Experimental and analytical study of unbonded and bonded scrap tire rubber pad as base isolation device

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SUMMARY
Utilizing the scrap tire rubber pad as seismic isolation units which contain interleaved steel reinforcing cords is investigated. These cords can be considered as an equivalent component to the steel plates used in conventional laminated rubber bearings. Experimental tests and finite element analysis (FE analysis) conducted on unbonded and bonded STRP isolators provided useful information including stiffness, damping values and an eventual instability of the isolation unit. The STRP isolators were tested under unbonded application with support surfaces so that the cost of fastening could be reduced. The experimental tests and FE analysis results are compared and the results are found to be in close agreement in both the cases. The tested isolators show that the damping is much larger than the natural rubber bearings. This study suggests that the bonded STRP isolators serve positive incremental force resisting capacity up to shear strain level of 150% when loaded with 5MPa axial pressure.

Keywords: STRP isolators, compression test, cyclic shear test, FE analysis, base isolation

1. INTRODUCTION

Base isolation is the technique to reduce the seismic demand on structures instead of increasing the load resistant capacity of the structures. The reduction of seismic demand on structures can be achieved by providing certain degree of flexibility in the structure by installing certain devices having low horizontal stiffness. Rubber bearings of different types including lead rubber bearings, high damping rubber bearings and steel laminated rubber bearings are currently used to serve this purpose. Now a days, this technology is becoming an attractive alternative to the conventional seismic resistant design methods.

The problem with adopting the isolation system in developing countries is that conventional isolators are large, expensive and heavy. To extend this earthquake resistant strategy to housing and commercial buildings, the weight and cost of the isolators must be reduced (Kelly 2002). Experience of the past earthquakes in developing countries suggests that the seismic performance of the structure could be significantly improved by the introduction of a simple seismic isolation system either at the construction or during the retrofitting stage. This would have resulted in fewer buildings failure and decreased loss of lives during the past earthquake events (Toopchi-Nezhad et al. 2008).

Although the base isolation showed its effectiveness, the technology is still perceived as expensive and difficult to implement. Thus in the recent years, a new approach emerges in the research field and this approach focuses on developing a low cost base isolation system in order to extend the use of this method in developing countries. A few studies have been conducted using either steel laminated rubber bearing (Kelly, Konstantinidis 2007) or fiber-reinforced elastomeric isolators (Kelly 2002, Toopchi-Nezhad et al. 2008, Mordini et al. 2008, Ashkezari et al. 2008) as low cost base isolation systems for highly seismic regions of the world. These types of seismic isolators are still expensive considering the purchasing capacity of poor families in the developing countries. This research is intended to develop low cost seismic isolators having similar properties of commercially available seismic isolators in context of the behavior with exceptions in case of axial load carrying and lateral deformation capacity.

In this study, the scrap tires for buses/trucks were used to produce the specimen isolators. Only tread part of the scrap tire was used. Two types of scrap tire rubber pad (STRP) samples were prepared; first type consists of the STRP layers just stacking one on top of another without applying bonding agent and the second type consists of the STRP layers properly bonded using the adhesive chemical. The detail specimen sample preparation procedure is discussed in subsequent chapter. In an unbonded application, the STRP isolator is laterally displaced with its upper and lower faces roll off the contact supports. This type of deformation decreases the effective horizontal stiffness of the isolator during the increase in lateral displacement. This phenomenon will elongate the period of the isolation system provided that the stability of the isolation system including building structure is maintained (Toopchi-Nezhad et al. 2011).

In this paper, the results of experimental tests and FE analysis conducted on unbonded and bonded square STRP isolators are presented. These results are discussed to investigate the improvement of performance after the application of adhesive. The hyperelastic material constants used in FE analysis were derived by conducting uniaxial tension in order to accurately capture the nonlinear behavior of rubber. The results of experimental tests and FE analysis are further compared in terms of force displacement relationships. The experimental test results were used to compute the mechanical properties of the isolator including stiffness and damping values. The stress-strain state within the isolators was studied by means of FE analysis. These results were further compared with relevant code provisions (UBC 1997, Eurocode 8 2004, ASCE-7 2005) to check the viability of using the STRP as a base isolation device.

2. SCRAP TIRE RUBBER PAD SPECIMEN SAMPLE

The specimen sample preparation procedure for unbonded and bonded STRP specimen isolators is described herein. The STRP samples taken from the tread part of the scrap tires were prepared by companies specialized in tire re-processing for re-treading. This process is mechanized in Japan for the reprocessing of tires. Similar methodology can be adopted to produce the STRP isolators in developing countries. The rectangular strip cut from the tread part of tires can be used to produce small to sufficiently large size rubber bearings. Stacking of these small strips in different orientations in alternative layers can produce even larger size rubber bearings as per the requirements. The required thickness of rubber bearings were obtained by stacking one on top of another, as assemblies of horizontal layers.

Figure 2.1 Unbonded STRP-6 specimen isolator

Figure 2.2 Bonded STRP-4 specimens isolator

The STRP layers were sanded using a belt sanding machine so that smooth plain surfaces of uniform thickness were obtained. These individual layers were used to produce two types of specimen samples; namely, layer unbonded and bonded (see Figures 2.1 and 2.2). The latter types of specimen samples were produced by applying adhesive chemical while the former types were produced by just stacking the layers one on top of another in vertical layers. Each layer of STRP isolator comprises the five layers of reinforcing steel cords interleaved and bonded between the layers of rubber. These steel reinforcing cords comprise a number of strands in twisted form. The geometrical and material properties are given in Table 2.1.

Table 2.1 Material and geometrical properties of specimen isolators

Material properties	Geometrical properties (mm)
Shear modulus of tire rubber G = 0.89MPa Poisson's ratio of steel reinforcing cords υ = 0.30 Young's modulus of steel cords E = 200GPa	Size of isolator = 100x100 Thickness of single layer STRP = 12 Thickness of steel reinforcing cords = 0.4 Thickness of STRP-6 = 72, t_r = 60 Thickness of STRP-4 = 48, t_r = 40

3. EXPERIMENTAL SETUP AND TESTS

The schematic view and boundary conditions used in the experimental test and FE analysis are shown in Figure 3.1. The STRP isolators were placed between the upper and lower steel plate surfaces of the loading test setup without any fastening system between the contact surfaces. The vertical load was applied to the specimen by a vertical hydraulic actuator and horizontal load was applied by a horizontal hydraulic actuator.

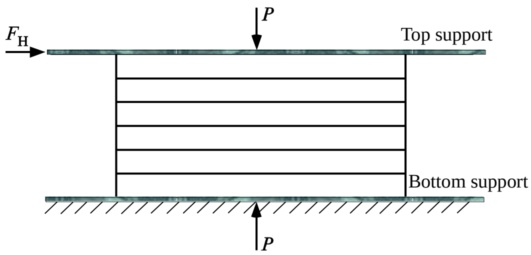


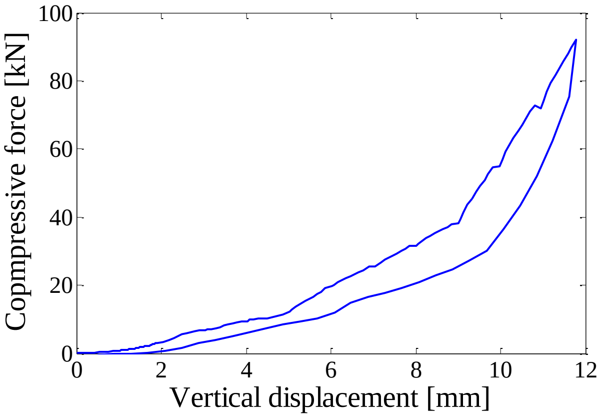
Figure 3.1 Loading setup and boundary conditions

3.1. Compression tests of unbonded specimen

The compression modulus as well as the vertical stiffness of the isolators was evaluated through vertical compression tests. The STRP-6 specimen isolator was tested under vertical displacement control. The specimen was monotonically loaded to the vertical force of 91.9KN which is equivalent to 9.19MPa vertical pressure on the STRP-6 specimen.

3.2. Cyclic shear tests of unbonded specimen

The cyclic shear test on isolators provides reliable methods to determine the horizontal stiffness and damping values of any isolation system. The static shear test was performed under horizontal displacement control. The STRP-6 specimen was tested in cyclic shear with three fully reversed cycles at four maximum shear displacement amplitudes of 12mm, 24mm, 36mm, and 48mm. These cycles were applied at a constant vertical pressure of 5MPa. Figures 3.2 and 3.3 contain the force displacement relationship in vertical compression and cyclic shear, respectively.



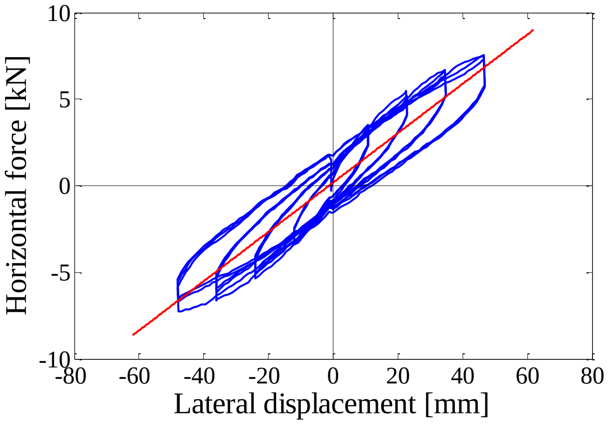


Figure 3.2 Vertical load displacement relationship

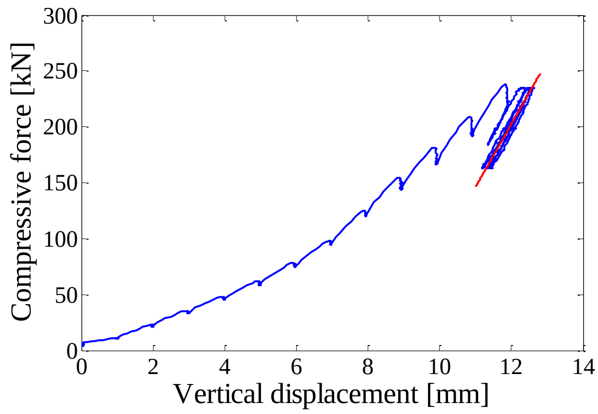
Figure 3.3 Lateral load displacement relationship

3.3. Compression tests of bonded layers specimen

The STRP-4 isolator was tested in vertical compression including a cyclic test at its maximum amplitudes. The sample was tested under vertical displacement control. At the initial stage, the sample was loaded to equivalent pressure of 13.7MPa and unloaded. Then the compressive load was increased to 200kN which is equivalent to 20MPa axial pressure on the SRTP-4 isolator. The STRP-4 specimen was monotonically loaded up to 20MPa axial pressure and three fully reversed cycles with ±4MPa amplitude. The force displacement relationship in the vertical compression test is presented in Figure 3.4.

3.4. Cyclic shear tests of bonded layers specimen

The shear test was performed under horizontal displacement control. The STRP-4 specimen sample was tested in cyclic shear with three fully reversed cycles at four maximum shear displacement amplitudes of 15mm, 30mm, 45mm and 60mm. These cycles were applied at a constant vertical pressure of 5MPa. A small slip can be seen at shear displacement amplitude of 45mm in Fig. 3.5. This phenomenon again disappears for higher levels of shear displacement amplitudes.



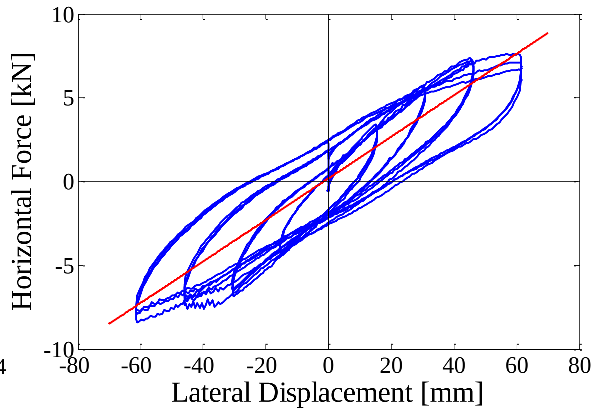


Figure 3.4 Vertical load displacement relationship

Figure 3.5 Horizontal load displacement relationship

The average horizontal stiffness of the STRP isolators was evaluated using the least square fitting technique. The effective horizontal stiffness corresponding to each load cycle of the test can be calculated based on the peak lateral load and peak lateral displacement using Eqn. 3.1 (UBC 1997).

$$K_{eff} = \frac{F^{+} - F^{-}}{\Delta^{+} - \Delta^{-}} \tag{3.1}$$

where F^{+}, F^{-}, Δ^{+}, and Δ^{-} are the peak values of horizontal load and horizontal displacement at the positive/negative extremes of the cyclic displacement range, respectively, K_{eff} is the effective horizontal stiffness. The computed average stiffness values of unbonded and bonded isolators are reported in Tables 3.1 and 3.2, respectively.

The effective damping ratio of the tested isolator was computed using the Eqn. 3.2 (UBC 1997).

$$\beta_{eff} = \frac{2}{\pi}\left[\frac{E_{Loop}}{K_{eff}\left(\left|\Delta^{+}\right| + \left|\Delta^{-}\right|\right)^{2}}\right] \tag{3.2}$$

where β_{eff} is the effective damping ratio and E_{Loop} is the energy dissipated per cycle of the loading. The calculated damping ratio with 5MPa axial pressure corresponding to 80% and 150% shear deformation on unbonded STRP-6 and bonded STRP-4 isolators are 0.12 and 0.15, respectively.

Table 3.1 Horizontal stiffness of unbonded STRP isolator

Tests	Sample	Axial pressure (MPa)	Horizontal Displacement (mm)	Horizontal Stiffness (kN/m)
1	STRP-6	5.0	48	142.5
2	STRP-6	5.0	62	102.2

Table 3.2 Horizontal stiffness of bonded STRP isolator

Tests	Sample	Axial pressure (MPa)	Horizontal Displacement (mm)	Horizontal Stiffness (kN/m)
1	STRP-4	10.0	60	85.3
2	STRP-4	5.0	60	124

4. FINITE ELEMENT ANALYSIS

The FE analysis of strip STRP isolators were carried out in order to assess the force-displacement relationship and to evaluate the stress state within the isolator. The sketch of the deformation pattern of the STRP isolators in an unbonded application with support surfaces is shown in Figure 4.1. The moment created by the offset of the resultant compressive force *P* balances the moment created by the shear force *V*. Due to this reason, no or negligible tensile stresses are produced within the STRP isolator.

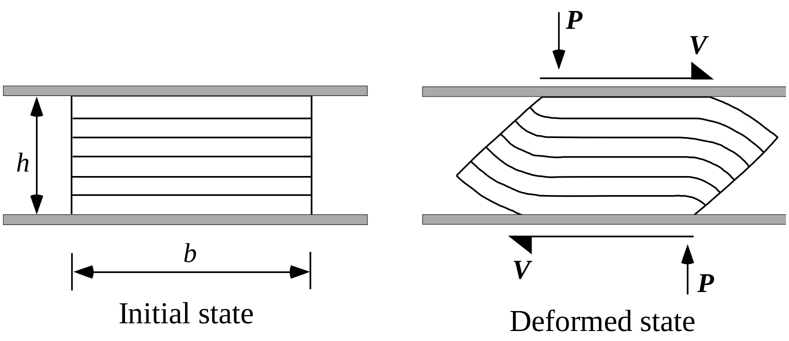


Figure 4.1 Free body diagram of laterally deformed STRP isolator

4.1. Modelling of STRP isolators

The STRP that constitutes the isolator is composed of a rubber body with embedded steel reinforcing cords. The simulated isolator's physical and geometrical properties are presented in Table 2.1. FE analysis of a strip STRP isolator was carried out using commercially available finite element software (MSC 2010). The rubber was modeled using four-node, isoparametric quadrilateral elements for plane strain incompressible applications. This element is preferred over higher-order elements when used in simulating large deformation and contact analysis. The reinforcing steel cords were modeled by using the isoparametric plane strain two-node line elements, which are referred to as rebar elements. These elements need to be used in conjunction with four-node plain strain continuum elements (host elements). These rebar elements which can be defined with any material property have to be embedded into their corresponding solid elements representing the matrix materials. Since the matrix element and the rebar element share the same nodal points, no additional degrees of freedom are introduced. The degrees of freedom of the nodes to be inserted are tied to the corresponding degrees of freedom of the host elements. The orientation of the rebar direction was assigned as ± 70º for belt layers about the reference axis (Clark 1981). The rubber is modeled by a hyperelastic material model while the steel reinforcing cords in finite element model are treated as linear elastic isotropic material with material properties given in Table 2.1.

Two horizontal rigid bodies (lines) were defined at the top and bottom of the STRP isolator to represent the superstructure and substructure, respectively. In this model, the vertical and horizontal loads were applied on the top support; the top support was allowed to move in vertical as well as in horizontal directions without rotation, while the bottom support was considered as a fixed support. In this contact model, the contact between the supports and the STRP isolator was modeled by the Coulomb friction law with a coefficient of friction of 0.8 in both the cases while the contact between the rubber layers was modeled as a touching and a glue contact model for unbonded and bonded layers cases, respectively. The coefficient of friction was selected such that no slips occur between the contact supports and the rubber. The individual STRP layers were modeled as deformable bodies with a local coefficient of friction of the surfaces as 0.95. The STRP isolator was not bonded to the top and bottom supports and its rollover deformation was allowed. This means that when the compression contact stresses approach to zero, the nodal points were allowed to detach from the contact supports.

Among various constitutive models, the Mooney-Rivlin model is commonly used to characterize the rubber material undergoing large strain (Ali et al. 2010). This model is the simplest hyperelastic model for elastomeric materials when material test data is insufficient. The Mooney-Rivlin material law is well suited for practical applications involving cord-reinforced rubber material (Helnwein et al. 1993). The strain energy polynomial is expressed by Eqn. 4.1.

$$U = \sum_{i,j=0}^{N} C_{ij} \left(I_1 - 3\right)^i \left(I^2 - 3\right)^j + \sum_{i=1}^{N} \frac{1}{D_i} \left(J_{el} - 1\right)^{2i} \tag{4.1}$$

where C_{ij} and D_i are material parameters that are found from the test data, J_{el} is the elastic volume ratio, I_1 and I_2 are the invariants of the green deformation tensor given in terms of principal stretch ratios λ_1, λ_2 and λ_3, by Eqns. 4.2 and 4.3.

$$I_1 = \lambda_1^{\ 2} + \lambda_2^{\ 2} + \lambda_3^{\ 2} \tag{4.2}$$

$$I_2 = \lambda_1^{\ 2}\lambda_2^{\ 2} + \lambda_2^{\ 2}\lambda_3^{\ 2} + \lambda_3^{\ 2}\lambda_1^{\ 2} \tag{4.3}$$

where λ_1, λ_2 and λ_3 are the stretch ratios in the principal directions. In Eqn. 4.1, the first summation is the contribution due to deviatoric effects and the second summation is the contribution due to volumetric effects. The deviatoric contribution to the strain energy density function is:

$$W = C_{10}(I_1 - 3) + C_{01}(I_2 - 3) + \ldots\ldots.. \tag{4.4}$$

where C_{10} and C_{01} are the material constants known as Mooney-Rivlin material constants. These material constants were evaluated by conducting uniaxial tension tests.

4.2. Finite element analysis of STRP isolators

To investigate the nonlinear behavior of the STRP isolator, the load was applied in an incremental manner. At the initial stage of the analysis, the target compressive load was applied in different incremental steps. Then the horizontal load was applied with the constant compressive load until a target lateral displacement was achieved. The target loads were selected such that the target lateral displacements were achieved.

The analysis was two-dimensional under the plane strain assumption. The low value of shear modulus of rubber causes the deformation pattern relatively severe as compared with other materials like steel and concrete. Its large deformability together with its near-incompressibility makes rubber a major challenge for finite element analysis. The large deformation that the rubber components experience can only be modeled with a finite strain formulation (Kelly, Konstantinidis 2007).

4.3. Results and discussion

The lateral load-displacement relationship of STRP isolators is nonlinear as shown in Figures. 4.2.1 and 4.2.2. Due to the rollover deformation, the effective secant stiffness decreases with increased lateral deformation. This results in period elongation which further increases the efficiency of the isolation system provided that lateral stability of the STRP isolator is maintained (Toopchi-Nezhad et al. 2011). As seen in Figures 4.2.1 and 4.2.2, reasonable agreement was found between the experimental tests and FE analysis results.

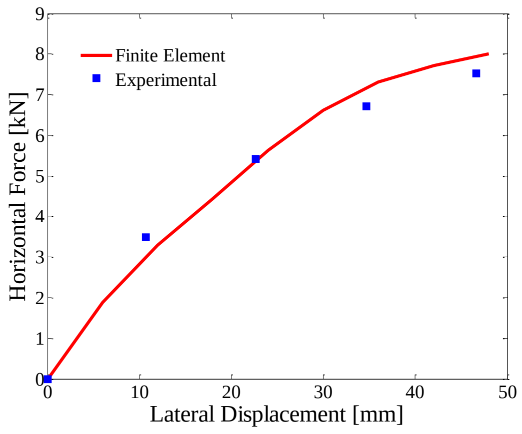


Figure 4.2.1 Load-displacement relationships of STRP-6: comparison of experimental and FE analysis results

Figures 4.2.3 and 4.2.4 contain the component 22 of normal stress distribution corresponding to mentioned shear deformation in STRP-6 and STRP-4 isolators for 5MPa axial pressure, respectively. As seen in these figures, as a result of rollover deformation, high level of stresses occurred at the corner regions while the stresses in the other regions are relatively lower. Due to the unbonded application with support surfaces, none or negligible tensile stresses are transferred to a laterally deformed STRP isolators.

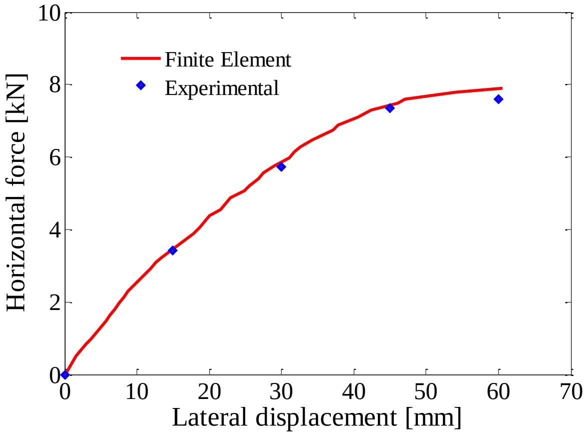


Figure 4.2.2 Load-displacement relationships of STRP-4: comparison of experimental and FE analysis results

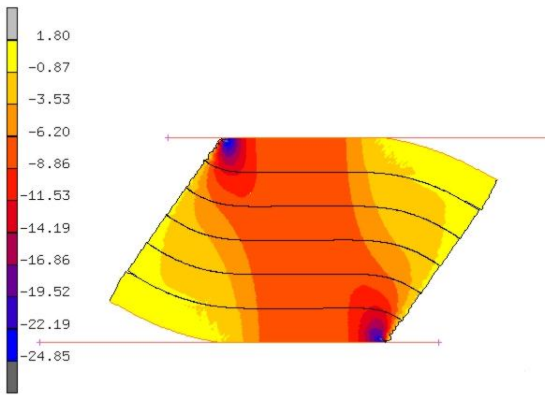


Fig. 4.2.3 Contour of normal stress S_{22} (MPa) in the rubber layers of the STRP-6 isolator

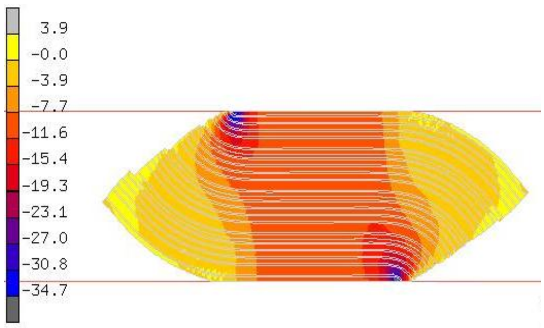


Fig. 4.2.4 Contour of normal stress S_{22} (MPa) in the rubber layers of the STRP-4 isolator

5. DISCUSSION ON VIABILITY OF THE STRP ISOLATORS

The isolation bearings are generally used at axial pressure levels ranging from 5 to 7MPa (Kelly 1997). The compressive stress on isolators used to be between 3 and 8MPa in the early years in Japan

(Pan et al. 2005). Due to the improved performance of the isolators, the compressive pressure is increased to 7-13MPa for natural rubber bearings and 5-10MPa for high damping rubber bearings. These isolators are generally adopted in multi-story building structures where the anticipated compressive load is much larger than residential buildings. The average axial load on each of the columns of a three-story reinforced concrete building is estimated to be 330kN. The expected average axial pressure on STRP isolators is approximately 3-7MPa in order to achieve 150% shear strain. The analytical study carried out on bonded STRP isolators (Mishra, Igarashi 2012), reveals that these types of isolators can serve positive force resisting capacity up to 150% shear strain when loaded with axial pressure of 8.6MPa. In this regards, the STRP isolators can serve the purpose of the base isolation system of low-rise residential buildings. The tested isolators show larger values of damping compared with typical natural rubber bearings such as the values shown by Naeim and Kelly (1999).

5. CONCLUSION

Experimental tests as well as FE analysis were conducted on two types of STRP isolators: one with unbonded and another with bonded layers. The aim of the study is to investigate the behavior of STRP isolators in static compression and in cyclic shear loading. The results of experimental tests are used to compute the different mechanical quantities of the isolator by employing established and simplified formulations. During the entire range of shear displacement, the bonded specimen samples did not show any sign of layer separation while the similar tests on STRP-6 shows layer separation before achieving 100% shear deformation. This result indicates that application of the bonding agent is effective in transmitting the shear forces. The results of experimental tests and FE analysis were compared in terms of load-displacement behavior and found to be in close agreement.

These mechanical properties are further compared with relevant code provisions in order to identify the viability of the STRP base isolation system. The bonded layers STRP serve positive incremental force resisting capacity up to shear strain level of 150% when loaded with 5MPa axial load. The ratio between vertical and horizontal stiffness is greater than 150 in any case so that the STRP isolator can be considered as a feasible base isolation device. In this regards, the STRP isolators can serve the purpose of base isolation systems of low-rise residential buildings. It can be concluded that the STRP isolator with axial pressure of 5-8.6MPa can be used as a seismic isolator to achieve 150% shear strain while the shear deformation capacity sharply decreases to 100% in case of unbonded STRP with equal axial pressure. It can be summarized that the STRP isolator needs to be bonded in order to increase the shear deformation capacity as well as to ensure stability. These types of base isolation devices are intended to be used for low axial pressure application such as residential buildings in developing countries.

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