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Analytical and Experimental Overview of Fiber Reinforced Elastomeric Isolator

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***Abstract:** There has been many researches in order to further improve the Base Isolation system by trying various combinations and alternative materials. In that fiber reinforced isometric isolators are emerged as a viable solution, because for the low cost and effective response to seismic waves as compared to the conventional isolators. Studies further shows that it provides high vertical stiffness and low horizontal stiffness, also having effective damping over the conventional one. Developing countries who doesn't have proper seismic protection solutions have found this convenient as they are comparatively less in cost and doesn't require complex installation. Studies also shows Un-bonded FREI has lower horizontal stiffness and considerably lower stress demand on rubber material as compared to the B-FREI and hence significantly higher seismic isolation efficiency.*
***Keyword:** Bonded Fiber-Reinforced elastomeric Isolators (B-FREI), Unbonded Fiber-Reinforced elastomeric Isolators (U-FREI), Fiber-Reinforced elastomeric Isolators (FREI), Steel Reinforced Elastomeric Isolators (SREI), vertical stiffness, horizontal stiffness, damping.*

I. INTRODUCTION

To protect structures from earthquake numerous devices are being invented and used these days to control the vibration caused by the seismic waves. However these devices are heavy, costly and complex in terms of installation, which is challenging for developing countries. In the recent past base isolators has emerged as a viable solution to this. Base isolators are isomeric rubber pads which helps in reducing the amplitude of the range of frequency to minimize the effect of seismic waves on structure by increasing the natural period and reducing the stiffness. Also there has been lot of studies happened in this area to explore the various alternatives and combinations. Conventionally Steel Reinforced Elastomeric Isolators (SREI) was used, with further progress in the field Fiber-Reinforced elastomeric Isolators (FREI) were introduced by replacing steel plates with fiber material. Basis on their connection with structure FREI are further classified in two types.

II. BONDED FIBER-REINFORCED ELASTOMERIC ISOLATORS (B-FREI)

In B-FREI, thick mounting plates are used at both the ends of isolators. These type of isolators are installed by connecting the steels plates to super structure (top) and substructure (bottom) using bolt connections. B-FREI has different characteristics (mechanical) as compared to the conventional SREI. When the BREI is laterally deformed, the fiber-reinforcement goes warping deformation at the edges.

III. UN-BONDED FIBER-REINFORCED ELASTOMERIC ISOLATORS (U-FREI)

When In U-FREI the base isolators is directly placed between the sub structure and super structure, without any rigid connection like bolted connection on steel plates in B-FREI. During sysmic effect the shear load on the surfaces of isolators is transferred through friction. Furthermore we can improve U-FREI behavior by choosing a stable design for improved stability to withstand against earthquakes.

IV. LITERATURE REVIEWS

Many researchers and scholars have done experimental and analytical work in the field of isolators, specifically FREI. Below is brief about some of their research work.

Habieb, Milani et al. [2017] carried out an experimental study on the behavior of low cost rubber isolator going through different deformations by using 3D FE analysis. For rubber pads, The Yeoh Hyper elasticity model is used. To construct a two story house prototype, an isolation system is being used to identify the 3D model with damped nonlinear spring model. Concrete damage plasticity (CDP) model is used for constructing a masonry. To evaluate the performance of isolated building, non-linear static analysis is managed. Under seismic load, by monitoring damage level of the masonry, dynamic behavior of the building is observed using ground motion data and the results are simulated. This can improve the seismic performance of the structure in a cost effective way.

Das et al. [2014] did experimental analysis on square FREI when subjected to vertical loading and constant lateral cyclic displacement by analysis of systems (ANSYS), a FEM software along with 3D finite element analysis (FEA). To replicate deformation of incompressible hyper-elastic materials, Ogden (3-term) material and Lagrange multiplier-based made up elements were used. By vulcanization of sheets, these bearings were manufactured by using bi-directional carbon fiber. Two lateral directions of 0/90 and 45 degrees were taken into account for the analysis of bearings with both boundary conditions namely, bonded and un-bonded. Efficiency of seismic isolation is higher than 0 degrees mounting direction and the outcome is that lateral stiffness of B-FREI is higher at higher later displacement when compared to U-FREI. Numerical results were taken with an experimental validation and mechanical properties of U-FREI are in good harmony with the deformed configuration.

Nezhad [2014] suggested two simplified analytical models which are based on geometry to estimate horizontal stiffness of U-FREI. To derive the horizontal stiffness of the bearing, both the contact and free area, horizontal displacement were used, which results analytical solution for stiffness. This showed direct agreement with finite element analysis (FEA) reducing the errors to 13% and can be used for initial design of FREI. However, effect of vertical loading and stress softening of elastomers, 3D effect design were not explained in the simplified model, while these limitations are noticed by another author.

Osgooei et al. [2014b] investigated response rate of square isolators by using 3D finite element analysis (FEA) on different materials in different horizontal loading directions which are having separate aspect ratios. These model results were authenticated by experiment outcomes. When loading direction changed from 0 to 45 degrees, effective stiffness (horizontal) of the bearing is also increased and results are analyzed. However, increased lateral response sensitivity depends on the loading directions as the aspect ratio is decreased.

Spizziuoco, Serino et al. [2014] in this research, we will go through the experimental study on un-bounded carbon. Under seismic loading, vertical and lateral behavior of Recycled Rubber Fiber Reinforced Bearings (RR-FRBs) are investigated. By using both test results and Finite Element Analysis (FEA), the seismic execution of RR-FRBs were estimated. Moreover, these statistics helped in understanding the horizontal and vertical stiffness and damping characteristics of the isolators. However, instability of the bearings and sensitivity of RR-FRBs under vertical pressure and lateral displacement applied on the bearing is left out.

Dezfuli, Alam et al. [2014] in this paper, superiority of carbon FREI in bounded applications is studied and the goal is to provide analysis about how efficient carbon fiber reinforced elastomers isolators under different loading conditions. Even at shear strain higher than 50%, these bearings can perform efficiently up to 100%. Partial cracks occur due to rollover deformation between rubber and steel plate, are observed. Higher the thickness of fiber-reinforced layers, higher the vertical stiffness and vice versa with elastomers. Lower the elastomers thickness, higher the stiffness. By increasing the overall thickness of the rubber layers, horizontal direction flexibility increases, meanwhile with increased thickness of both elastomeric layers and fiber-reinforcement, energy dissipation to enhanced to an extent.

Konstantinidis, Kelly et al. [2014] in this present article, we study about the modern advances in seismic isolation by using rubber as an applicant. This study entirely focuses on two kinds of elastomer bearings (multi-layer) where reinforcement materials, thin flexible reinforcement replaces the conventional thick inflexible steel plates. Firstly, carbon fiber is furnished as reinforcement; while in second type, replaced by thin flexible steel shims. Both the test outcomes and theoretical analysis confirms that, it is viable to manufacture a strip isolator which suits the behavior of steel-reinforced isolator. In addition, these un-bonded tested bearings with flexible reinforcement also survived extreme shear strains compared to expected seismic isolators.

Strauss, Apostolidi, Zimmermann, Gerhaher, Dritsos et al. [2014] conducted literature review on fiber reinforced elastomeric bearings and presented their mechanical characteristics. Limitations of modern day European standards pointing static and dynamic loaded bearings are also discussed in this topic. For comparison purposes, an experiment is conducted on elastomeric bearings under different loadings and support conditions along with various reinforcement materials are also studied. This procedure includes loading tests under vertical stress application for three types of bearings with different dimensions and properties. Effect of parameters like bearing height, reinforcement layers and material, bearing support type on effective shear module, vertical stress, number of elastomers, horizontal deflection and damping efficiency are also observed. However, analytical formulations are further discussed by comparing both experimental and analytical test outcomes.

Russo, Pauletta et al. [2013] carried out an experimental analysis by using bi-directional carbon reinforced with elastomeric isolators. The main purpose of this research is to investigate the static friction at the contact surfaces of structure. These isolators were subjected to stress and shear strain by exposing them to contact with the concrete surfaces. When the sliding isolator is in contact with the sub-structure and super-structure, frictional behavior is analyzed. Based on different parameters such as rubber material, level of compressive stress, loading rate, concrete roughness, aging, influences the frictional behavior. Higher the shear force, uncontrolled sliding of the isolator is in proportion to the value of applied compressive stress.

Naghshineh, Caner et al. [2013] Instead of fiber sheet, fiber mesh is used as substitute for this experimental study. Both conventional bearings and fiber mesh elastomeric bearings are taken in four pairs and are processed under same vertical pressure at strain levels of 25%, 50% and 100% of the total rubber thickness to various cyclic shear strain. The test results were noticed as, compared to conventional bearings, fiber-reinforced elastomeric bearings can evolve appreciable low horizontal stiffness.

Das, Dutta, SK Deb et al. [2012] used ANSYS for finite element simulation of fiber reinforced plastic to study the multilayer characterization of material. Here, circular and rectangular isolator models were used for analysis. At higher displacement, constant rollover deformation was using with the help of unbounded isolator. Thus, FREIs are better option as a result of high damping when compared with higher stiffness of conventional bearing isolators.

Engelen, D. Konstantinidis, Tait et al. [2012] investigated about the utilization and load displacement behavior of Stable Unbounded Fiber Reinforced Elastomeric Isolators (SU-FREIs). With two experiment test designs data, load displacement behavior of SU-FREIs were analyzed using bilinear model. To alter horizontal and vertical properties of bearing isolator, one isolator is supposed to have two holes on the loaded surface. In comparison with a fixed base structure to these base isolated structure, two seismic time histories are used to understand the performance. Key performance indicators such as inter story drift, peak acceleration and base shear were also differentiated. Response of the base isolated structures varies between approximately 20% and 30% to the response of fixed base. Also, isolators with holes on the loaded surface seems to have less effective horizontal stiffness.

Nezhad, Tait et al. [2011] this theory consists of strip fiber reinforced elastomeric isolator (FREI) which are subjected to both static and lateral loads and are verified by using finite element model (FEA). On the two sides of the isolator, this given model is capable of simulating both bonded and un-bonded boundary conditions. Stable un-bonded (SU-FREI) possess added challenges while FE-analysis when compared to bonded B-FREIs. Under lateral loads, these stable un-bonded FREIs show some deformation. Therefore, extra analysis challenges are responsible for the changes in boundary conditions because of the rollover deformation. To overcome this challenge, enhanced FE-mesh was used during the analysis along with deformed boundary of the isolator. Therefore, both B-FREI and SU-FREI results were verified using the proposed model. Test outcomes were documented, SU-FREI are much more efficient as a seismic isolator when compared to B-FREI when both the isolators were subjected to constant vertical loading using the same material with identical geometrical properties. Also, stress demands on SU-FREI were considered to be lower than B-FREI.

Nezhad, Tait et al. [2009] conducted analysis based on normal low-rise base isolated (BI) building, employing stable unbounded-fiber reinforced elastomeric isolator (SU-FREI) bearings is estimated by using two separate models. Substantially, efficiency of these two models can be measured by shaking table study. In this paper, two different analytical models are being measured by shake table study. The accuracies of two different analytical techniques used to model the lateral load–displacement hysteresis loops of SU-FREI bearings subjected to different input earthquakes were investigated in this paper. Both of these models were constructed based on lateral load–displacement hysteresis loops of the prototype SU-FREI bearings obtained from lateral cyclic testing. In the first model, based on the amplitude and lateral displacement, lateral efficiency of the bearings are being calculated but, that is not enough to completely record the rate of influence and lateral displacements to increase effective stiffness and damping. While in the second model, response estimation was great to an extent compared to the first model.

Kelly [2009] presented a detailed description of two types of isolation systems where sliding systems and elastomer bearings are used and their working principle has been studied. Earlier studies and development of base isolation theory is presented all over the world. In this paper, a review has been presented how rubber isolators are used in different parts of the world like the United States and Japan. Few defaults like mobility behavior, stability and failures of base material is also addressed. High vertical load carrying capacity and diameter of 1.5m are the major factors in the manufacturing of these bearings.

Pinarbasi, Mengi et al. [2008] here under pure bending, pure warping and uniform compression, new formulation has been presented for analyzing elastic layers bonding to flexible reinforcements. In the formulation, displacement boundary conditions are included by putting an end to random assumptions. Hence, the solutions derived from this formulation analysis is not only for thin layers but also for thick compressible material layers. Using zeroth and first order theory, can solve the governing equations of infinite-strip shape for bonded layers and the applications are demonstrated. For effective layer modulus and displacement/stress distributions, closed-form expressions are obtained for each deformation mode. Different effects of parameters such as Poisson's ratio of the layer material, shape factor of the layer and extensibility of the reinforcing sheets are also studied in this study.

Ibrahim [2008] created a new variety of isolators which are of ultra-low frequency and made developments using non-linear isolators. This research explained the ground motions of base isolated buildings/skyscrapers, bridges and many other storage tanks during the time of earthquake. Nonlinear visco-elastic and composite material springs, and smart material elements were described in terms of mechanical characteristics of the material.

Alfred strauss et al. [2008] conducted a test to find out how glass fiber fabrics are strengthening high damping rubber bearings. Using finite element analysis, a numerical test has been performed in order to verify thesis models for modern isolation devices. Hence, experiment on liquid storage tanks was run using FEA in both configurations i.e., isolated and un-isolated. There is reduction in acceleration and design choices validity, period shift were analyzed and recorded. By using FEA, stress and displacement checking all the test outcomes are verified and documented.

Nezhad, Tait [2008(a)] carried out analytical studies by conducting experiments on square carbon. In this study, how FREI is superior to SREI is being shown basing on different parameters like damping effect, total cost efficiency, vertical stiffness, horizontal stiffness etc. On FREI, vertical compression test has been done which in turn shows stable values of vertical stiffness depending on the superstructure load application. Similarly, square carbon FREI possess suitable aspect ratio which reduces the horizontal stiffness and increased efficiency of seismic isolation devices by showing stable lateral deformation. The results in this research suggested the use of square carbon FREI in high seismic prone areas throughout the world and is feasible for normal low-rise buildings.

Toopchi-Nezhad, Tait [2008b] conducted detailed study about the response characteristics of a square fiber-reinforced elastomer isolator (FREI) bearing. These are commonly used in low-rise structures as they result in stabled lateral deformation causing to decrease the horizontal stiffness and to increase the efficiency of the isolator in un-bounded condition. With unbounded load application, lateral load displacement of FREI bearing are found to be similar to that of high damped steel reinforced buildings.

Toopchi-Nezhad, Tait et al. [2008c] this study deals about the sensitivity of SU-FREI bearing when applied under vertical pressure and lateral displacement history on the bearing. Results turned out to be shown that changes in vertical pressure on lateral response can be forsaken. Similar to square fiber bearing, this is also widely used in low-rise buildings when structure is subjected light vertical pressure.

Tsai et al. [2006] in this study, circular bearing which consists of laminated elastic layers including with flexible reinforcements was used to derive compression stiffness. At first, stiffness of bearing with deformation is obtained. Bearings with both ends free from shear force and both ends free from being bonded to rigid plates were observed. The experiment results turned out to be similar with Finite Element Method (FEM), compression stiffness of bearings and the displacement assumptions seems to be reasonable.

Tsai et al. [2004] by using infinite-strip shape laminated elastomeric bearing with flexible reinforcements, compression stiffness is derived. Flexible reinforcements which are bonded with three types of elastic layers are being studied in this study. The first type simulates the interior elastic layers of the bearings with shear-free ends. The second type simulates the exterior elastic layers of the free-end bearings. The third type simulates the elastic layers in the bearings which ends are bonded to rigid plates. In comparison with Finite Element Method (FEM), the results of compression stiffness of bearings which are procured by theoretical model are almost similar, which in turn demonstrates that displacement assumptions used in the theories are sensible.

Moon, Kang, Kelly et al. [2003] proposed a strip fiber-reinforced elastomer to carry out variable characteristics of isolator by using theoretical and experimental analysis. In horizontal loading test, horizontal stiffness of the fiber reinforced isolator is greater compared to conventional ones. For seismic isolation formulation, the isolator adjusts with the present UBC code for a specific period. In vertical test by applying constant average pressure, suitable vertical vibration frequency which is vital for any kind of isolation application with effective compression modulus is acquired.

Tsai and Kelly [2002b] in this paper, a theoretical approach is used to estimate the bending stiffness dominant and the stiffness formulae is also derived from the test. Mechanical properties such as pressure in elastomer, bonding shear stress between elastomer and reinforcement of the FREI were subjected to pure bending moment depending on the fiber flexibility. This reinforcement is affected by the bending of the fiber.

Kelly and Takhirov [2002] did experimental study using strip isolator. In this study, long strips of rectangular isolators were used in the place of regular isolators. These isolators are having added advantages in case of buildings where lateral resistance is provided by the walls. Normally, in base isolation, at base level of structures, wall beams are established between isolators to support load of walls. These wall load beams can be replaced by using this modern long strip isolators on the foot of the building. Strip isolators in cooperation with carbon reinforcement fiber are much feasible. The isolator should be made up of long rectangular strip and adjusted according to the width required to place below the wall of the building. Also the capital investment and manufacturing cost of these strip isolators are much cheaper than that of individual circular or rectangular isolator.

Moon et al. [2002] by using various kinds of fiber materials like glass, nylon, carbon and polyester, designed and manufactured significant models of fiber-reinforced multi-layer elastomer isolators. These researches were carried out to compare the performances of conventional steel reinforcement to fiber reinforcement, among different types of fiber reinforcement materials.

The test results came out to be that the performance of carbon FREI was much more dominant to that of SREI both in terms of damping and vertical stiffness, which is higher compared to glass fiber reinforcement. In comparison, vertical stiffness of carbon is thrice higher than SREI. Hence, deformation of carbon is significantly lesser than steel reinforcement isolator.

Kelly and Takhirov et al. [2001] conducted both theoretical and experimental analysis to derive the FREI's mechanical characteristics. Flexible reinforcement was derived with the compression stiffness of isolator. With a pressure of 6.90 MPa, four 305mm diameter isolators under vertical load were tested in pairs. At maximum strain levels of 50%, 100%, 150%, isolators were tested at regular intervals with different fully reversed cycles. The result turned up that it is feasible to use un-bounded isolators for structures. Even though there occurs a slight edge uplift, force displacement curve had positive stiffness. This shows that even at 150% strain level, bearing will be stable even after going through a rolled deformation.

Kelly et al. [1999] studied the mechanical characteristics of the fiber reinforced isolator and provided the evaluation compared to conventional steel isolators. Fiber has high material stiffness in extension but there is deficiency in bending moment. This paper also studies the effect of fiber flexural rigidity on horizontal and vertical stiffness of FREI. Few benefits of FREI are also noticed in this study such as light weight, low capital investment, abundance of material supply and ease of manufacturing.

R.I. SKINNER, [1993] started the modern era of base isolation in the mid 60's with help of The New Zealand Department of Scientific and Industrial Research. To resist the seismic loading, rubber elastomer bearings are constructed and equipped with enough vertical stiffness. The Pestalozzi School in Skopje, Macedonia was the first building to be incorporated with base isolation in 1969, while the foremost rubber building was constructed in 1985 in the US.

Kelly JL, et al. [1986] conducted extensive theoretical experiments and numerous studies to understand the design and analyze the base-isolated structures. He also experimented shaking table tests of a standard base-isolated building structure. From 1900 to 1984, a summary of literature on the theory of seismic isolation is also published. In Skokie, Yugoslavia, non-reinforced rubber block was used as an earthquake protection for the first time. The deformation occurred at the base isolator level for the first vibration. For higher node, seismic load was treated as an equivalent lateral load which was proportional to the rigid body mode. Thus, working principle of base isolation system is to deflect energy rather than to absorb energy.

Charles Roeder and John Stanton [1983] gave brief synopsis about the knowledge of elastomeric rubber available throughout the world. By the process of vulcanization, series of modern rubbers alternating with steel plates are joined together. The steel provides better confinement and also reduce the deformation of the rubber which in turn enhances the vertical stiffness of the bearings. This theoretical and experimental research also helped many other engineers to study the strain and material behavior of the elastomer bearing. Different failures of the bearings are also recorded and presented.

V. CONCLUSION

The previous work done in this field shows us how FREI is more efficient as compared to SREI and further how un-bonded inherits better response to seismic effect as compared to bonded-FREI. SREI uses steel-rubber combination, while in FREI we can use alternate materials instead of steel to make it cheaper, light weight and also ease the process of installation. In bonded FREI thick steels plates are mounted on both the sides which is used to make connection between structure and isolator, while in un-bonded FREI no such plates are provides and the shear loads is transferring through friction. In the previous literary works, it is seen FREI have significantly higher vertical stiffness as compared to the traditional base isolators, that makes it viable alternative over the traditional SREI. Studies shows it has better response in filtering out predominant frequencies and reduce seismic effect on structure. There is further scope which needs to analyzed considering different height of medium rise buildings with FREI. Also static analysis and response spectrum analysis should be conducted to evaluate the responses of structure.

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