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# Design and manufacturing of fiber reinforced elastomeric isolator for seismic isolation

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**Abstract**

In this paper an experimental analysis is presented for the mechanical characteristics of multi-layer elastomeric isolation bearings where the reinforcing element—normally steel plates—are replaced by a fiber reinforcement. The fiber reinforced elastomeric isolator (FREI), in contrast to the steel reinforced elastomeric isolator (SREI) which is assumed to be rigid both in extension and flexure, is assumed to be flexible in extension, but completely lacking flexural rigidity. The FREI is designed and fabricated for evaluation of the performance on seismic isolation. Experiments are carried out to evaluate and compare the performances of fiber reinforcement with performance of steel reinforcement, and the differences in performance among different kinds of fiber reinforcements. From the experiments, the performance of the FREI is shown to be superior to that of the SREI in view of horizontal stiffness and vertical stiffness of the isolator. Therefore, it is possible to produce an FREI that matches the behavior of an SREI. Consequently, the FREI could replace the conventional SREI for seismic isolation with low-cost manufacturing and lightweight installation.



*Keywords:* Steel reinforced elastomeric isolator; Fiber reinforced elastomeric isolator; Base isolation; Design of isolator; Experiment of mechanical properties

## 1. Introduction

Base isolation is a technique in which isolation bearings are installed in structure foundations to reduce the damaging motion that horizontal earthquakes transmit to structures. Generally, an isolation bearing consists of thin sheets of rubber bonded to steel plates. Therefore, it provides sufficient vertical rigidity to sustain gravitational loading and yet allows horizontal flexibility to shift the fundamental frequency of an isolated building away from the dominant frequency range of most earthquakes.

Seismic isolation technology is applied almost entirely to large, expensive buildings housing sensitive internal equipments, such as computer centers, chip fabrication factories, emergency operation centers, hospitals, and so on. Hence, the isolators used in these applications are large, expensive and heavy. An individual isolator weighs 1 $t_f$ and often more. To extend this valuable earthquake-resistant strategy to housing and commercial buildings, it is necessary to reduce the cost and weight of the isolators.

However, most studies carried out by structural designers have focused on the performance of seismic isolators and dynamic behavior of seismically isolated structures. Othman [1] studied the profile of a laminated rubber bearing. Tai and Hsueh [2] investigated the mechanical properties of isolation bearings identified by a viscoelastic model. A macroscopic model for predicting large deformation behaviors of laminated rubber bearings has been studied by Iizuka [3]. Chung et al. [4] evaluated the seismic performance of base-isolated structures using a shaking table and a pseudodynamic test. A study on response during large deformation in a seismic isolation system was conducted by Masaki et al. [5].

All these investigations are concerned with the steel reinforced elastomeric isolators (SREIs), but little effort have been made to reduce the cost and weight of the isolators. In order to apply the advanced technology of seismic isolation in poor countries or in low-cost buildings, a study for reducing the cost and weight of isolators must be carried out.

Therefore, this study suggests that eliminating the steel reinforcing plates and replacing them with the fiber

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reinforcement of same stiffness can reduce both the weight and the cost of isolators. Fiber materials are lighter weight but still have an elastic stiffness comparable to that of steel. Fiber also allows a simpler, less labor-intensive manufacturing process that would reduce fabrication cost.

The results of the seismic test are obtained and compared with a conventional isolator. The effectiveness of the proposed isolator is shown by comparing it with the various types of isolators.

## 2. Design and manufacturing of an FREI

### 2.1. Modeling of an FREI

The conventional steel plate of an isolator can be replaced with fiber. In order to evaluate the efficiency of the FREI in the case of seismic excitation in comparison with a conventional isolator, the fiber reinforced elastomeric isolator (FREI) was designed to be the same size of the SREI. The difference between steel plate and fiber thickness was adjusted for using multi-layers of fiber and rubber. Fig. 1(a) is a model of the SREI, which consists of two steel end plates on the top and bottom, and multi-layers of rubber and steel. Fig. 1(b) is a model of the FREI. The reinforcement of the pad is fiber layer instead of a steel plate.

### 2.2. Manufacturing of the FREI

In order to convert the short frequency of the earthquake wave to a long frequency earthquake wave, the fiber reinforcement must have high elongation and must be designed to have high tensional stiffness. For the FREI to have these kinds of properties, natural rubber and chemical materials are mixed several times. An extensional stiffness test, extensional ratio test, hardness test, properties test after aging, crevice endurance test, and resistance against ozone test were carried out according to the test rules of KSM6518, the Korean standard test classification number. The manufacturing processes of the FREI are displayed in Fig. 2(a) and (b).

Two of the raw materials are rubber and fiber. A rubber material and a chemical are mixed in making the rubber pad. The fiber goes through a dipping process consisting of isocyanine treatment and resorcinol formaldehyde latex (RFL) treatment. The bonding ability between rubber and fiber improves due to the dipping process, shown in Fig. 2(a) and (b). The rubber and fiber layer, as shown in Fig. 2(a), is cut to form the isolator shape. The FREI consists of a unit of multi-layers of rubber and fiber as shown in Fig. 2(a). After the molding process through which the molecules of rubber have sufficient elastic characteristics for seismic excitation, the FREI is formed as shown in Fig. 2(c).

## 3. Evaluation of FREI efficiency

In order to investigate the characteristics of fiber reinforcement for the elastomeric isolator, three kinds of tests were carried out, which are summarized in Table 1.

### 3.1. Description of the elastomeric bearing test machine

All tests were carried out in the elastomer bearing test machine. The elastomeric bearing test machine is capable of subjecting a set of single bearing to simultaneous vertical and horizontal loadings. When testing a single bearing, it is placed between the horizontal actuator housing and the base platen to develop a maximum load of 1000 $t_f$.

The vertical load is applied through the upper loading platen that distributes the forces from the vertical actuator to the test bearings. A vertical actuator, including the weight of the upper loading platen, can develop a maximum axial load of 3000 $t_f$ on the bearing. Table 2 shows the elastomeric bearings tester. The size of the experimental test machine is W 12,000 mm × 3500 mm × H 8000 mm.

### 3.2. Data acquisition and control system

A software package of test system is used for the data acquisition and control of the hydraulic actuators for the testing machine. The program runs on a personal computer.

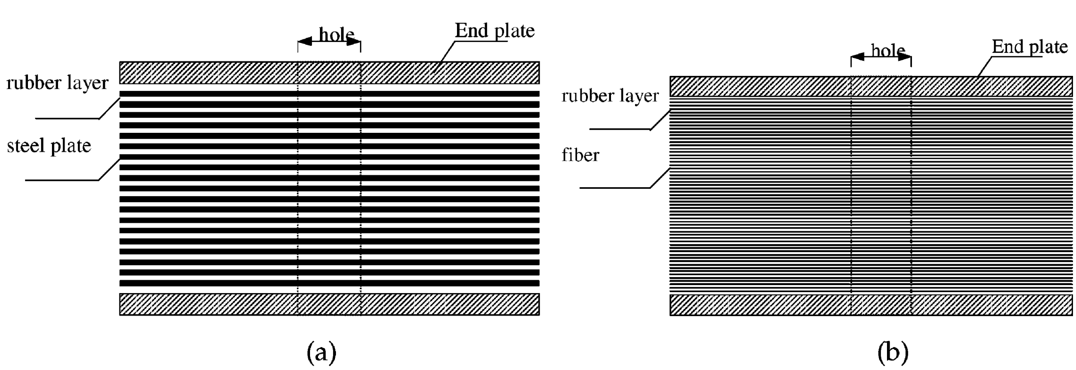


Fig. 1. Modeling of isolators: (a) SREI; (b) FREI.

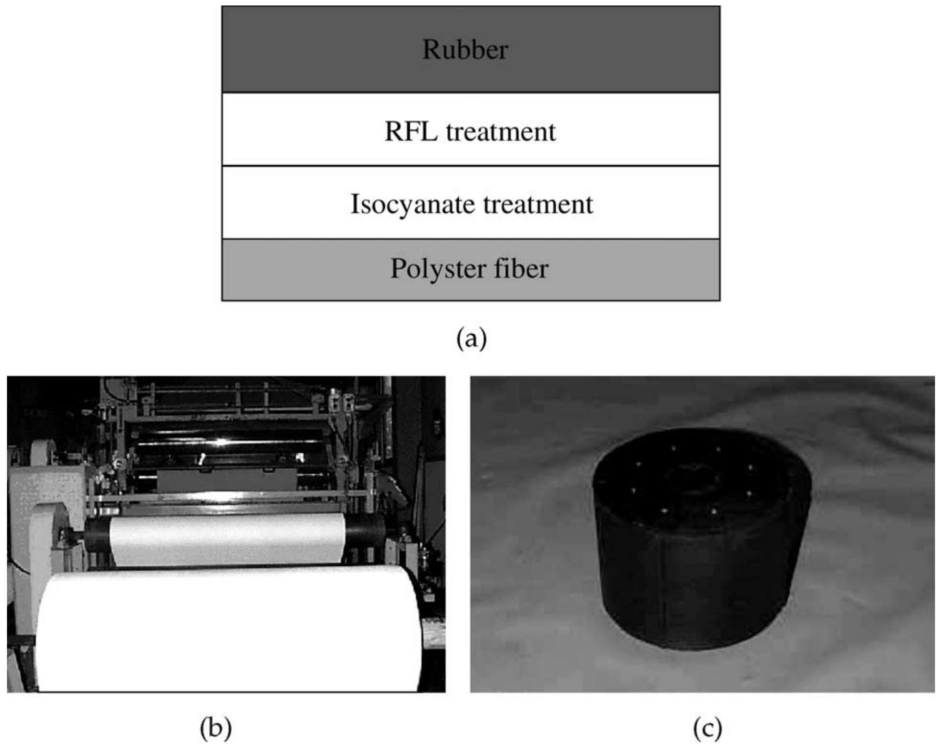


Fig. 2. Manufacturing of FREI: (a) schematic diagram of dipping process to improve bonding characteristic between rubber and fiber; (b) dipping process; (c) FREI in final form.

Table 1
Three kinds of test specification for FREI

| Test no. | Specimen no. | Specimen size | Reinforcement | Type of elastomer | Test objective |
|---|---|---|---|---|---|
| Case 1 | 1-1 | $200 \times 300 \times 43T$ | Polyester-200 | Isolator | Comparison between vertical stiffness and shear modulus among different kinds of fibers |
| | 1-2 | $200 \times 300 \times 43T$ | Nylon-200 | Isolator | |
| | 1-3 | $200 \times 300 \times 43T$ | FIBP-01 | Isolator | |
| | 1-4 | $200 \times 300 \times 43T$ | FIBP-05 | Isolator | |
| Case 2 | 2-1 | $200 \times 300 \times 43T$ | Carbon fiber | Isolator | Comparison between different types of fiber |
| | 2-2 | $200 \times 300 \times 43T$ | Glass fiber | Isolator | |
| Case 3 | 3-1 | $\varnothing 698 \times \varnothing 172 \times 345T$ | Carbon fiber | Isolator | Comparison between fiber and steel reinforcements |
| | 3-2 | $\varnothing 698 \times \varnothing 172 \times 345T$ | Steel | Isolator | |

It can simultaneously control up to three channels of data, with the additional capability of channel calibration and real-time display of the data. For the test machine, the controller in the program always keeps the horizontal load beam in a horizontal position and maintains a constant axial load on the bearing. The typical data sampling rate was 25 points per second, and it could be changed according to the loading rate and duration of the test.

Table 2
Explanation of elastomeric bearings tester

| | Main vertical actuator | Main horizontal actuator |
|---|---|---|
| Maximum load | 3000 $t_f$ | 1000 $t_f$ |
| Stroke variation | ±800 mm | ±800 mm |

### 3.3. Vertical test

In order to investigate the vertical stiffness of a bearing, a vertical test was performed. There were three cycles of loading with peak-to-peak values. Some bearings were tested to obtain vertical stiffness under various maximum values of vertical load. Vertical stiffness of a carbon FREI and an SREI were compared. The vertical stiffness was computed using a linear regression method on the linear portion of the hysteresis loops. The vertical stiffness, $K_v$, of a rubber bearing was computed according to $K_v = E_c A / t_r$, where $A$ is the area of the bearing, $t_r$ the total thickness of rubber and $E_c$ the instantaneous compression modulus of the rubber–fiber composite under a given axial stress.

### 3.4. Horizontal test

Shear moduli of several kinds of elastomer with fiber reinforcement were obtained with a horizontal test. Average effective horizontal stiffness and equivalent damping was obtained in various shear strains. Shear moduli of some plates with fiber reinforcement were investigated at various thicknesses of elastomers. The effects of different kinds of fiber on shear moduli were investigated with a through horizontal test. The combined compression and shear tests were generally evaluated by calculating the effective elastomer modulus and the equivalent viscous damping of each hysteresis loop from the cyclic tests. Effective horizontal stiffness and the equivalent viscous damping of the bearing are the most important characteristics to be determined from horizontal dynamic tests. These properties can be examined with the plots of horizontal shear force shown in constant to horizontal displacement. This force–displacement relationship shows hysteretic behavior. The size of the area enclosed by the hysteresis loop depends on the imposed strain level. The effective horizontal stiffness, $K_{\mathrm{eff}}$ corresponding to each loading cycle, was computed from the secant line, measured from peak-to-peak in each loop.

$$K_{\mathrm{eff}} = \frac{F_{\max} - F_{\min}}{\Delta_{\max} - \Delta_{\min}} \quad (3.1)$$

where $F_{\max}$ and $F_{\min}$ are the maximum positive and negative shear forces, respectively, and $\Delta_{\max}$ and $\Delta_{\min}$ are the maximum positive and negative shear displacements, respectively. The equivalent viscous damping was computed by measuring the energy dissipated in each cycle (EDC), which is the area enclosed by the hysteresis loop. The formula to compute $\beta_{\mathrm{eq}}$ is

$$\beta_{\mathrm{eq}} = \frac{\mathrm{EDC}}{2\pi K_{\mathrm{eff}} \Delta_{\max}^2} \quad (3.2)$$

where $K_{\mathrm{eff}}$ is obtained from Eq. (3.1) and $\Delta_{\max}$ is the average of the positive and negative maximum displacements. This linear viscous model assumes that the energy dissipated in each cycle is linear in frequency and quadratic in displacement.

## 4. Test results and discussion

### 4.1. Test results

In order to investigate the effect of fiber reinforcement in the elastomer different kinds of experiments were carried out. First, four kinds of nylon fiber reinforced elastomer were compared. Second, the effects of horizontal and vertical characteristics were investigated for glass FREI and carbon fiber elastomeric isolator. The third, the mechanical characteristics of carbon reinforced elastomeric isolator and SREIs were compared.

### 4.2. Case 1: comparison of horizontal and vertical test results

First of all, we have to inquire into the characteristics of the nylon fiber and rubber. In this case, four kinds of fibers are investigated, for example, of nylon fibers. The nylon fibers used to evaluate the mechanical characteristics of rubber and fiber layers are Polyester-200, Nylon-200, FIBP-01 and FIBP-05. Fig. 3 shows vertical stiffness versus maximum vertical load with four kinds of fibers. Fig. 4 shows shear modulus versus elastomer thickness with three kinds of fibers.

The vertical stiffness of the Nylon-200 shown in Fig. 3 has better efficiency than those of other fibers. The vertical stiffness of Nylon-200 reinforced elastomeric isolator becomes almost linear to maximum vertical load. Also, the stiffness characteristic of Polyester-200. Nylon-200, FIBP-01, and FIBP-05 shows similar trends of vertical stiffness with increase maximum vertical load. Shear modulus results as shown in Fig. 4 shows that the shear modulus of FIBP-01 is higher than that of Nylon-200 and Polyester-200. The shear modulus variation with an increase of elastomer thickness of Nylon-200 and Polyester-200 is almost the same.

### 4.3. Case 2: the effects of carbon fiber and glass fiber reinforcement on vertical stiffness

Carbon fiber, glass fiber and aramid fiber is the well-known kinds of fibers. In this paper, two kinds of fibers are used to compare the vertical stiffness. The stiffness of carbon fiber is assumed to be higher than the stiffness of glass fiber. Simple tests of vertical stiffness are needed, however, to confirm the characteristics of rubber carbon fiber layers and rubber glass fiber layers, before full-scale

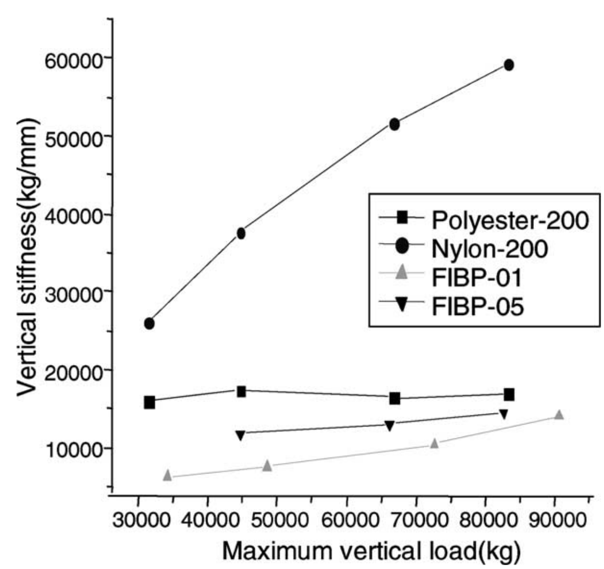


Fig. 3. Vertical stiffness versus maximum vertical load for several fibers.

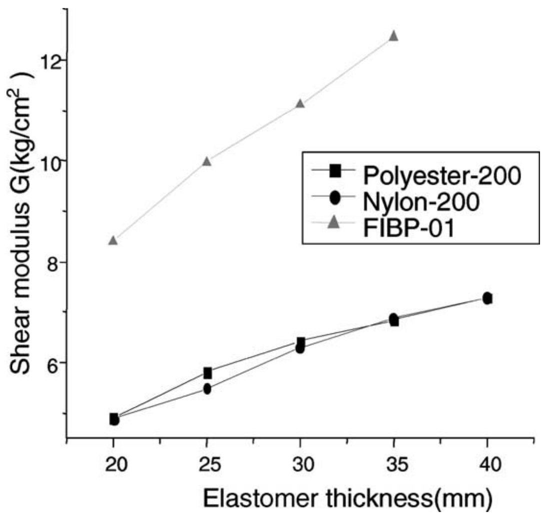


Fig. 4. Shear modulus versus elastomer thickness for several fibers.

test of isolator. The test specimen is fabricated with total initial thickness of elastomer of 40.0 mm and tested with test speed of 5.0 MPa/min. The effects of carbon reinforcement and glass fiber reinforcement on vertical stiffness were examined. Fig. 5 shows a vertical stiffness comparison graph of carbon reinforced elastomers and glass FREIs. The results show that vertical stiffness of carbon fiber reinforcement is higher than that of glass fiber reinforcement. Thus, by the test results, carbon fiber is selected as the reinforcement of FREI.

### 4.4. Case 3: the comparison of carbon reinforcement and steel reinforcement

The comparison of test results between carbon reinforcement and steel reinforcement is shown in Table 3.

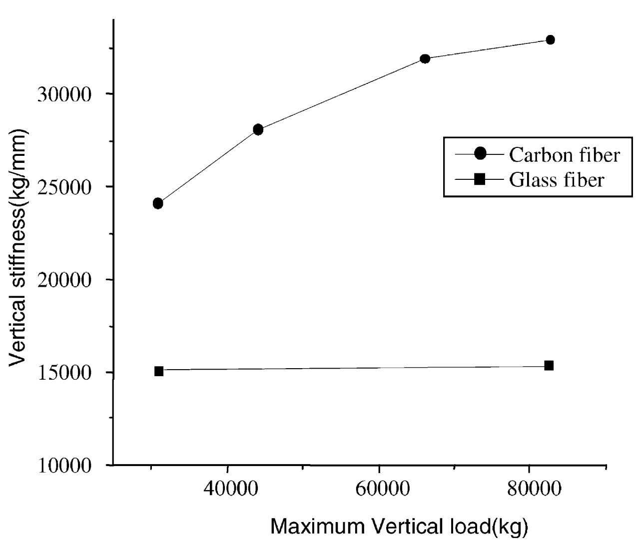


Fig. 5. Vertical stiffness versus maximum vertical load for carbon and glass FREIs.

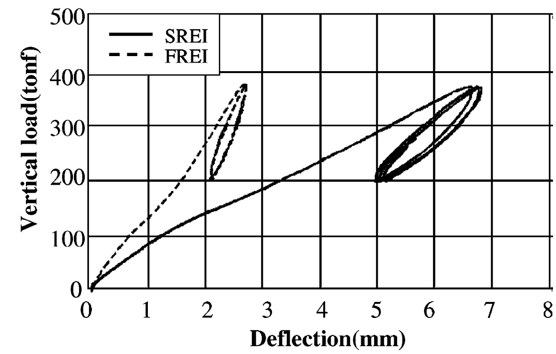


Fig. 6. Comparison of vertical load versus deflection in SREI and FREI.

Vertical stiffness of the carbon fiber reinforcement is three times higher than the vertical stiffness of the steel reinforcement. Because the layer of carbon fiber elastomers is more reinforced than steel reinforcement elastomers, the bulging of carbon reinforcement elastomer is smaller than steel reinforcement elastomers. Equivalent damping of carbon fiber elastomers is 2.5 times higher than in an SREI. Therefore, the carbon fiber elastomers can dissipate a much more severe earthquake than an SREI.

Vertical loads of an SREI and an FREI, when three cycles of loads from 190 to 370 $t_f$ are loaded, are compared as shown in Fig. 6. The average vertical stiffness of an SREI and an FREI are 107,322 $kg_f$/mm and 320,857 $kg_f$/mm, respectively. The vertical test indicated that the vertical stiffness of carbon reinforcement elastomers was three times higher than those of an SREI. The vertical test result shows that an FREI has strong enough vertical stiffness.

Fig. 7 shows hysteresis loops of the horizontal test for a carbon SREI and an FREI. The test results of the FREI revealed the effective stiffness of 330 $kg_f$/mm and the equivalent damping of 15.85%. The test results of the SREI revealed an effective stiffness of 350 $kg_f$/mm and the equivalent damping of 6.20%. The horizontal test results showed that carbon reinforcement elastomers were over two times

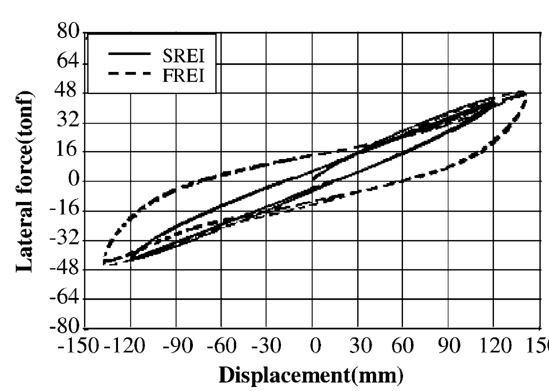


Fig. 7. Hysteresis loops for SREI and FREI at 50% shear strain.

Table 3
Test results of the comparison between carbon and steel reinforcements

| Specimen no. | Reinforcement | Vertical test | Horizontal test | | |
|---|---|---|---|---|---|
| | | Vertical stiffness ($kg_f$/mm) | tan($\gamma$) | Effective stiffness ($kg_f$/mm) | Equivalent damping, $\beta$ (%) |
| 3-1 | Carbon fiber | 320,857 | 0.5 | 330 | 15.85 |
| 3-2 | Steel | 107,322 | 0.5 | 350 | 6.20 |

higher in damping than steel reinforcement elastomers. Thus, by the test and comparison results, carbon can be replaced with steel of SREI.

## 5. Conclusions

This paper proposes a new FREI, which replaces steel plate of SREI with fibers. The design and manufacturing of seismic isolators reinforced with fibers such as carbon fiber, glass fiber, nylon fiber, and polyester fiber were carried out. Experimental works demonstrate that it has high possibility to replace steel reinforcements in isolators used currently for the seismic protection of buildings with a fiber reinforcement. As a result, it is proved that the FREI reinforced by carbon gives higher vertical stiffness and superior to effective damping than that of SREI. This fact is competitive to the conventional isolator and is expected to be utilized as seismic isolator in structural system.

## Acknowledgements

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