International Journal of Scientific & Engineering Research, Volume 7, Issue 10, October-2016
ISSN 2229-5518

Nonlinear Analysis of High Damping Rubber Bearing with Different Material & Geometry

Neethu K Assainar, Dr Sreemahadevan Pillai P R

Abstract— High damping rubber bearings are amongst the most commonly used devices for seismic isolation. Components of laminated rubber base isolator are a flexible material and a reinforcing material. Conventionally used reinforcing material is steel. Nowadays different fibre reinforced polymers (FRP) which have strength comparable to steel are developed. By replacing steel by FRP sheets, we can have the advantage of light weight and easier manufacturing of different geometry. The isolation efficiency and cost can be optimized by considering material, geometry, orientation of fibres in FRP sheets and changing the design parameters. Here, nonlinear finite element analysis is conducted on high damping rubber isolators with steel and CFRP in 3 different geometry using ANSYS under vertical and lateral load.

Index Terms— CFRP, FREI, Geometry, High damping Rubber Bearing, Orientation, SREI, Stress contour

1 Introduction

BASE isolation plays an important role in seismic protection of structures. It is a collection of structural elements which should substantially decouple superstructure from its substructure resting on a shaking ground. The technique was developed to prevent or minimize damage to buildings during an earthquake by reducing seismic stresses in an effective way.

This study is intended to understand the behaviour of laminated rubber bearing by replacing the steel by CFRP and with different geometry and configuration. Numerical modeling is done in ANSYS 11 and nonlinear analysis is conducted.

2 Theoretical Background

In rubber bearings, the building or superstructure is decoupled from the horizontal components of the earthquake ground motion by interposing a layer with low horizontal stiffness between the structure and foundation. This gives the structure, a fundamental frequency that is much lower than its fixed base frequency and also much lower than the predominant frequencies of ground motion. The first dynamic mode of the isolated structure involves deformation only in the isolation system. The structure above being to all intents and purposes rigid. The higher modes that will produce deformation in the structure that are orthogonal to the first mode and consequently also the ground motion. These higher modes do not participate in the ground motion, so that if there is high energy in the ground motion at these higher frequencies, this energy cannot be transmitted into the structure.

- *Neethu K Assainar is currently pursuing masters degree program in Structural Engineering in NSS College of Engineering, Palakkad.PH-9946807265, E-mail: neethuk787@gmail.com*
- *Dr. Sreemahadevan Pillai is currently working as Professor in Department of Civil Engineeringineering in NSS College of Engineering,Palakkad.PH-9447056075,E-mail: sreemahadevanpillai@gmail.com*

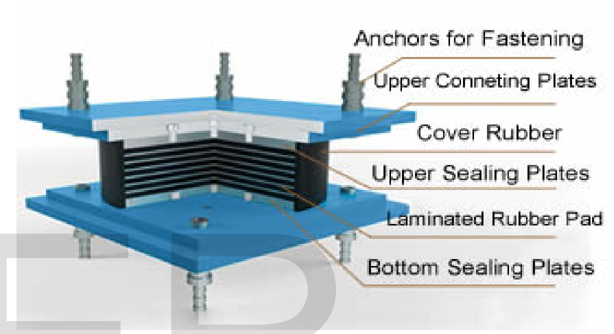

Fig. 1. Laminated Rubber Bearing

The laminated rubber bearings for base isolation devices are made of alternating thin horizontal layers of natural or synthetic rubbers bonded to steel plates.Several systems of isolation exists, the most predominant is the use of base isolation techniques involving the separation of a structure from the ground with the use of rubber bearings

The steel plates prevent the rubber layers from blown up or busting. They are bonded together to provide vertical stiffness and horizontal flexibility. On the top and bottom, steel plates are used to attach the bearing to the foundation. The internal steel layers do not restrict horizontal deformations of the rubber layers in shear. So, the bearings are much more flexible under lateral loads than vertical loads. This is why the bearing behaves as flexible unit. Steel can be stretched to about 2% of original dimension while still remaining elastic. Rubber on the other hand can keep most of its elasticity when stretched anywhere from around a hundred to several hundred percent.

One of the distinguishing mechanical properties of rubber is its capacity to recover from large deformations. Certain rubber compounds can recover from nominal strains of up to 600%. What is particular about this behaviour is the nonlinear stress-strain relationship encountered throughout such deformation. It is generally characterized by initial softening, then sudden stiffening as the material approaches its elongation limit.

Seismic isolators are usually made with compounds known as high damping rubbers (HDR) that are nonlinear and have

ISSN 2229-5518

large hysteresis which can make interpretation of the measurements difficult. But in some cases, the compounds known as linear natural rubber (LNR) have almost no hysteresis and are very linear in shear up to very large shear strain. High damping rubber bearing, also known as HDR, has very similar appearance to lead rubber bearings, but they are totally different in nature. High damping rubber bearing is composed of special rubber with excellent damping attribute, sandwiched together with layers of steel without any lead plugs.

HDR adopt best rubber material of high damping ability, which enable it to absorb large energy of earthquake, taking advantage of its high elasticity, friction damping and viscosity damping characteristics as well as high durability. The bulk modulus is several orders of magnitude larger than their shear modulus, so that the material will deform only in shear. The behavior of the rubber bearing is affected by the loaded area and hence the shape factor. A linear elastic theory is the most common method to predict the compression stiffness of a thin elastomeric pad. When the vertical load is applied the height of the rubber decreases and in the meantime the rubber overflows on the lateral part of the isolator.

Typical shape factors for bearings of different shapes are as follows,

b/t - for an infinite strip of width, 2b

R/2t - for a circular pad of radius, R

a/4t - for a square pad of side length, a

where, t is the single-layer thickness.

The vertical stiffness of the bearing is several hundred times the horizontal stiffness due to the presence of internal steel plates. Horizontal stiffness of the bearing is controlled by the low shear modulus of elastomer, while steel plates provides high vertical stiffness as well as prevent bulging of rubber. High vertical stiffness of the bearing has no effect on the horizontal stiffness. Elastomeric isolators usually possess very small tensile strength and develop relatively large strains during tensile loading. Tension stresses cause a set of small cavities within the bearing rubber, which grow progressively under cyclical loading. This significantly reduces the vertical stiffness of the isolators. The vertical stiffness of a rubber bearing is given by the formula,

$$K_v = E_c A / t_r \quad (1)$$

where, A - area of the bearing,

gjddgadgdzgddddzdvzzdgzd t_r - Total thickness of rubber in the bearing

E_c - Instantaneous compression modulus of the rubber-steel composite under the specified level of vertical load.

The compression stiffness determines the ability of the material to bulge when it is subjected to the vertical load. If the laminate is stiff, it results in less ability to bulge. It is the property that makes the rubber bearing capable to carry the vertical load. The capacity to undergo deformation varies with the geometry and configuration. The shear stiffness of the laminated rubber bearing is directly proportional to the cross sectional area 'A' and inversely proportional to its height 't'. The shear stiffness is given by 'k_s' must provide an appropriate natural period of lateral oscilation for the structure.

$$k_s = GA/t \quad (2)$$

where 'G 'is the shear modulus. For a number of layers ' n' in a bonded stack in a bearing to give a total thickness 'T', T = t_n.

Then, $$k_s = GA/t_n \quad (3)$$

Thus while a structure can be made very flexible laterally by increasing the height or decreasing the cross sectional area of a bearing, a compromise is to be reached in the design.

3 Scope of the Work

The scope of the work is limited to the non-linear finite element analysis of the isolator in finite element software ANSYS by taking into consideration the loads acting on it, as the three dimensional modelling of the frame along with the isolator is time consuming. The scope of the work is limited to modeling the isolator alone with the load due to the building applied as compressive load. Only circular, rectangular and square geometries are analysed. FRP with comparable strength to steel is used as a replacement for steel layer.

4 Methodology

Modelling of steel reinforced elastomeric isolators(SREI) and fibre reinforced elastomeric isolators(FREI) is done in ANSYS, by choosing appropriate elements and material model for steel, CFRP and high damping rubber. Performance of SREI and FREI is compared, by conducting displacement controlled nonlinear static analysis. Circular, rectangular and square isolators are modelled and the results are compared by displacement controlled nonlinear static analysis. In the case of FREI, unidirectional and bidirectional CFRPs are compared.

5 Objective of the Project

- To study the behaviour of high damping rubber bearing
- To compare the isolator performance with steel and fibre
- To study the economical aspects of high damping rubber
- To study the effect of geometry on isolator performance
- To study the effect of number of layers on isolator performance
- To study the effect of orientation of fibres and thickness of reinforcing and rubber layer

6 Modelling in Ansys

6.1 Material Model

For the present study the software used is ANSYS 11. Thus the numerical modelling needs to take care of high material and geometrical nonlinearities. Normally 3-D finite element modelling is adopted to analyse the laminated rubber bearing. The hyperelastic material is characterised by the existence of strain energy function W, measured per unit volume of reference state, which is a function of deformation gradient.

The form that has been adopted is:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + C_{20}(I_1 - 3)^2 + C_{02}(I_2 - 3)^2 + C_{11}(I_1 - 3)(I_2 - 3) \quad (4)$$

Where, C_{10}, C_{01}, C_{20}, C_{02} and C_{11} are the parameters, they depend on the material that has to be model and should be chosen to fit the material behavior and is as follows.

C_{10} = 0.797, C_{01} = -0.0591, C_{20} = 0.01609, C_{02} = -0.00529, C_{11} = 1.103e-3

Steel is modelled as linearly isotropic material and fibres are modelled as linearly orthotropic material. SOLID185 is used to model the rubber. Shell63 is used to model steel and CFRP. Nonlinear MPC 184 is used for contact modelling.

Rubber layer is created as volume and meshed using hexahedral mapped meshing in the case of square, rectangular and circular bearing. Steel and fibre layer is created as area and mapped meshing is done. The rubber steel interfaces are defined with nonlinear multi point constraint elements.

Top and bottom nodes are used to impose all loads and boundary conditions to the model. Vertical and horizontal actions are applied by means of vertical force in Y direction and horizontal displacement in X direction, respectively. Bottom node is fixed ($U_x = U_y = U_z = R_x = R_y = R_z = 0$) and loads are applied at the top node. For circular model only half the isolator is modelled and so symmetric boundary conditions are applied on the symmetric plane.

6.2 Geometry of Models

For the current study, the following dimensions are chosen and the single laminate with single steel layer sandwiched between two rubber layers is studied. Then the full thickness is created by repeating the steps. For all the geometries the top area is kept equal but with different shape factors.

Diameter of circular bearing, D = 250 mm
Size of square bearing, a = 220 mm
Size of rectangular bearing,2lx2b = 320 mm x 150 mm
Thickness of Rubber layer = 2.5 mm
Thickness of Steel layer = 1 mm
Number of layers = 6
Total thickness of rubber = 15 mm

Shape factor for the adopted geometries are as follows.
For square bearing, Shape factor, $S_s = a/4t$
For circular bearing, Shape factor, $S_c = D/4t$
For rectangular bearing, Shape factor, $S_r = b/t$
$S_s = 3.66$, $S_c = 4.16$, $S_r = 5$

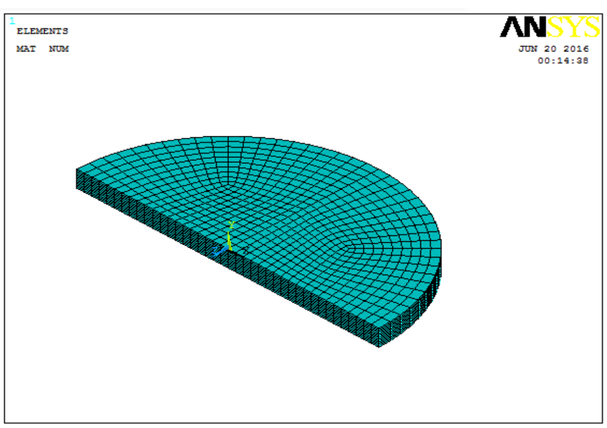

Fig. 2. Circular isolator modelled

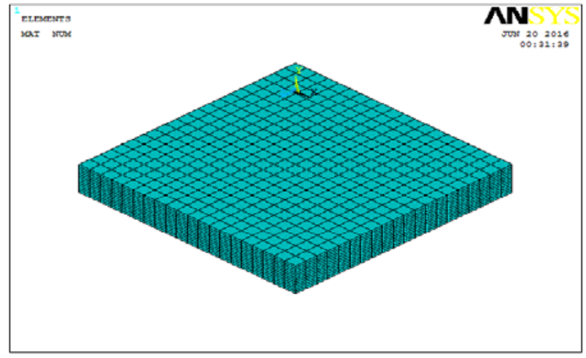

Fig. 3. Square isolator modelled

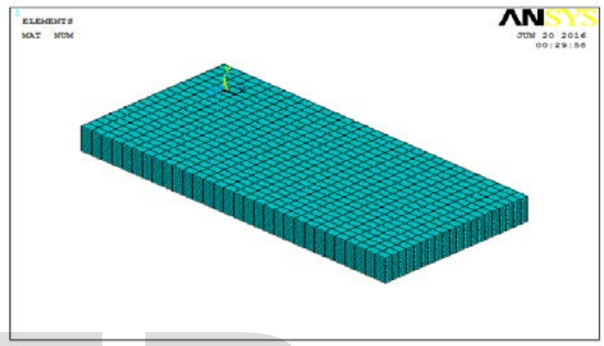

Fig. 4. Rectangular isolator modelled

7 Results and Discussion

7.1 Comparison Between SREI and FREI

Rubber behaves as nonlinear in laminated rubber bearing. Hence linear analysis is not adequate to study the behavior of rubber, thus a nonlinear static analysis is carried out. The combination of vertical and horizontal forces can create a critical condition for the isolators. Hence model was subjected to vertical load as well as horizontal load due to earthquake forces acting on it.

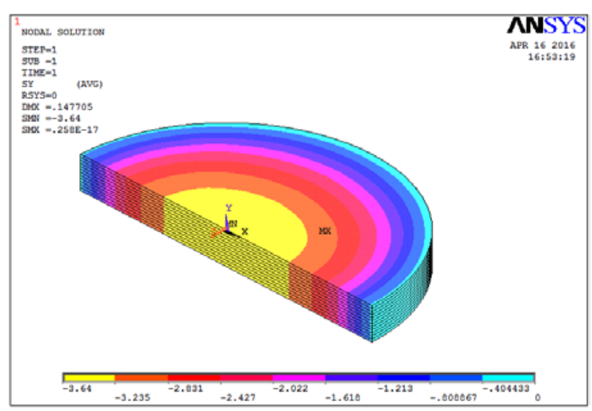

Fig. 5. Vertical stress contour(SREI)

For comparing the performance of FREIs and SREIs, 12 layered circular isolators were selected.

ISSN 2229-5518

In case I, only constant vertical load is applied. This is important because under no other lateral displacements or forces, the isolator is only subjected to vertical load from the superstructure.

TABLE 1
ANALYSIS CASES FOR COMPARING SREI AND FREI

Analysis case	Applied load (F_y) kN	Applied displacement (U_x) mm
I	50	
II	50	30
	50	60
	50	90
	50	122

Under vertical load, the tensile stress is negligible. All other stresses are negligible because there is no lateral displacement is applied. At the time of earthquake, the vertical load in the structure increases. Since the isolator stresses under constant vertical load is far away from failure, it can take increased vertical load at the time of earthquake.

The performance of isolators under lateral load is analysed by displacement controlled nonlinear static analysis. Lateral displacement corresponding to 100%, 200% etc of shear strain are applied until the failure of the model along with the constant vertical load. In all aspects, FREIs have lesser stress compared to SREI. In SREIs the reinforcing layer is steel and it is isotropic, possessing the same mechanical properties in all direction. But the FRP layer is orthotropic which has different mechanical properties in 3 mutually perpendicular directions. The FRP used here is CFRP (carbon fibre reinforced polymer), the properties of which are highly varying. So the performance of FREIs can be varied accordingly by selecting the suitable CFRP. Steel reinforcing layer is inextensible and rigid in flexure.

CFRP consists of fibres grouped and coiled together and it is more flexible in tension and flexible in bending. During shear loading the plane cross section become curved. Tension in the chords acting on the curvature of the CFRP layer causes individual strands to slip resulting in additional frictional damping.

TABLE 2
COMPARISON OF STRESS OF SREI AND FREI (ANALYSIS CASE I)

	FREI	SREI
Sx	6.776	7.66
	-3.074	-3.638
Sy	-3.074	-3.64
	0	0
Sz	-3.074	-3.638
	10.76	12.016

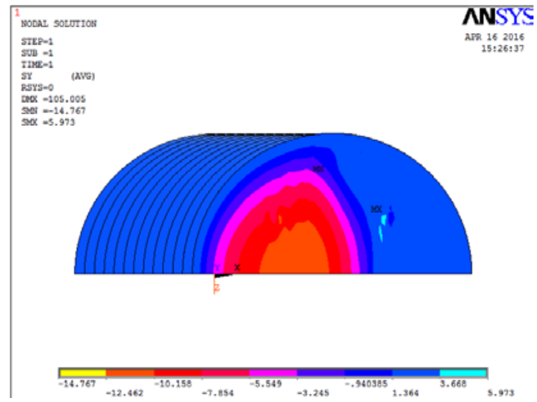

Fig. 6. Vertical stress (SREI) – Case II

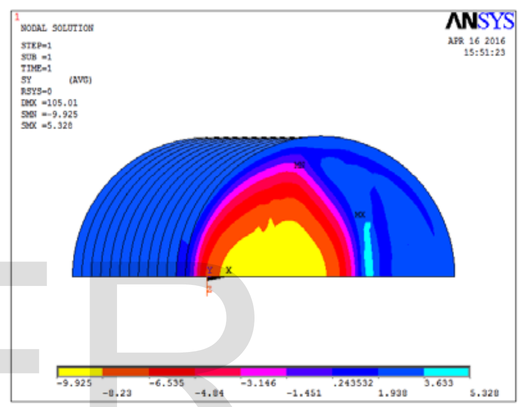

Fig. 7. Vertical stress (FREI) – Case II

The CFRP layer may be unidirectional or bidirectional. The orientation used here is alternate CFRP layer with 0 degree and 90 degree.

Generally, high damping rubber can withstand 400% shear strain. But using it in isolator with intermediate reinforcing layer (steel or CFRP) , how much shear strain can these isolators withstand? This is the question to be examined. By this nonlinear static analysis , it is observed that SREI and FREI with circular shape can withstand upto 400% shear srain without failure. But the permissible tensile stress in rubber is 3 times its shear modulus(1.42 MPa) approximately 5 MPa. This permissible limit reaches near at 350% shear strain. FREIs reaches this limit first. Above this tensile stress, cavitation may occur in rubber. From this it is clear that,high damping rubber isolators are stable upto 350% shear strain.

From the results , it is clear that vertical stress (compressive and tensile) is lesser in FREIs. In both FREIs and SREIs, maximum vertical stress occur in the rubber layer.

Both vertical stress and shear stress transfers across the area of contact. Contact stress is transmitted in the normal direction of isolator. Shear stress has greater magnitude in SREI. The maximum XZ shear stress occurs in the reinforcing layer. But XY and YZ shear stress maximum occurs in rubber layer. Rubber layer have less shear stress because rubber is highly extensible in shear. Because of this property, rubber is used as the flexible material in

ISSN 2229-5518

rubber isolator. Shear stresses are comparatively lesser than normal stresses.

In FREIs also, normal stress has lesser magnitude. Normal stress in X and Z direction is maximum in the reinforcing layers. All type of stresses have similar trend in each rubber layer and reinforcing layer. The maximum value will be always in the top. layer.

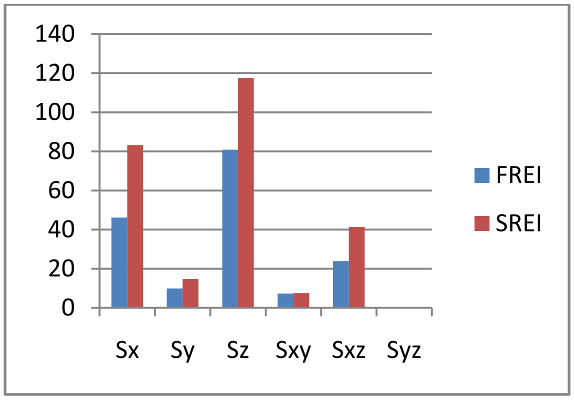

Fig. 8. Stress comparison between SREI and FREI

	7.31	7.3
Syz	-0.792	-0.676
	0.2	0.14
Sxz	-41.326	-23.928
	43.246	27.306

From the stress contours, it is clear that square, circular and rectangular have similar contour having greater compressive stress in the centre region of isolator and decreasing trend towards the outer. Square and rectangular isolators have only a slight difference in their stress values. These results are of FREIs. For SREIs, similar results were observed. For all the geometries, FREIs have lesser stress magnitude compared to SREIs.

TABLE 4
ANALYSIS CASE FOR COMPARING GEOMETRIES

Analysis case	Applied load (F_y) kN	Applied displacement (U_x) mm
I	50	
II	50	15
	50	30
	50	45
	50	60

TABLE 5
COMPARISON OF STRESSES OF 3 GEOMETRIES
(ANALYSIS CASE I)

	Circular	Square	Rectangular
Sx	7.2	-3.524	3.564
	-3.35	-1.492	-1.528
Sy	-3.35	-1.492	-1.529
	0	0	0
Sz	-3.35	-1.492	-1.528
	11.536	5.682	6.161

7.2 COMPARISON BETWEEN 3 GEOMETRIES

Comparison between circular, square and rectangular isolators is conducted on a 6 layered model. All geometries are having same top area and different shape factor.

Diameter of circular isolator = 250 mm
Size of square isolator = 220mx220mm
Size of rectangular isolator = 320mmx150mm

From the constant vertical load analysis, it is observed that, in all geometries no tensile stress develops. Compressive stress developed is greater in circular isolators. Square isolators have better performance under constant vertical load. All other stresses are negligible in all 3 geometries.

From the displacement controlled nonlinear static analysis, it is concluded that circular isolators can withstand higher shear strains than the other two geometries (380%). Rectangular isolators withstand 6.7% more shear strain than the square isolator. Similar to the analysis case I, square and rectangular isolators have similar behaviour in all types of stresses. Following results are plotted for 350% shear strain.

It is observed that, the variation of vertical stress along the length of isolator (diameter in the case of circular isolator) is different in circular isolator from rectangular and square. In rectangular and square isolator, the variation is exactly the same, but the stress magnitude is different as explained above.

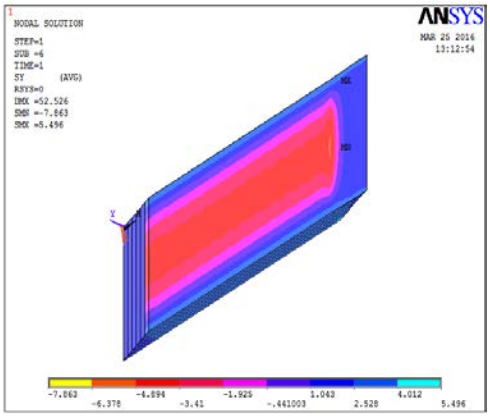

Fig. 9. Vertical stress in Rectangular Isolator

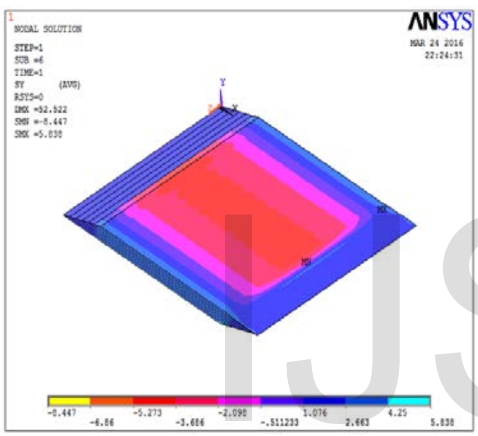

Fig. 10. Vertical stress in Square Isolator

The trend of variation is alike along the edge line and centerline (cross sectional line along the centre). Along the centre line, tensile stresses develop only at the end. At the centre portion of the isolator, no tensile stresses develop (in figure A) tensile stress is only at the end. Along edge, development of tensile stress starts from the end as the lateral displacement increases. At 300% shear strain (45 mm displacement), the edge of isolator is fully under tensile stress and it further increases and lead to failure.

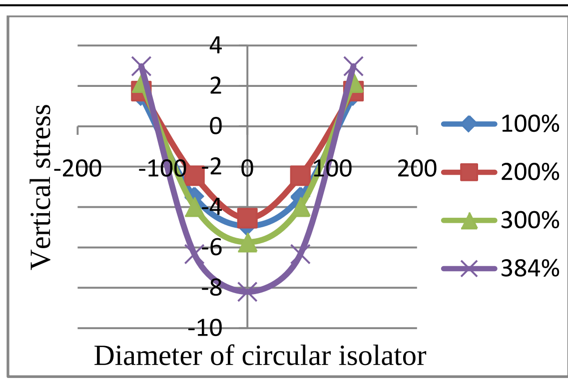

Fig. 11. Variation of vertical stress along the length

In circular isolator, tensile stresses develop only at the edges and the variation is same along all the diametrical section. In all isolators, maximum tensile stress develops at the extreme ends where the rubber is stretched maximum.

7.3 Orientation of Fibres in CFRP

TABLE 6

Comparison of Stresses of 3 Geometries

(Analysis Case II)

	Circular	Square	Rectangular
Sx	45.73	42.471	33.392
	-50.797	-58.52	-51.45
Sy	4.855	5.838	-5.496
	-7.029	-8.447	-7.863
Sz	89.246	79.437	97.182
	-66.732	-59.511	-74.571
Sxy	7.534	7.49	7.505
	-1.69e-8	-3.39e-15	-3.38E-15
Syz	0.144	0.772	0.836
	-0.74	-0.772	-0.836
Sxz	28.731	15.701	14.096
	-19.2	-15.701	-14.096

CFRP is a polymer – matrix composite. Fibre reinforced polymers consists of one species of polymer (carbon fibre) in a resinous matrix of another polymer. Orthotropic elastic properties of FRPs are determined by combining elastic properties of fibre and epoxy resin.

When unidirectional CFRP layer is used (fibres in only one direction), the isolator couldn't sustain the shear strain as much as that of bidirectional laminates and the stress values were greater. This is because; stiffness of unidirectional CFRP in x direction is greater and in the other two directions is less.

8 Conclusion

The conclusions drawn based on the study are:

High damping rubber bearings with steel as the reinforcing layer (SREI) are conventionally used for base isolation. Replacing the steel laminates with CFRP sheets, base isolation technique can be brought to a more economic level. Appropriate selection of material and design of components of isolators will lead to more economy and efficient seismic protection.

ISSN 2229-5518

Regarding the material for reinforcing layer, SREIs and FREIs can sustain equal amount of lateral displacement or shear strain. But lesser stress values were seen in FREIs under vertical and lateral load. And suitably selecting the best performance CFRP (CFRP sheets with better mechanical properties), efficiency of FREIs will improve. The failure of all isolators is due to the development of tensile stress in rubber. Bidirectional laminate show better performance than unidirectional laminates.

The manufacturing process of FREIs is easy compared to SREIs. Due to this reason various geometries can be made. When 3 different geometries with equal base area is examined, it is observed that circular, square and rectangular isolator have comparable performance. But circular isolators show better performance under lateral load. It takes more lateral displacement than other two (20% more). Square isolators take 6.7% less lateral strain than rectangular isolators. The development pattern of tensile stress in all geometries is from edges to the centre, since edges are more strained. All models could sustain lateral shear strain more than 360%.

REFERENCES

[1] Arya G and Dr. Alice Mathai, "Nonlinear Finite Element Analysis of High Damping Rubber Bearings for Base Isolation", *International journal of civil engineering and technology*, Vol.5, No.9, pp.252-259, 2014

[2] Botis M and Harbic C, "A Brief History upon Seismic Isolating Systems", *Engineering sciences*, Vol.5, No.1, pp.93-98, 2012

[3] Bhoje S.B, Chellapandi P, Chetal S, Muralikrishna R, Salvaraj T,"Comparison of Computer Simulated and ObservedForce Deformation Characteristics of Anti-Seismic Devices and Isolated Structures", Indira Gandhi Centre for Atomic Research, India, 1998

[4] Charles A Kircher, "Seismically Isolated Structures" *FEMA P – 751 NEHRP*

[5] Ghodke R .B and Dr. Admane S .V, "Effect of Base-Isolation for Building Structures", *International Journal of Science, Engineering and Technology Research* , Vol. 4, No. 4, pp.971-974, 2015

[6] Bianchi and Corradi dell'Acqua, "HDRB Isolating Devices: Criteria for FE Modeling and Failure Characterization", *Ricerca Di Sistema Elettrico, 2010*

[7] Gomase O.P and Bakre S.V, "Performance of Non-Linear Elastomeric Base-Isolated Building Structure", *International journal of civil and structural engineering*,Vol.2, No.1, pp.280-291, 2011

[8] James M Kelly and Niel C Van Engelen, "Single Series Solution for the Rectangular Fiber-Reinforced Elastomeric Isolator Compression Modulus", *PEER Report No. 2015/03 Pacific Earthquake Engineering. Research Center Headquarters at the University of California, Berkeley, 2015*

[9] Kelly J.M, Calabrese A and Serino G, "Design Criteria for Fiber Reinforced Rubber Bearings", *15th World Conference of Earthquake Engineering, 2012*

[10] Makoto Ohsaki, Tomoshi Miyamura, Masayuki Kohiyama, Takuzo Yamashita, Masas Yamamoto and Naohiro Nakamura, "High-Precision Finite-Element Analysis of Rubber Bearing for Base-Isolation of Building Structures",*4th ECCOMAS Thematic Conference, Kos Island, Greece*, pp.12–14, 2013