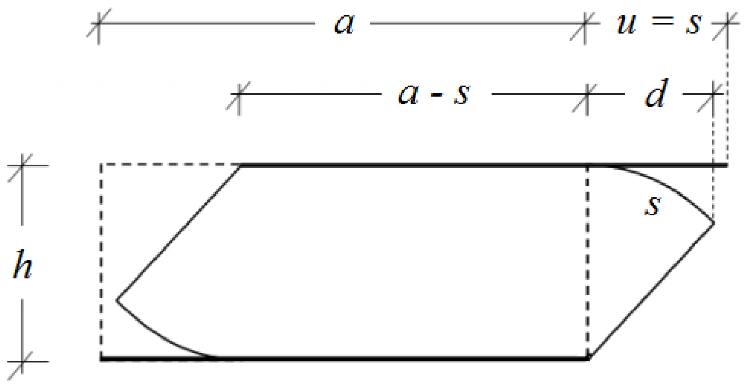
(a) Isolator *B1*

Contours of normalized stress S_{11} (N/m^2) in rubber layer of a half isolator at horizontal displacement of 135 mm (positive value indicates tension)

AN ANALYTICAL APPROACH FOR PREDICTING THE HORIZONTAL STIFFNESS OF U-FREIs

$$K_b = \frac{G_{eff} A}{t_r}$$

$$K_{ub} = \frac{G_{eff} A_{eff}}{t_r} \quad or \quad K_{ub} = \left(\frac{A_{eff}}{A}\right) K_b$$



Deformed configuration of a U-FREI

- Effective plan area:

$$A_{eff} = a(a-d)$$

According to Nezhad [2014], d is evaluated as

$$d = \frac{25}{16}\alpha h$$

α is geometrical parameter which relates d and curved length, s, at a given displacement, u.

Relation between u, s and α as proposed by Nezhad [2014] is expressed as

$$u = \frac{25}{64} h\left[2\alpha\sqrt{1+4\alpha^2} + \ln\left(2\alpha + \sqrt{1+4\alpha^2}\right)\right]$$

AN ANALYTICAL APPROACH FOR PREDICTING THE HORIZONTAL STIFFNESS OF FREIs

- **Proposed method 1:**

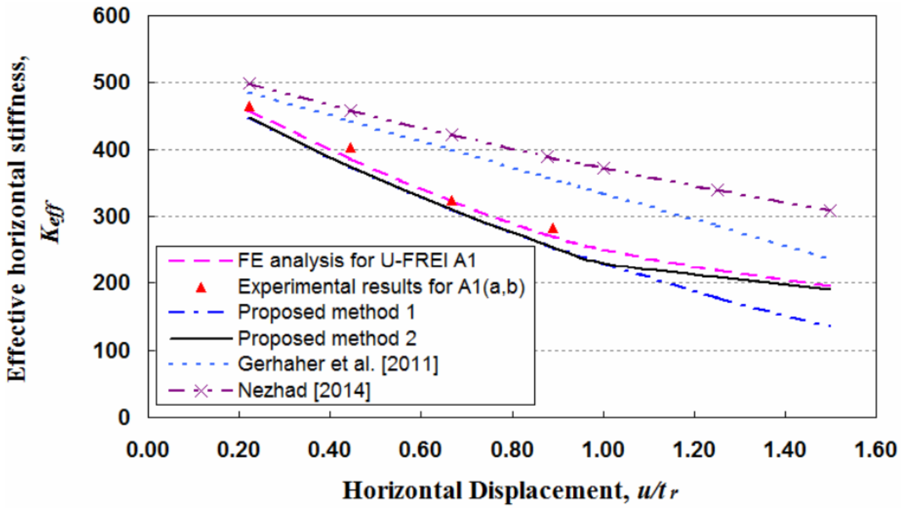
$$G_{eff} = G\left[1-\left(\frac{p_z}{p_{crit,0}\left(1-\left(\frac{u}{a}\right)^2\right)}\right)^2\right]\left(1-\frac{u}{a}\right)$$

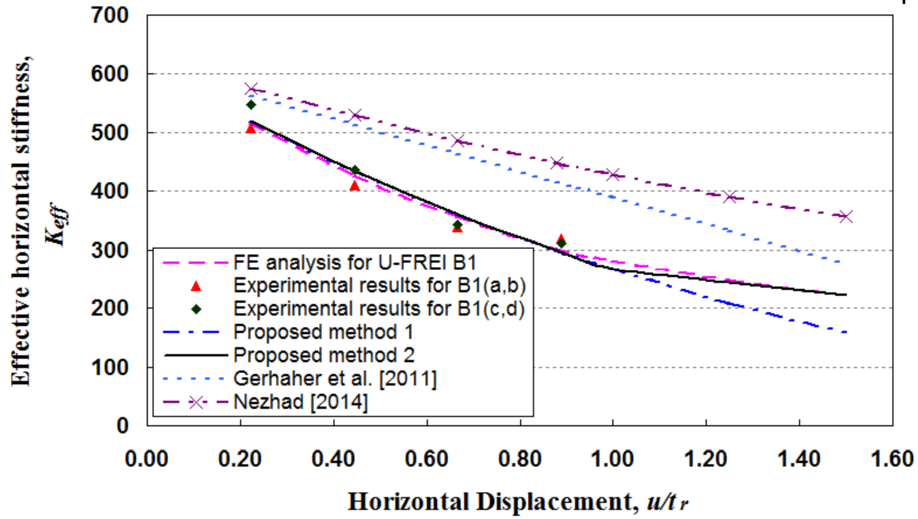
- **Proposed method 2:**

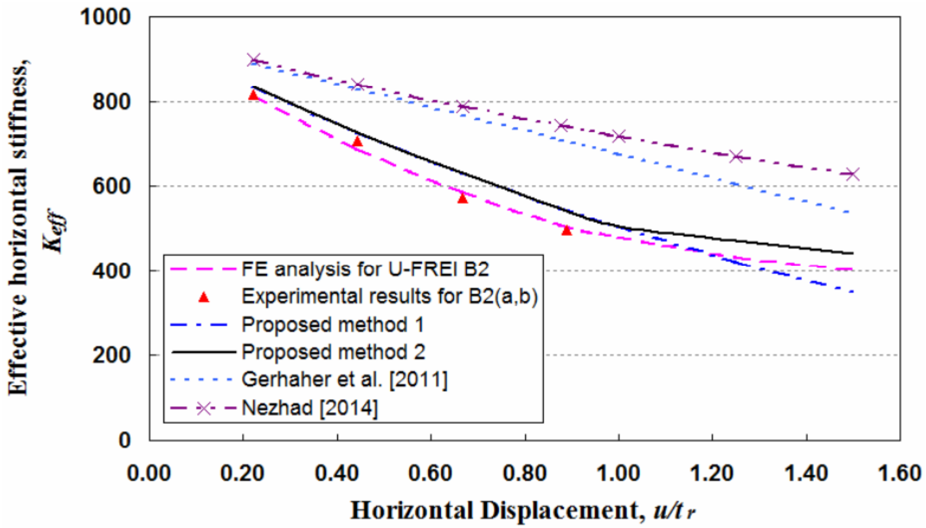
$$\begin{cases} G_{eff} = G\left[1-\left(\dfrac{p_z}{p_{crit,0}\left(1-\left(\frac{u}{a}\right)^2\right)}\right)^2\right]\left(1-\dfrac{u}{a}\right) & \text{for} \quad 0 \le u \le 1.0t_r \\ G_{eff} = G\left[1-\left(\dfrac{p_z}{p_{crit,0}\left(1-\left(\frac{1.0t_r}{a}\right)^2\right)}\right)^2\right]\left(1-\dfrac{1.0t_r}{a}\right) & \text{for} \quad 1.0t_r < u \le 1.5t_r \end{cases}$$

Ngo, T.V., Dutta, A. and Deb, S.K. (2017), "Evaluation of horizontal stiffness of fibre-reinforced elastomeric isolators", ***Earthquake Engineering and Structural Dynamics*** (Wiley Inter-Science), Vol. 46, pp. 1747-1767

ANALYTICAL APPROACH FOR PREDICTING THE HORIZONTAL STIFFNESS OF FREIs

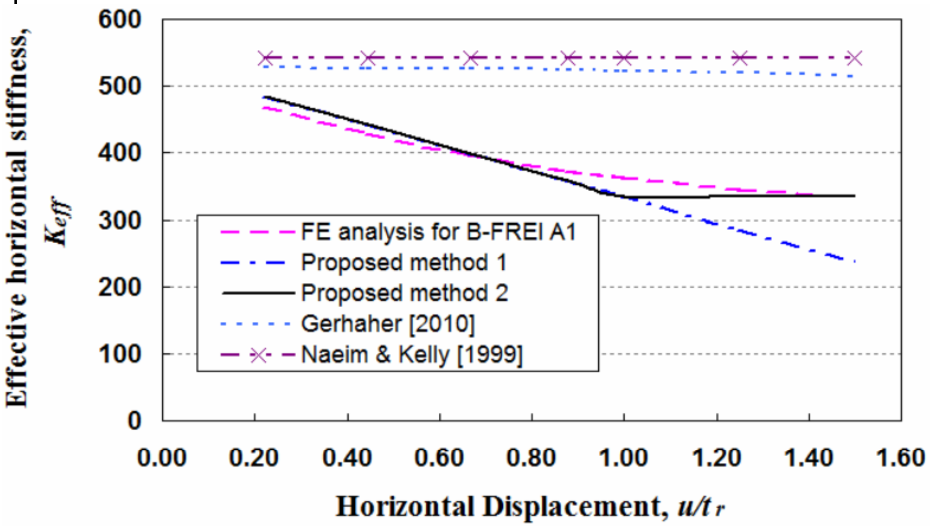


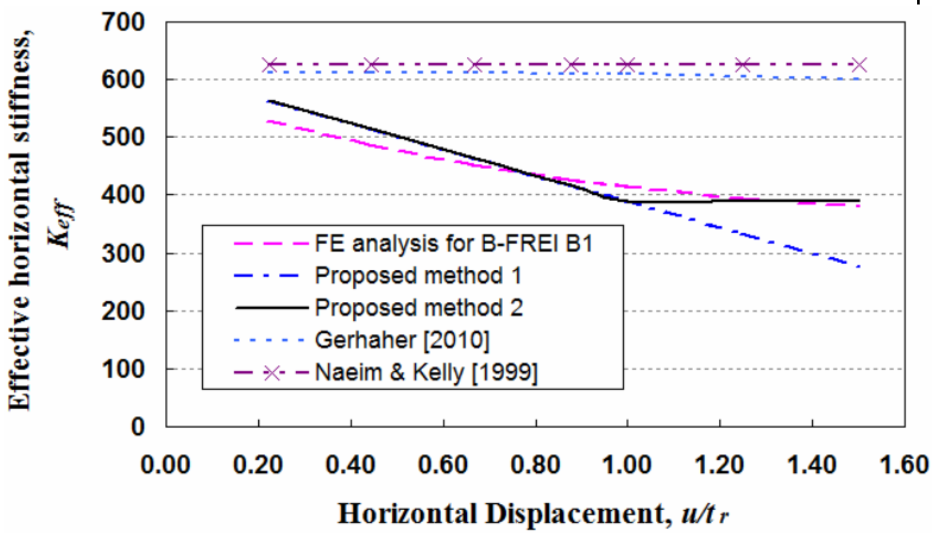


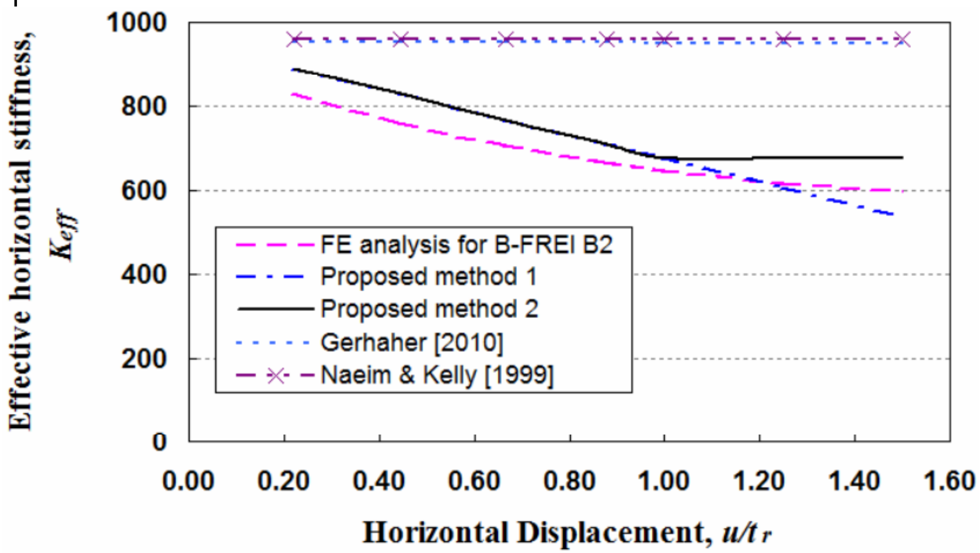


- **For U-FREI:**
- **Good agreements** are observed between proposed method 1 & 2 and experimental and FE analysis results up to $1.00t_r$.
- $1.0t_r < u < 1.5t_r$: Proposed method 2 has agreed better for isolator *A1* and *B1*, while proposed method 1 is better than proposed method 2 for isolator *B2*.
- The K_{eff} based on Gerhaher, et al. [2011] and Nezhad [2014] are **having significant deviation** with experimental results up to $0.89t_r$.

ANALYTICAL APPROACH FOR PREDICTING THE HORIZONTAL STIFFNESS OF FREIs

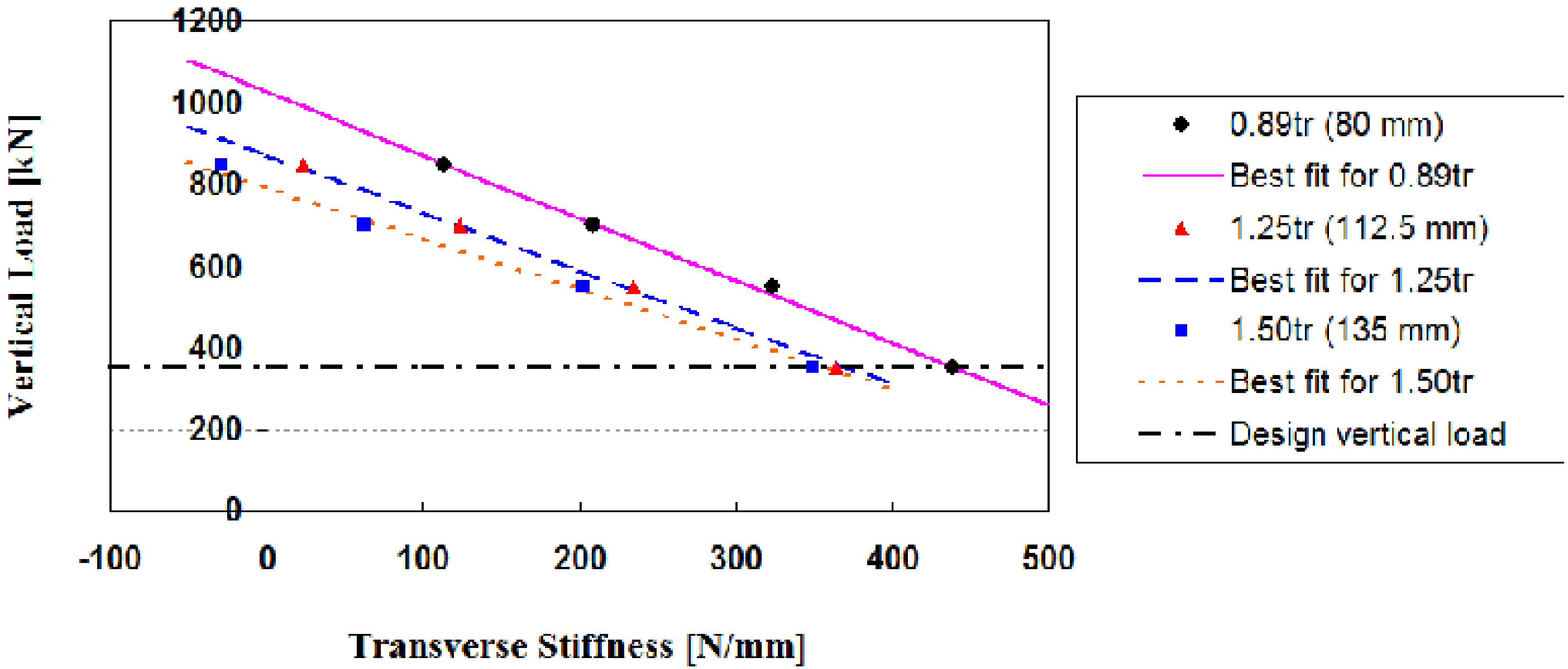




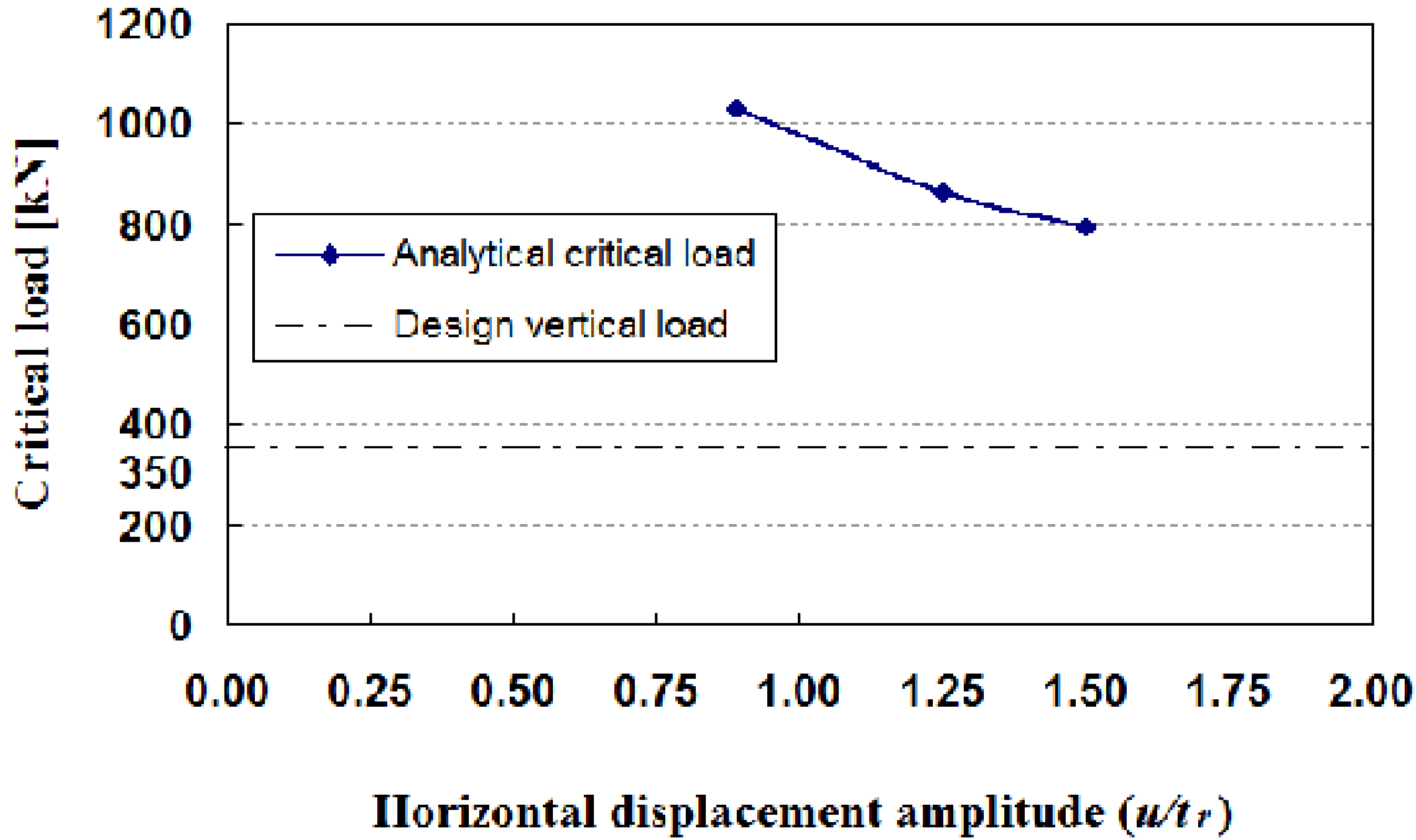


- **For B-FREI:**
  - The rate of decrease in K_{eff} obtained from Gerhaher [2010], Naeim and Kelly [1999] are almost constant and show **significant deviation** from those obtained from FE analysis.
  - Both proposed methods **have matched very well** with FE analysis results.

Stability Analysis



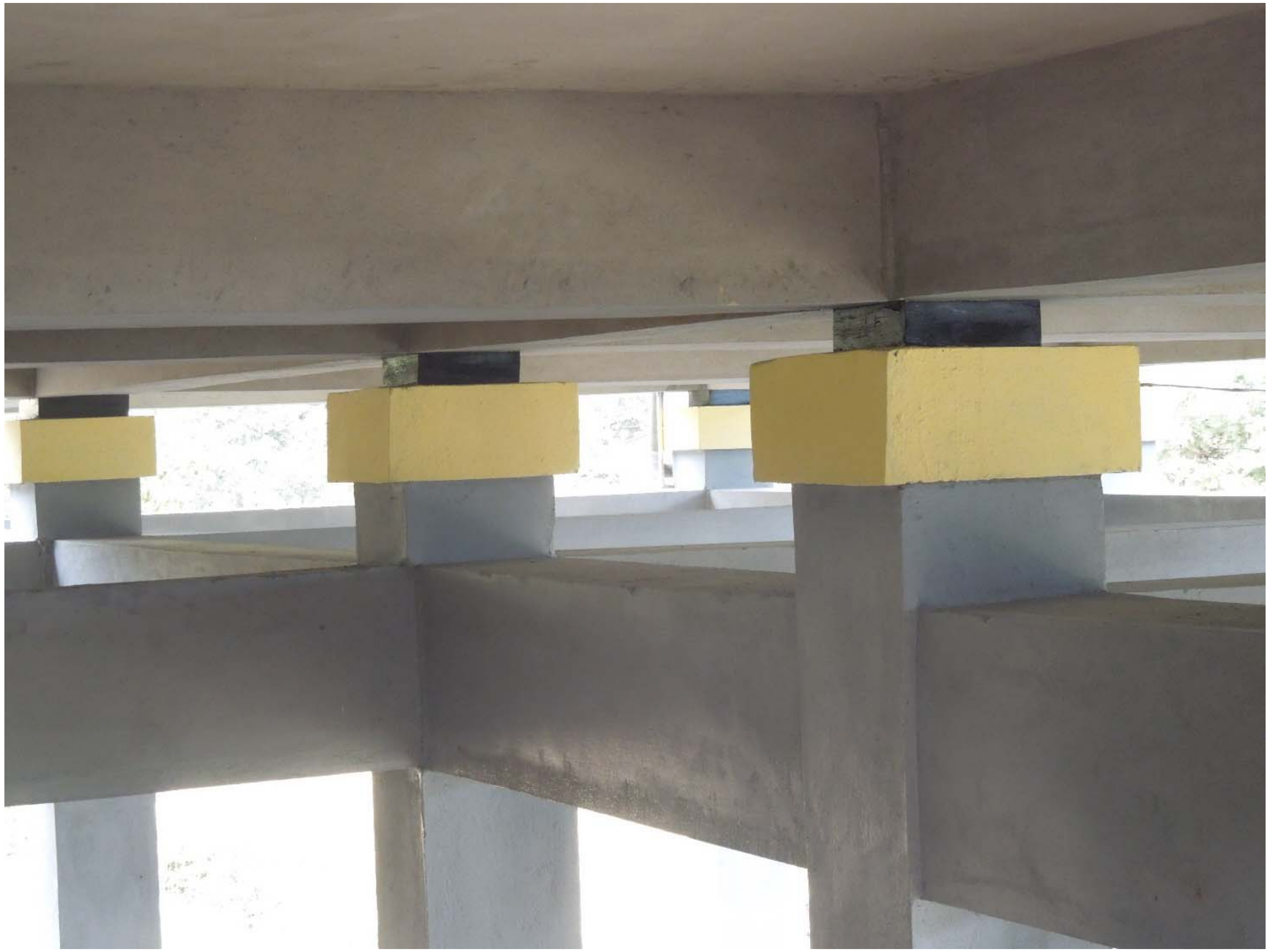
Stability Analysis




7-b


Level A
Level B
Base Isolator

View of UFREI

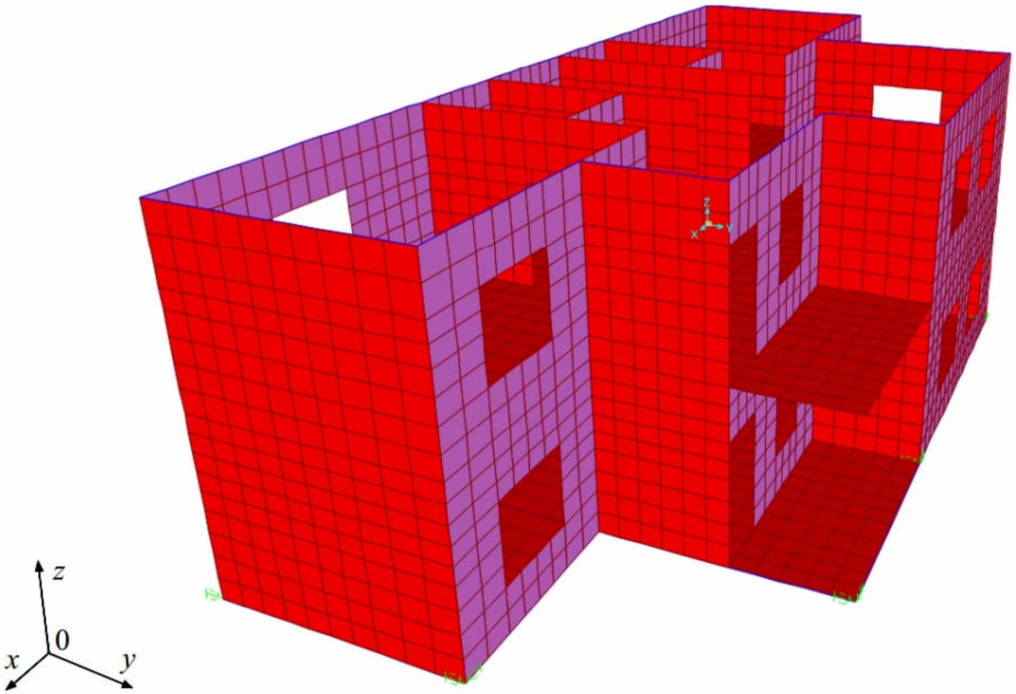


VULNERABILITY ASSESSMENT OF A LOW-RISE MASONRY BUILDING SUPPORTED ON U-FREIs

Numerical modelling of masonry building:

- 3D models of fixed-base and base-isolated buildings are simulated by SAP2000.
- ***Masonry wall:*** Nonlinear layered shell element

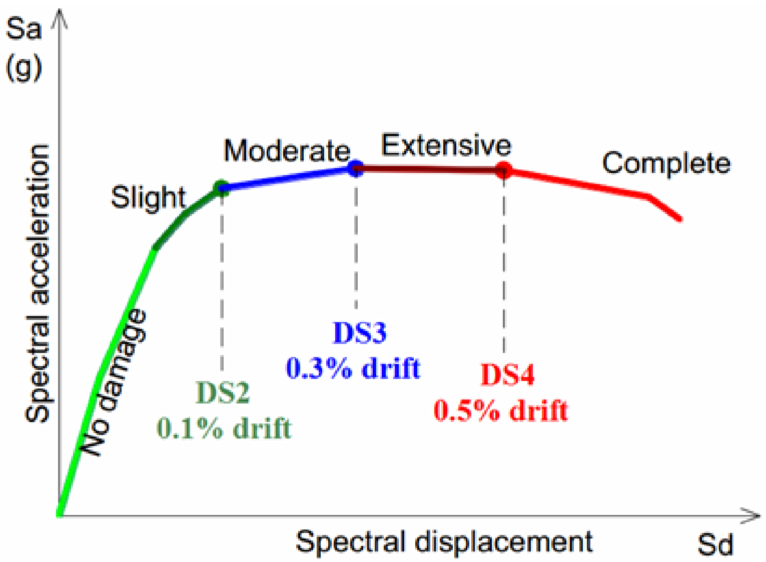
  Isolator: as rubber isolator in link/support type element using bilinear hysteresis loop



FE model of the URM building

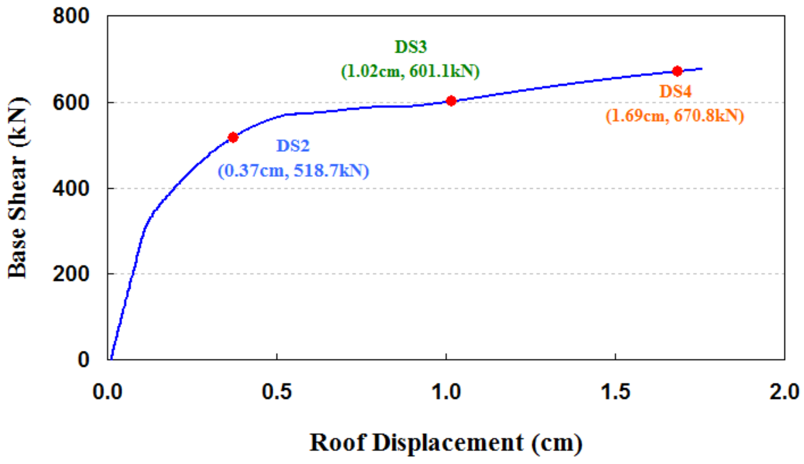
Identification of Damage States (DS):

- Thresholds based on inter-storey drift from Calvi [1999] are employed to define damage states for the masonry building.
- **For base-isolated building: a damage state is added to evaluate the damage of U-FREIs in base isolation system (DS5). The damage state limit of horizontal displacement of U-FREIs is considered at hardening behaviour with u_h = 155 mm (i.e. 1.70t_r).**

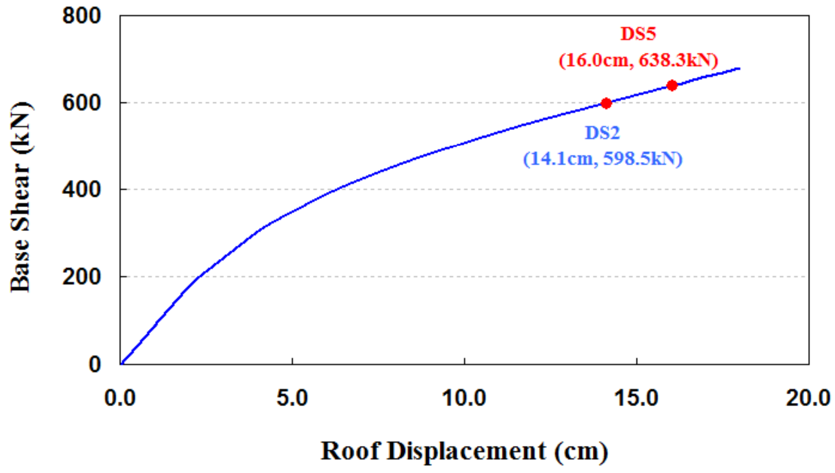


Performance levels on pushover curve (Calvi [1999])

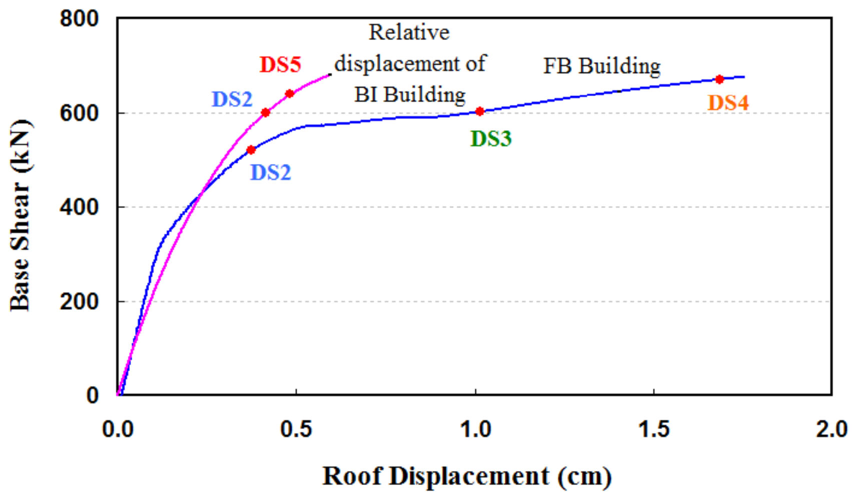
Vulnerability assessment of masonry building: - Pushover analysis



(a) FB building

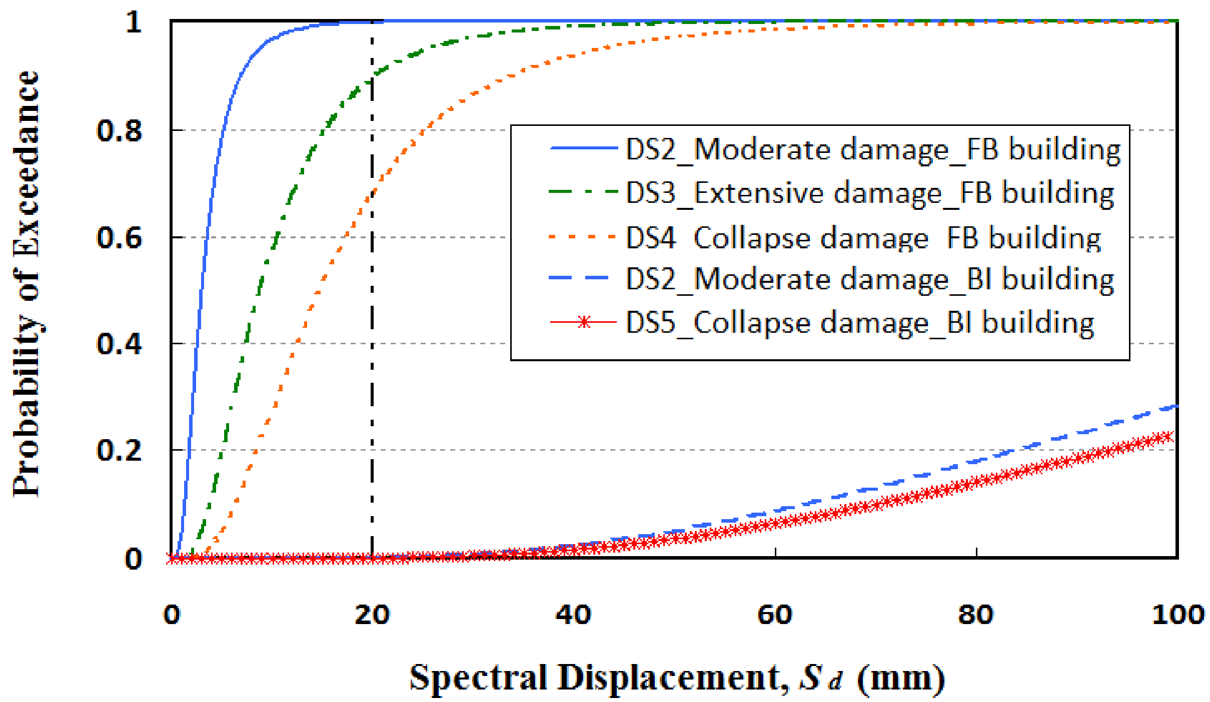


(b) BI building



(c) Comparison of pushover curves of fixed-base and relative base-isolated buildings

Comparison of fragility curves of FB and BI building



Ngo, T.V., Deb, S.K. and Dutta, A. (2017), "Mitigation of seismic vulnerability of a prototype low-rise masonry building using U-FREIs", accepted for publication in ***Journal of Performance of Constructed Facilities,*** ASCE

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Thank you for your kind attention