INVESTIGATIONS ON SEISMIC RESPONSE OF LRB EQUIPPED WITH SMA WIRE

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Abstract - *Shape memory alloy wire-based lead rubber bearing is new type of smart isolators. They possess superior self-centering property with unique hysteresis and energy dissipation capacity compared to traditional elastomeric isolators. The objective of the study is to investigate the effectiveness of LRB equipped SMA by using ABAQCUS FEM platform by developing finite element model of conventional and SMA LRB. To analyze the response of a ten-story building isolated with SMA LRB. For evaluating the performance of SMA LRB isolation system in structural applications, non-linear dynamic time history analyses of the ten storied building was conducted in the fixed model and model equipped with SMA LRB 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 building. Thus, SMA equipped LRB base isolation are found to be very effective in reduction of the seismic effect for multi-story building*

Key Words: **Base isolation, LRB, SMA wire, ABAQUS, Non linear time history analysis**

1.INTRODUCTION

Base isolation is one of the most popular means of protecting a structure against earthquake forces. It is a collection of structural elements which should substantially decouple a superstructure from its substructure resting on a shaking ground thus protecting a building or non-building structure's integrity. Seismic base isolators are of different types. Elastomeric bearings like laminated rubber bearings, fiber reinforced rubber bearings, lead rubber bearings, high damping rubber bearings etc. Frictional bearings like friction pendulum bearings, flat surface sliding bearings etc. and Magnetorheological bearings.

W. H. Robinson (1982), has provided Lead-rubber hysteretic bearings in a single unit the combined features of vertical load support, horizontal flexibility and energy absorbing capacity required for the base isolation of structures from earthquake attack.

I N Doudoumis (2005), [2]Two alternative micro-models were formed and investigated, in an attempt to define the bounds of the effects of the lead core's confinement to the behavior of the bearing. Shear experienced by the system was less when there is no bond between lead core and rubber.

Wilde et al. (2000)[6], studied the seismic response of bridges with LRB and shape memory alloys (SMA)The proposed isolation system utilizes the different responses of the SMA at different levels of strain to control the displacements at various excitation levels.

M.Shahria Alam et al. (2012), this study was devoted towards evaluating seismic performance of a three-span continuous highway bridge subjected to moderate to strong earthquake ground motions in its longitudinal direction. Two types of isolation bearings were used in the analysis: high damping rubber bearing (HDRB) and SMA-rubber bearing (SRB) consisting of Ni-Ti SMA wires and natural rubber bearing. The seismic responses of the bridge are affected by the use of different isolation systems; more specifically the displacements of the bridge pier are noticeably reduced in the case of SRBs compared to those in the case of HDRBs.

F Hedayati Dezfuli et al. (2013)[8], in this study, a diagonal configuration of SMA wires is proposed for natural rubber bearings and its performance was compared to the straight arrangement. In terms of the lateral flexibility and wire strain level, the smart rubber bearing with a cross configuration of SMA wires is more efficient.

1.1 SMA-Based Lead Rubber Bearing

SMA-based smart base isolators will have many advantages, such as stability, recentering capability, high energy dissipation capacity and long service life. They will not only mitigate the seismic response of structures in terms of acceleration, displacement and internal forces, but they also will have superior performance in terms of fatigue properties and energy dissipation capacity compared to existing lead rubber bearings. Regarding the variable properties of shape memory alloys (e.g. stiffness), they are suitable candidates to be incorporated in seismic base isolators which are subject to various excitation forces with different magnitudes and frequencies (Wilde et al 2000). For example, with small external loadings, such as winds or small earthquakes, SMA based lead rubber bearings can act as a stiff link to prevent damage in the expansion joints or other supporting elements of the bridge. In mid-size earthquakes, SMA-based elements enhance the damping capacity of the rubber bearing due to the stress-induced martensitic (SIM) transformation. In strong ground motions, in addition to providing additional hysteretic damping, they can confine the relative displacement of the deck in the design range. This characteristic is due to stiffness hardening of shape memory alloy after completion of the austenite to martensite phase transformation. Although there is a big difference in the hysteretic responses of an SMA device (flag-shaped hysteresis model) and an LRB (elasto-plastic model), both systems have similar displacement and force demand.

The objective of the paper was to investigate the effectiveness of LRB equipped SMA for highway bridges by using ABAQUS FEM platform

- By developing finite element model of conventional and SMA LRB
- By analyzing the performance of conventional LRB, and cross SMA LRB
- To investigate the response of a ten-storey building isolated with SMA LRB.

2. NUMERICAL MODELLING OF LEAD RUBBER BEARING

3D finite element model were created and analyzed using ABAQUS FEM platform. Fig-1 illustrates the FE model of the LRB investigated in this study, with an indication of the main geometrical characteristics. It consists of alternative layers of rubber of 5 mm and steel layers of 2.3mm, with a central lead core of diameter 40 mm. There were 7 layers of rubber and 6 layers of steels of cross section 210mm × 210mm. Cross section of loading plate was 360mm × 360mm. [9]

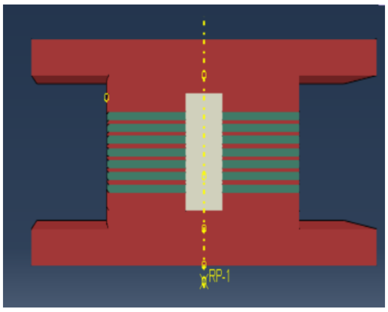

Fig -1: Geometry of the FE model of the UFREI

There are different material models are available in ABAQUS for rubber elasticity. Rubber is categorized as hyper viscoelastic material, Here, Ogden hyper elastic model is combined with a 2-parameter Prony viscoelastic model and the whole model is attributed to the elastomer Material constants of the hyper viscoelastic model are listed in table 1

Table -1: Hyperviscoelastic model parameters

Hyper Elastic - Ogden Model	Visco-Elastic – Prony Model
$\mu_1 = 1.89 \times 10^6 \mathrm{N}/m^2$	$a_1 = 0.3333,\ t_1 = 0.04$
$\mu_2 = 3.6 \times 10^3 \mathrm{N}/m^2$	$a_2 = 0.3333,\ t_2 = 100$
$\mu_2 = 3.6 \times 10^3 \mathrm{N}/m^2$	
$\propto_1 = 1.3, \propto_2 = 5, \propto_3 = -2$	

Reinforcement and supporting end plates are made of mild steel, which is modeled as an isotropic material with an elastic modulus of 210 GPa and a Poisson's ratio of 0.3.lead is simulated using a bilinear material model with a modulus of elasticity of 18 GPa, a Poisson's ratio of 0.43, a yield strength of 10.5MPa.

Contact between the parts of the bearing is assumed to be bonded. This type of contact can be implemented in ABAQUS with TIE constraint. The bottom surface of the bearing is fixed for all rotation and translations. A vertical pressure of 7.84 MPa, and a lateral frequency of 0.01 Hz. Cyclic sine wave loading is provided in the lateral direction.[9]

8 Node Hexahedral elements are used for meshing. The reason being they predict deformation accurately. The Rubber are by default assigned as hybrid elements. The meshing is done with 8 node solid hexahedral brick elements. C3D8R (An 8-node linear brick, reduced integration, hourglass control) for steel and lead material, C3D8H (An 8-node linear brick, hybrid, constant pressure) for Rubber material. In general, the hybrid elements are used for incompressible materials to avoid volumetric locking.

3. HORIZONTAL CHARACTERISTICS OF LRB

The operational characteristics of bearings are obtained from the lateral force-deflection hysteresis curves plotted at different amplitudes. Shear forces are plotted against the shear strain percentage to obtain the hysteresis loop for the isolator. Chart-1 shows the hysteretic shear behaviour at 20% - 150 %. At smaller strain of 20% slightly linear behaviour is observed but as the strain in increases non-linear behaviour is observed

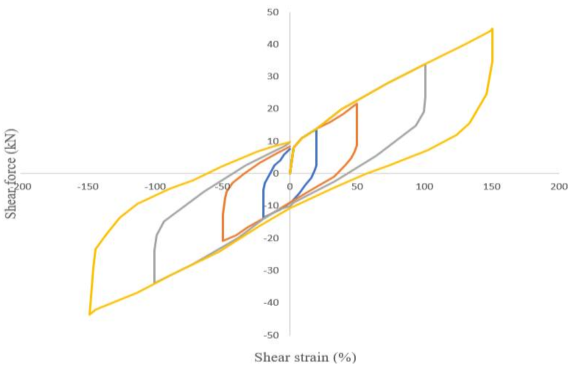

Chart-1: Hysteretic shear response of LRB at 20%, 50%, 100% and 150% shear strains

The shear force is plotted against the applied horizontal displacement. By computing the hysteretic behaviour of LRB, 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 LRB. The plots obtained were analyzed to obtain the effective horizontal stiffness (K^h_{eff}) and damping ratio (β).

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

F_{max} is maximum value of shear force, F_{min} is minimum value of shear force, d_{max} is maximum value of displacement, d_{min} is minimum value of displacement. The area contained in the hysteresis loop in force vs displacement curve gives the energy dissipated. The damping ratio was calculated as

$$\beta = \frac{W_d}{4\pi W_s} \qquad \text{Equation 3.2}$$

W_d is the dissipated energy and evaluated as the area under hysteretic loop, W_s is elastic energy and is written as

$$W_s = K^h_{eff} {\Delta_{max}}^2 \qquad \text{Equation 4.3}$$

Δ_{max} is average of positive and negative maximum displacement.

Table -2: Results of horizontal stiffness and damping ratio of LRB

Displacement percentage	Effective horizontal stifness (kN/m)	Damping ratio (%)
50	1188.01	19.97
100	887.589	17.87
150	749.95	14.91

It indicates that the effectiveness stiffness of the device decreases as the level of shear strain increases while the damping ratio slightly increases increases with increasing level of shear strain under same vertical stress. Decrease in horizontal stiffness tend to increase the lateral flexibility of the elastomeric isolator leading to an increase in the fundamental periods of the isolation system and accordingly improves its performance of the structure. However damping ratio show any trend, and its average is approximately 17.583%.

4. MODELING OF SHAPE MEMORY ALLOY WIRE

Lead rubber bearing is placed and fixed in its location and then, SMA wires is mounted on the bearing. In generating the finite element model of SMA-LRBs, a method of superposition is implemented in order to simplify the system by decoupling the rubber bearing and SMA wires. Here, a smooth contact is assumed between the steel hook and the SMA wire. This assumption considerably reduces the complexity of the finite element simulation. Decouple SMA-LRB is shown in Fig- 2. Here 2.5mm radius wire is used.[7]

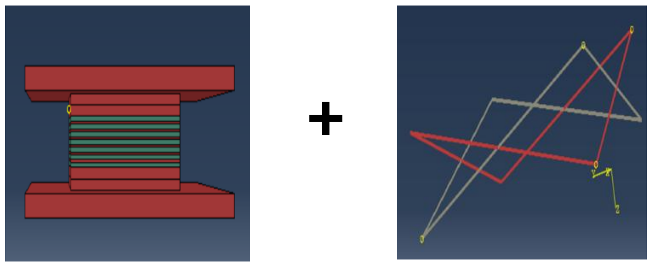

Fig- 2 Decoupled SMA-LRB

For the SMA wire, a user defined material model according to Auricchio's approach is used for expressing super elastic behaviour of SMA.SMA material property is not available in ABAQUS material models.so it is required to give UMAT (user defined material) coding in the subroutine level. T3D2: A 2-node linear 3-D truss element is used for SMA wires. Loading condition same as that of LRB is given here.[8]

By evaluating the responses of decoupled models of LRB and SMA, the hysteresis of SMA equipped LRB 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-shear strain curves of the SMA wire device are combined with the shear force-displacement curve of the LRB obtained through the 3D FE model. The combined curve is shown in chart-2. The horizontal characteristics of SMA-LRB is calculated using equation 3.1 to equation 3.3. The results are listed in table-3

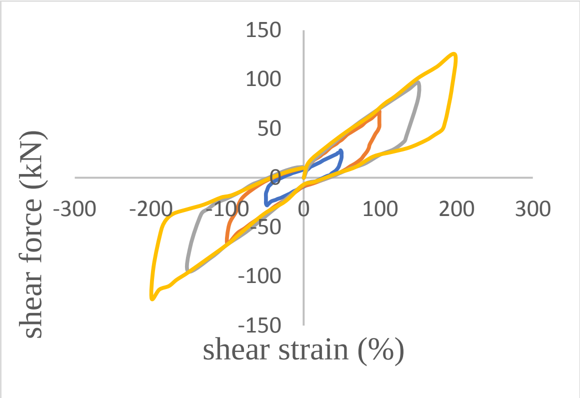

Chart-2: Hysteretic shear response of SMA LRB at 50%, 100%, 150% and 200% shear strains

From the chart-2 it is observed that at low shear strains (e.g. 50%), the behaviour of SMA-LRB is almost the same as that of the LRB. The reason is that at γ=50%, SMA wires are not activated since no transformation happens from austenite to martensite. When the shear strain goes above 100%, the effect of the flag-shaped hysteresis of SMA can be observed on the overall behaviour of SMA-LRBs.

Table -3: Results of horizontal stiffness and damping ratio of SMA LRB

Displacement percentage	Effective horizontal stiffness (kN/m)	Damping ratio (%)
50	1597.142	11.70
100	1857.143	12.44
150	1809.523	13.35
200	1785.714	19.97

Here also the effective horizontal displacement decreases with shear strain. But the stiffness is increased as compared to the LRB. When on comparing horizontal stiffness of SMA LRB to LRB and SMA LRB it can be seen that there is an increase in horizontal stiffness of SMA LRB as compared to LRB. SMA has a high initial elastic modulus in the austenite phase, which may increase the effective horizontal stiffness. The stiffness at 50 % for both bearing is having much closer value this is because SMA wires are not activated since no transformation happens from austenite to martensite. It is visible that the area under the curve is increased as compared to the area under in the case of LRB. So, this indicate an increase in energy dissipation capacity and increase in damping ratio.

5. MODELLING AND ANALYSIS OF MULTI STORY BUILDING

Dynamic analysis is carried out with ETABS 15 software package. Non-linear modal time history analysis is carried out. This type of analysis is termed as Fast Non-Linear Analysis (FNA) in ETABS software. In this analysis the non-linear properties of link element that is isolator are considered. A plan symmetric structure is selected for the analysis. generally base isolation is done only for plan symmetric structures. The Fig-3 and Fig-4 shows plan and elevation of the frame structure respectively. The column to column spacing is 5 m. total plan area is 25 m x 25 m.

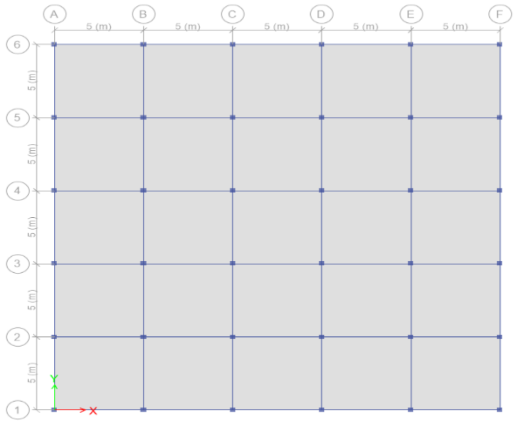

Fig-3 Plan of the selected structure

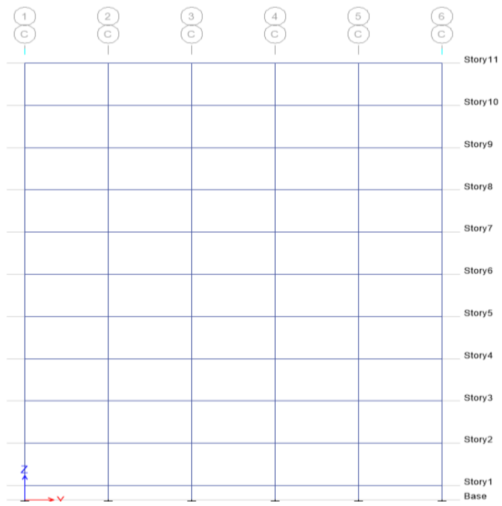

Fig-4 Elevation of the selected structure

The total height of the building is 39 m. Each story having a height of 3 m, the building consists of 10 stories. Columns at the base are connected by beams to prevent excessive stress formation at the joints of story 1 level. Generally, all isolated buildings are connected the columns with beams in base level.

Table 4 Properties of the structure

Materials	M30 concrete and Fe550 steel
Beam	300 mm x 450 mm
Column	300 mm x 300 mm
Slab	150 mm thick
Story height	3 m
Number of stories	10
Span length of beams	5 m
Plan dimension	25 m x 25 m

All beams in the structure are loaded by the weight of brick infill wall that is 13.77 kN/m (0. 3× unit weight ×clear height), for parapet load is 3.6 kN/m. Floor load of 5 kN/m2 is applied to all the floors. This load includes imposed dead and live load. This load is defined in dead load case in order to consider the mass contribution from this load also. Earthquake time history data of Corralitos, California state, USA is used to define ground acceleration.

Both fixed base and isolated bearing models were analysed and designed in ETABS 2015 software. Link element is used for analyses with base isolation. A link object connects two joints, i and j, separated by length L, such that specialized structural behaviour may be modelled. Here base isolation is done with SMA LRB isolator. Table 5 shows the input parameters of link element.

Table 5 Properties of link element

Vertical Stiffness = 3370.236 kN/mm	
SMA LRB	
Displacement (mm)	Force (kN)
-70	-125.35
-52.5	-96.99
-35	-67.73
-17.5	-27.95
0	0
17.5	27.95
35	67.73
52.5	96.99
70	125.35

6. RESULTS AND DISCUSSIONS

Both fixed base and isolated bearing models were analysed and designed in ETABS 2015 software. The main seismic parameters selected for the comparison of models are time period, story response and base shear.

6.1 Time period

Time period of structure is defined as time taken to complete one oscillation. Usually time period is more for 1st mode shape which is known as fundamental period. Value of time period depends on the building flexibility and mass. In general, taller buildings are more flexible and have larger mass, and therefore have a longer time period. The fundamental time period of the fixed base building is 2.27s, that of base isolated building by SMA LBR is obtained as 4.772. This will increase the time of oscillation and thus this will improve the performance of building under seismic loading.

6.2 Base shear

The base shear obtained is 40069 kN for fixed base and 13384kN for base isolated building by SMA LRB. 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 Response

Chart-3 shows storey displacement of 36.5mm and 40.2mm in x and y direction respectively at the ground level of the base isolated building. It is found that the storey displacement is 0mm at ground level for fixed base building and 40.2mm mm for base isolated building. The base isolated building has more Storey displacement as compared to the fixed base building. The is seen that there is a large inter storey displacement in the case of fixed base. Inter storey displacement is also reduced when isolation is used. From the results it can be seen that the SMA LRB is able to provide amount of motion at base level and reducing the inter storey displacements compared to the fixed base condition.

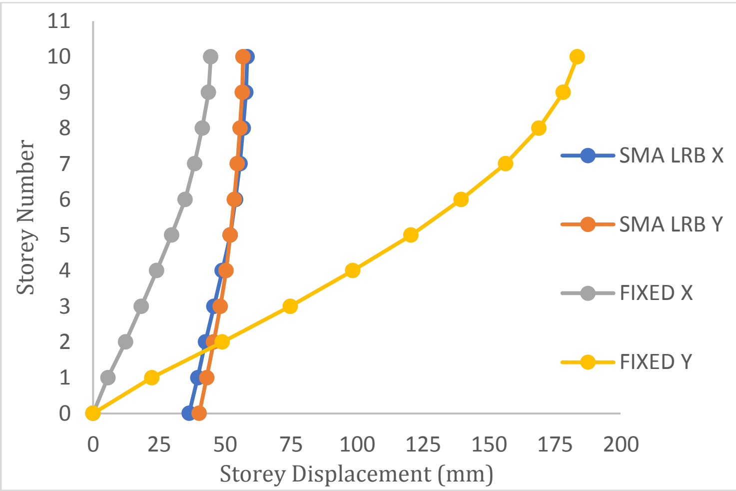

Chart-3 Variation of story displacement along height

SMA equipped LRB, SMA-LRB, was evaluated in this study by wrapping Nitinol SMA wires, around the LRB in a cross configuration. Here, a superposition method was used for modelling and analyse of SMA wires and LRB. A ten-storied framed building supported on base isolators (SMA, SMA LRB) is selected to evaluate seismic vulnerability underground motions. Threedimensional FE models are simulated for both fixed base and base isolated building, and nonlinear time history analyses are carried out for the above building buildings.

The results can be summarized as follows:

• At shear strain levels lower than 50%, no phase transformation happens in SMA and as a result, wires are not activated. Therefore, SMA-LRB and the LRB have almost the same behaviour up to 50% shear strain. The reason is that at γ=50%, SMA wires are not activated since no transformation happens from austenite to martensite, When the shear strain exceeds 50%, the super elastic effect and the flag-shaped hysteresis of SMA wire cause increase in the energy dissipation capacity of SMA-LRB.

• Time period of the structure increases by the use of SMA LRB base isolators which reduces the transfer of lateral forces at the time of earthquake.

• Base isolated models showed reduced base shear compared to fixed base building. Combining the LRB with SMA helps to reduce the base shear.

• All the fixed base building show zero displacements at the base whereas, the base isolated building show increase in amount of Storey displacements at base.

• The results show that the responses of structures can be reduced by the use of the SMA LRB.

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

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