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PERFORMANCE EVALUATION OF CARBON FIBER-REINFORCED ELASTOMERIC ISOLATORS (C-FREI) THROUGH EXPERIMENTAL TESTS

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Abstract: Recent studies showed that new elastomeric base isolation systems (rubber bearings) can be produced by using fiber fabrics as reinforcement in the place of steel shims. This type of bearings can be fabricated through a simple and cost-effective manufacturing technique called cold-vulcanization process. In this study, scaled size rectangular carbon fiber-reinforced elastomeric isolators (C-FREIs), which have been cold-bonded fabricated, are tested under vertical compression and lateral cyclic displacements. Vertical and lateral responses of C-FREIs are obtained and analyzed in order to evaluate their performance in terms of flexibility and energy dissipation capacity. Results reveal that C-FREIs possess acceptable amounts of stiffness and equivalent viscous damping compared to traditional steel-reinforced rubber bearings. As a result, these new isolation systems can be safely used instead of heavy and expensive steel-reinforced elastomeric bearings in civil applications, such as low rise residential buildings, in developing countries.

1 INTRODUCTION

In order to seismically protect a structure from devastating effects of earthquake, different protective systems including active, semi-active, hybrid, and passive vibration control systems have been developed. Passive systems have been extensively implemented in civil engineering applications since they can operate without using an external power supply [1]. Such passive systems are mainly two types: sliding bearings and rubber bearings. Conventional elastomeric isolators or rubber bearings are laminated devices consisting of rubber layers and steel shims as reinforcement. Steel shims in steel-based rubber bearings (SRB) can be replaced by fiber-reinforced polymer (FRP) composite plates to reduce its weight and make it easy to handle during transportation and placement [2, 3]. The production cost of fiber-reinforced elastomeric isolators (FREIs) is also reduced due to automated manufacturing process [2, 4]. SRBs have axial and flexural rigidity while, FREIs are completely flexible under bending due to the presence of fibers [2]. The density of carbon-FRP composites is much lower than that of steel. The density of epoxy matrix composite reinforced by 70% carbon fibers is 1600 kg/m3 while, mild steel has a density of 7850 kg/m3. Due to high strength-to-weight ratio of CFRP composite materials, carbon-FREIs are much lighter than SRBs with superior performance [4]. Hence, they can be implemented into a wide range of applications such as bridges, buildings, and other civil infrastructures.

The possibility of using carbon-FRP composite layers in seismic isolators for producing light-weight and low-cost rubber bearings was investigated in order to extend their applications to public and low-rise buildings in developing countries [3]. Kelly observed that the performance of FREIs is similar to that of steel-based RBs based on experimental and analytical studies. He derived analytical equations for vertical and horizontal stiffness of FREIs to show that it is possible to produce these kinds of rubber bearings with adequate mechanical properties [2]. Tsai and Kelly studied the effect of fibers on the flexibility of base isolators by presenting formulations for compressive and bending stiffness of rectangular FREIs based on analytical method [5]. They assumed that the elastomer is incompressible and isolator is in form of an infinite strip pad. Results indicated that the stiffness increases with increasing the shape factor (loaded to force-free area ratio) and decreases by using more flexible reinforcement.

Different types of fibers such as glass, carbon or aramid can be used in the reinforced layers of FRP-based laminated isolators. Moon et al. designed and manufactured such FREIs in order to compare their performance and behavior with those of SRBs through various experiments [4]. According to the obtained results, FREIs are superior to SRBs in terms of effective horizontal and vertical stiffnesses, and equivalent viscous damping. Flexural rigidity of fiber-reinforced polymer composite layers is much lower than that of the steel shims used in steel-based rubber bearings. This characteristic causes the FREI to show a rolling deformation under lateral shear force and as a result, it produces lower forces in the transverse direction compared to the SRB. Therefore, FREI can be laterally deformed with a higher flexibility. Moreover, it was observed that using carbon fibers in reinforced layers could lead to higher effective vertical stiffness and equivalent viscous damping relative to other types of fibers. Dehghani Ashkezari et al. carried out combined compression and cyclic shear tests on different samples of FREIs and showed that carbon FREIs are more efficient in terms of vertical and horizontal stiffnesses as well as effective damping [6]. They concluded that the presence of carbon fibers increases the energy dissipation of the base isolator since frictional movements of fibers generates an additional damping in the system. Based on the results, although the amount of vertical pressure has considerable effects on the damping coefficients of fiber and steel-based rubber bearings, its influence on the shear behavior of RBs is negligible within testing load range. Another important finding is that, if cyclic lateral loading is repeated with amplitude less than the maximum load previously applied, horizontal flexibility and energy damping properties will decrease due to stress softening phenomenon [6].

Regarding the boundary conditions, rubber bearings can be divided into two groups: bonded and unbonded. In bonded-RBs steel supporting plates at the top and bottom are bolted to the superstructure and substructure, respectively while in an unbonded application, supporting plates are removed and elastomeric isolator is free to move horizontally between substructure and superstructure without any constraint. Toopchi-Nezhad et al. investigated the mechanical characteristics and behavior of a carbon-FREI with unbonded boundary conditions [7]. Test results indicated that the horizontal stiffness of this type of FREI is reduced owing to rollover deformation under cyclic shear loadings. Their proposed RB had undesirable behavior because of low damping capacity and inadequate (very low) horizontal stiffness. They suggested that high damping rubber or additional elements can be used. In another study, Toopchi-Nezhad et al. tested a square scaled model of FREI made of natural rubber and bi-directional carbon fiber fabric under vertical pressure and cyclic lateral displacement [8]. Results demonstrated that the performance of unbonded-FREIs is comparable to that of the high damping rubber bearings (HDRBs).

Zhang et al. studied the mechanical properties of FRP-based elastomeric isolators after manufacturing and testing a number of samples [9]. Specimens were subjected to vertical pressure for calculating the effective vertical stiffness and compressive modulus. The effective horizontal and damping capacity were determined by applying cyclic horizontal displacements. The hysteretic curves for three FREIs with different thickness and number of elastomeric and reinforced layers subjected to vertical and cyclic shear loads illustrated that the operational characteristics of FRP-based rubber bearings are comparable to those of traditional ones. Indeed, FREIs have adequate performance in terms of the energy dissipation capacity (i.e. capacity of the device in damping the earthquake’s energy) and the effective vertical strength. Therefore, implementing them in the seismic base isolation is an applicable idea [9]. Hedayati Dezfuli and Alam probed the effect of physical and mechanical properties such as thickness and shear modulus of rubber layers on the performance of the FREIs in the bonded applications [10]. They observed that the lateral flexibility and the damping capacity are highly dependent on the shear modulus of the elastomer while, the vertical stiffness is mostly affected by the number of rubber layers.

In this study, a simple and fast manufacturing process is presented for producing carbon fiber-reinforced elastomeric isolators (C-FREIs) in bonded applications. In order to show how efficient C-FREIs can operate under different loading conditions, operational specifications of C-FREIs in the vertical and horizontal directions are determined through experimental tests. In this regard, four scaled C-FREIs are produced and then the performance characteristics including vertical and horizontal stiffnesses as well as energy dissipation capacity and equivalent viscous damping are assessed through experimental investigations. C-FREIs are bonded to the substructure and superstructure using steel supporting plates. Long strip laminated pads consisting of rubber layers and carbon fiber fabrics reduce the time of the manufacturing process. Cutting laminated pads produced without using a mold in required sizes, makes the whole manufacturing process simple and easy as well. The performance characteristics are determined by conducting vertical pressure and horizontal cyclic displacement tests. Furthermore, future investigations are suggested regarding the performance variation of C-FREIs through a sensitivity analysis.

2 MANUFACTURING TEST SPECIMENS

Four carbon-FREIs were manufactured with the support of GoodCo Z-Tech Company in Laval, Quebec. Each rubber bearing is made of commercial elastomeric layers with a hardness of 55 Shore A and a minimum tensile strength of 17 MPa specified by the CHBDC CAN/CSA S6-06 [11], fiber-reinforced polymer composites as reinforcement, and two steel supporting plates at the top and bottom. Fiber-reinforced layers are plain woven carbon fabrics with a tensile strength of 4413 MPa [12]. C-FREIs have identical width and length (70 mm by 70 mm) but with different number and thickness of elastomeric and reinforcement layers. Therefore, the total height of C-FREIs varies in a range of 19.1 mm to 41.8 mm. The shape factor (defined as the ratio of loaded (plan) area to load free (side) area of a rubber layer) are S = 5.8 or 11.7 for four base isolators since the thickness of elastomeric layers is either 1.5 mm or 3 mm. This geometrical parameter is calculated according to Equation (1).

$$S = \frac{L \times W}{2t_e\,(L+W)} \tag{1}$$

where L, W, and t_e are length, width, and thickness of each rubber layer, respectively.

Elastomeric layers are bonded to bi-directional (orientations 0/90°) carbon fiber fabrics using rubber cement (see Figure 1). After fabricating a laminated pad consisting of elastomers and reinforcement with a proper number of layers, C-FREIs are subjected to a certain amount of pressure for 24 hours without using a mold (cold vulcanization process). The plan dimensions (length and width) of layers are more than 70 mm. Then, each laminate is cut to the required size using the high precision waterjet technology in order to have smooth surfaces as shown in Figure 1c. Side faces are coated by two layers of bonding compound in order to improve the bonding between layers and prevent premature delamination that might occur during shipping, installation, and testing.

Supporting plates made of mild steel are attached to the C-FREI at the top and bottom using rubber compound. Four C-FREIs with different number and thickness of rubber layers and carbon fiber fabrics are depicted in Figure 2. Physical and geometrical properties of C-FREIs are listed in Table 1.

3 EXPERIMENTAL TESTS

The test setup is equipped with two hydraulic jacks: vertical and horizontal. Force and displacement in the horizontal and vertical directions are measured in each test. The load applied by the vertical hydraulic jack is measured by three load cells, each of them with a capacity of 44.5 kN. Same mechanism is implemented for evaluating the lateral force applied by the horizontal hydraulic jack using one load cell. In order to measure the vertical displacement, laser displacement transducer (LDT) is used. The vertical displacement is the average of four values determined by four LDT devices which measure the vertical deflection at four sides of the C-FREI (see Figure 3). The horizontal displacement is determined by a string potentiometer (String POT). Different parts of test setup are identified in Figures 3 and 4.As shown in Figure 3, C-FREIs are fixed in the test setup by screwing the steel supporting plates to fixing plates using a total number of eight bolts. The lower fixing plate in the test setup is attached to the lower steel platen. Two bearings are installed between the upper steel platen and the fixing plate in order to transfer the load (see Figure 4a). In all tests, the lower platen is fixed and the vertical pressure and horizontal displacement are applied to rubber bearings through the upper platen.

3.1 Vertical Compression Test

The objectives of the vertical compression test are to evaluate the vertical stiffness and the maximum vertical deflection of rubber bearing. This test is performed under load control since the vertical force is controlled during the tests. For each C-FREI, three tests with different values of design vertical pressure, PD, including 0.75, 1.50, and 3.00 MPa (3.7, 7.4, and 14.7 kN) were conducted. C-FREI is loaded monotonically up to the design pressure. Then, three fully reversed cycles with a variation of 20% of the design pressure is applied with a frequency of f_V = 0.2 Hz. Finally, C-FREI is monotonically unloaded. Figure 5 shows the behavior of pressure changes versus time for three considered design pressures.

After conducting the vertical tests, the operational characteristics including the vertical stiffness, K_V, the compressive modulus, E_c, and the maximum vertical deflection at the design pressure, Δ_V are determined. According to Equation (2), the compressive modulus can be calculated from the vertical stiffness obtained from the tests [13].

$$E_c = \frac{K_V t_r}{A_f} \tag{2}$$

where t_r is the total thickness of rubber layers and A_f is the cross-sectional area of the fiber-reinforced layer which is bonded to the elastomer.

3.2 Cyclic Test

Cyclic test is performed under vertical load control and horizontal displacement control by applying a vertical pressure and lateral cyclic displacements simultaneously. The horizontal stiffness and the equivalent viscous damping are two performance specifications of rubber bearing evaluated through this test. The horizontal stiffness determines how much the base isolator is flexible against lateral cyclic loading. The equivalent viscous damping represents the capability of the device in dissipating the earthquake’s energy transmitted to the elastomeric isolator.

While the C-FREI is under a constant vertical pressure of 3.0 MPa, the cyclic horizontal displacements are applied. At each amplitude of horizontal deflection including 25% t_r, 50% t_r, and 100% t_r, three fully reversed sinusoidal cycles are applied at constant horizontal rate of V_H = 20mm/s. Variation of vertical pressure and cyclic horizontal displacement versus time are demonstrated in Figures 6a and 6b, respectively.

The effective horizontal stiffness of C-FREIs, $K_{H\,eff}$, and the effective shear modulus, G_{eff}, at each shear strain amplitude (γ), is calculated according to Equations (3) and (4), respectively [14, 15].

$$K_{H\,eff}(\gamma) = \frac{F_{\max} - F_{\min}}{\Delta_{\max} - \Delta_{\min}} \tag{3}$$

$$G_{eff}(\gamma) = \frac{K_{H\,eff}(\gamma) t_r}{A} \tag{4}$$

where $\Delta_{\max}$ and $\Delta_{\min}$ are the peak lateral displacements and $F_{\max}$ and $F_{\min}$ are the peak shear forces, respectively, at each shear strain amplitude. A is the cross-sectional area of the elastomeric layer which is in contact with the fiber-reinforced layer. The equivalent viscous damping of rubber bearing, β, is defined as a ratio of the dissipated energy to the elastic energy restored in the C-FREI [13].

$$\beta = \frac{1}{4\pi}\frac{U_d}{U_e} \tag{5}$$

in which Ud is the energy dissipated per cycle and equals to the area inside the lateral force-deflection hysteresis curve in each cycle and Ue is the energy restored in the rubber bearing measured according to Equation (6) [7].

$$U_e = \frac{1}{2}K_{H\,eff}\Delta_{avg}{}^{2} \tag{6}$$

where $\Delta_{avg} = (\Delta_{max} + |\Delta_{min}|)/2$.

In order to show the whole cyclic test for each specimen, four stages are selected as shown in Figure 7. At the first stage, the rubber bearing is subjected to a constant vertical pressure. Then, the maximum lateral displacement occurred during the cyclic sinusoidal deflections is depicted at stages two, three and four by increasing the shear strain amplitude from 25% t_r to 100% t_r while the vertical pressure remains constant.

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1. HEADING 1

1.1 Heading 2

1.1.1 Heading 3

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[1] $AP = \sigma$

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Figure 1: Deflection of a plate subjected to a uniform temperature rise

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Table 1: Example table caption

Heading*	Heading Subheading (units)	Heading Subheading (units)
Line heading	1234	4321
Line heading	1321	8765

*Footnote~ for this table

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