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Comparative Mechanical Behavior Low-Cost Flax Fiber Reinforced Elastomeric Isolator (FREI) with Shape Variation

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Abstract Indonesia is a country that has a high potential for earthquakes. Many have highlighted that even though earthquakes are a global phenomenon, their impact on deaths is disproportionate, with the majority of fatalities happening in single- and double-story residential buildings. Indonesians need a sturdy building structure that can resist earthquake effects in light of these circumstances, especially those constructed for public housing. One of the most well-liked methods for protecting residential buildings from the effects of progressively stronger earthquakes uses a base isolation system. However, the cost of existing base isolation systems for residential buildings is relatively high. Therefore, this research focuses on fiber-reinforced elastomeric insulators (FREI) with economical fabrication and residential applicability. The flax fiber utilized in this isolator takes the place of the typical steel shim found in the majority of base isolators. This base isolator is analyzed by a finite element approach using the ABAQUS software to ascertain its mechanical behavior. In contrast, the base isolator's mechanical properties include damping, vertical stiffness, and effective horizontal stiffness. It also discussed how the performance of fiber-reinforced elastomeric isolators (FREI) differs depending on shape variation. The outcomes of this study include the impact of form alterations on the analyses of horizontal stiffness, vertical stiffness, damping, and effective horizontal stiffness in fiber-reinforced elastomeric isolators (FREI).

Keywords Disaster Risk Reduction, Earthquake Engineering, Fiber Reinforced Elastomeric Isolator, Finite Element Analysis, Residential Buildings

1. Introduction

The fact that earthquakes are a worldwide occurrence, many people have drawn attention to the fact that their toll on lives is disproportionate, with the majority of fatalities occurring in single- and double-story residential buildings [1]. The risk of earthquake-related building damage has been decreased by scientists using a variety of methods. Calantarients proposed one method of resisting seismic forces in August 1909 by situating the construction on a "free joint" which would allow for unrestricted horizontal movement of the structure, hence decreasing forces applied to the building. Base isolation or seismic isolation is the term that describes this method [2]. Seismic isolation is a rather straightforward idea. This method isolates the structure from horizontal movement by supplying the least amount of horizontal stiffness between the base and the structure [3]. As a result, the fundamental frequency of the isolated structure is significantly less than the dominant frequency of the ground motion as well as the fixed frequency. Isolation uses system dynamics to deflect seismic energy rather than absorb it to eliminate potential resonances at the isolation frequency [4]. Because base isolation separates ground motion from structural motion, it's a rather effective way to reduce seismic loads. An extremely flexible base isolation system is typically favorable when an earthquake occurs, especially to lessen ductility needs [5]. Over the past few decades, base isolators have gained a lot of popularity in passive seismic protection. This expensive approach is frequently used on mid-rise buildings. The cost-effectiveness of the seismic protection system is essential for low-rise buildings, which make up the bulk of structures in Indonesia. One of the most popular base isolation methods is composed of alternating sections of rubber and steel plate. High vertical stiffness is produced when vertical loads are applied because the steel-rubber bond prevents the rubber from lateral expansion. Conventional isolators composed of layers of steel and rubber laminate are frequently used in many countries and are costly and heavy, resulting in an excessively high construction cost. The weight and cost of conventional isolators are roughly equal to 50-60% of that of building construction [6]. Therefore, the base isolators with minimal costs by replacing the use of steel lamina using fiber and waste materials have been carried out in previous studies [7,8] and this study. Consequently, fiber-reinforced elastomeric isolators (FREI) are an economical and effective alternative to traditional isolation systems for low-rise buildings [9]. Without flexural stiffness, flexible tensile stress is considered to exist in fiber reinforcement [10]. Steel plates can be replaced with fiber-reinforced materials because of the way that fiber reinforcing affects the behavior of isolators in terms of lateral and vertical stiffness. Because fiber reinforcement is a highly lightweight material and the manufacturing process requires little labor, production costs can be kept to a minimum [11]. Improved fiber composition has been the subject of considerable research to reduce the cost of base insulation. The use of fiber instead of shims resulted in a decrease in the manufacturing cost of base isolator materials in a recent study by Sistla and Mohan [12] that used six types of fiber materials in dwellings in India and was based on FREI. Kelly and Takhirov [9] conducted an extensive empirical study on FREI and its application in evaluating its performance concerning viscous damping, vertical stiffness, and horizontal stiffness. They experimentally evaluated FREIs with a variety of shapes, including round, square, and rectangular. Habieb et. al [13] used rubber containing a Shore for the development of a high-pressure unbonded fiber reinforced elastomeric isolation (UFREI) system used for structures with masonry walls, a hardness of 40 and an approximate damping of 10 to 12% was used. The finite element approach in ABAQUS was used for modeling in this investigation. A five-story building was isolated using circular FREI, which Sierra et al. [14] tested experimentally. The experimental identification of the circular UFREI's failure mode was one of their study's intriguing findings. Calabrese et al. [15] Hysteresis models have been developed for recycled rubber fiber-reinforced (RR-FRB) bearings. According to experimental tests, they used a bi-linear hysteresis model to represent the base isolators layer of the scaled steel frame model. In this study, we discuss the mechanical behavior of an innovative low-cost fiber-reinforced elastomeric isolator (FREI) using flax fiber to replace the steel lamina with bonded and unbonded bonds of various shapes. This model only analyzes the mechanical behavior without a cost calculation to observe the behavior of low-cost FREI with shape variation was conducted using finite element software ABAQUS [16,17].

2. Materials and Methods

2.1. General

The experimental model must be used to evaluate the finite element model to guarantee that the validity of the chosen modeling approach is performed utilizing the model from the study and the test results Carbon-Fiber-Reinforced Elastomeric Isolators (CFREI) by Dezfuli et al [18]. Figure 1 and Figure 2 illustrate the isolator model's validation and elevation findings. In Figure 2, the red parts represent steel plates, while the gray and black elements represent rubber and fiber, respectively. The numerical validation analysis FREI model test utilizing ABAQUS will be tested using vertical pressure and cyclic displacement with 25% (loop 1), 50% (loop 2), and 100% (loop 3) total rubber thickness to obtain a hysteretic curve for numerical validation of FREI.

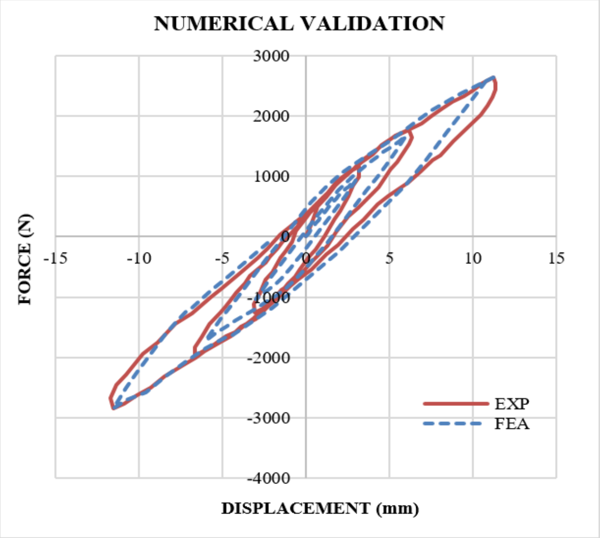


Figure 1. Numerical Validation FREI

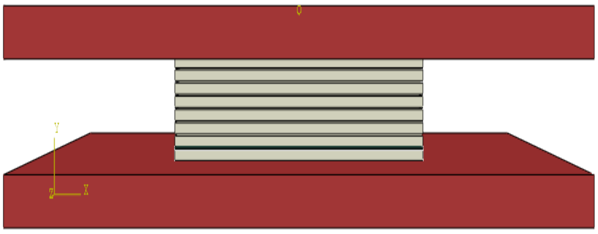


Figure 2. Fiber Reinforcement Elastomeric Isolators (FREI)

2.2. Material Properties

Hyperelasticity and viscoelasticity are the two fundamental characteristics of native rubber from Indonesia. In contrast to viscoelasticity, which is crucial for rubber material's ability to dissipate energy, hyperelasticity allows an isolation system to withstand huge strains without yielding. In this case, Yeoh's hyperelasticity model and the Prony series are utilized to evaluate the hyperelastic and viscoelastic properties of rubber, as shown in Table 1 and Table 2 [19]. The focus of the current study is the utilization of flax fiber, also called linseed or flax. As a food source and fiber, this crop is mainly grown in cold regions. Table 3 includes information about the fiber's elastic characteristics [20].

Table 1. Hyperelastic properties of local Indonesian rubber

C_{10} (MPa)	C_{20} (MPa)	C_{30} (MPa)
0.360513664	0.01241458427	-0.0001519227504

Table 2. Viscoelastic properties of local Indonesian rubber

g_1	t_1 (s)	g_2	t_2 (s)
0.22	0.156	0.082	2.56

Table 3. Elastic properties of flax fiber

E	v
50000	0.23

2.3. Numerical Modeling with ABAQUS

Low-cost FREI will be used in a one-story reinforced concrete building in the Indonesian city of Denpasar, which is in a high seismic zone. Figure 3 shows the floor plan of the building used in this study. The ETABS was used for gravity load analysis and design, and the members were kept safe. Table 4 provides information about construction and loading.

The values of vertical stiffness, horizontal stiffness, effective horizontal stiffness, and damping value should be evaluated. The finite element program ABAQUS is used to simulate low-cost FREI numerically. Based on effective horizontal stiffness and damping value, base isolator quality is assessed. The preliminary design equation discussed in earlier work [21] is utilized to compute the FREI dimensions based on the goal period as well as the location of the seismic area used for this base isolation. Tables 1-3 present the material properties for numerical modeling. Table 5 and Table 6 present the boundary conditions and geometry utilized for modeling and simulation of low-cost FREI (Bonded and Unbonded). The low-cost FREI is subjected to horizontal cyclic displacement following the literature [22] using the strain factor shown in Figure 4. Low-cost FREI was also subjected to a 1 N/mm^2 vertical pressure load applied to the top plate shown in Figure 5. The pressure was obtained from ETABS analysis of the force column. The article "Troubleshooting Finite-Element Modeling with Abaqus with Application in Structural Engineering Analysis" [23] is useful for fixing modeling problems that happened during simulation and modeling.

Table 4. Loading and structural parameters.

Description	Details
Beam dimensions	150 mm x 150 mm
Column dimensions	150 mm x 120 mm
Slab Depth	120 mm
Gravity Load	1.833 kN/m^2
Concrete Grade	M25
Steel Grade	Fe415

Table 5. Boundary condition bonded and unbonded FREI

Description		Boundary Condition
Bonded	Fiber and rubber	Tie constraint
	Top Plate and rubber	Tie constraint
	Bottom plate and rubber	Tie constraint
Unbonded	Fiber and rubber	Tie constraint
	Top Plate and rubber	μ= 0.85 (penalty friction)
	Bottom Plate and rubber	μ= 0.85 (penalty friction)

Table 6. Geometry properties of FREI for numerical modeling

Model	Shape	Interaction	Plate Dimension (mm)	Diameter Base Isolators (mm)	Rubber thickness (mm)	Fiber thickness (mm)	Number of rubber layer	Number of fiber layer
A1	Rounded	Bonded	250x250	160	10	0.5	12	11
A2	Rounded	Unbonded	250x250	160	10	0.5	12	11
B1	Rectangular	Bonded	250x250	160	10	0.5	12	11
B2	Rectangular	Unbonded	250x250	160	10	0.5	12	11

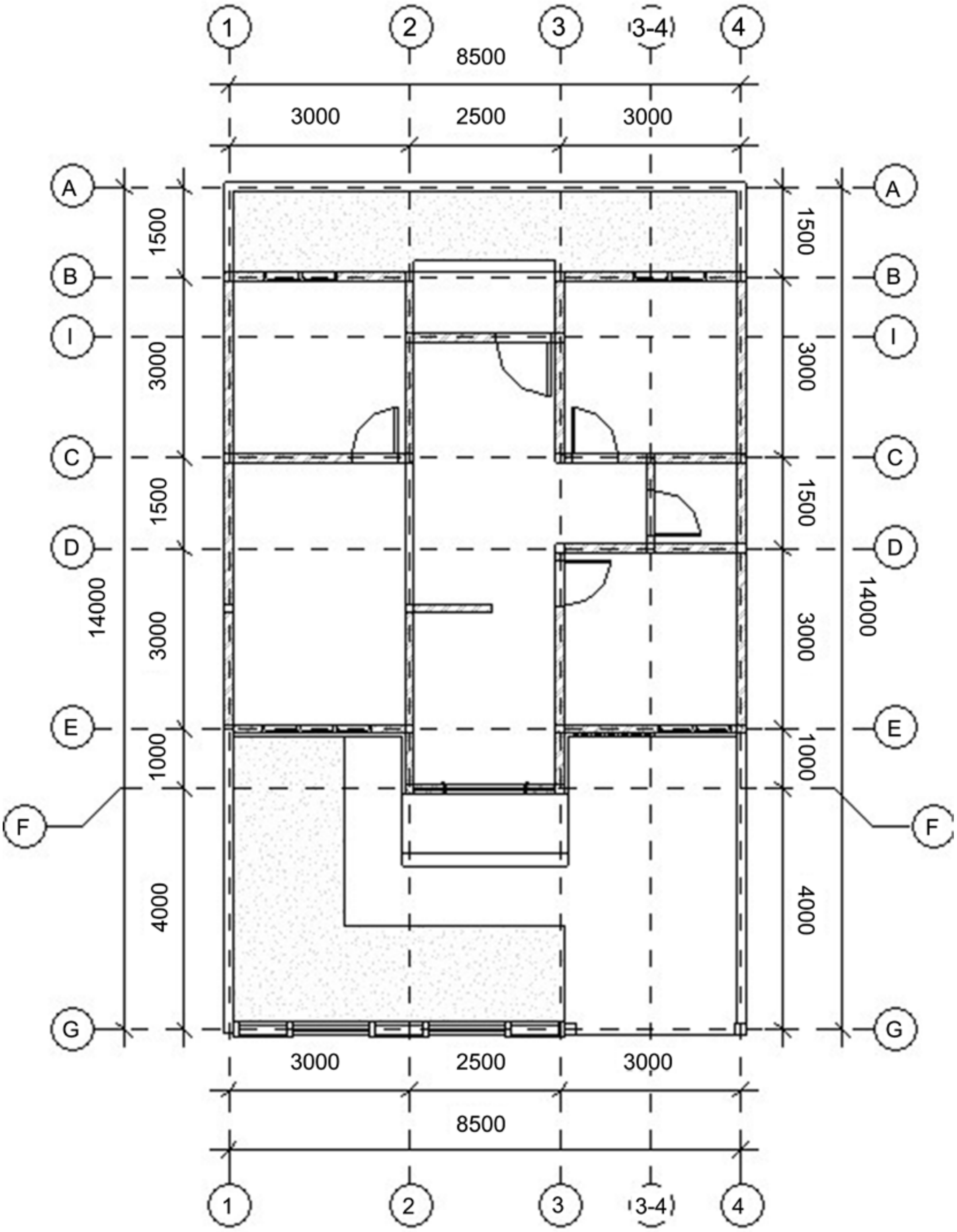


Figure 3. Floor plan of residential house

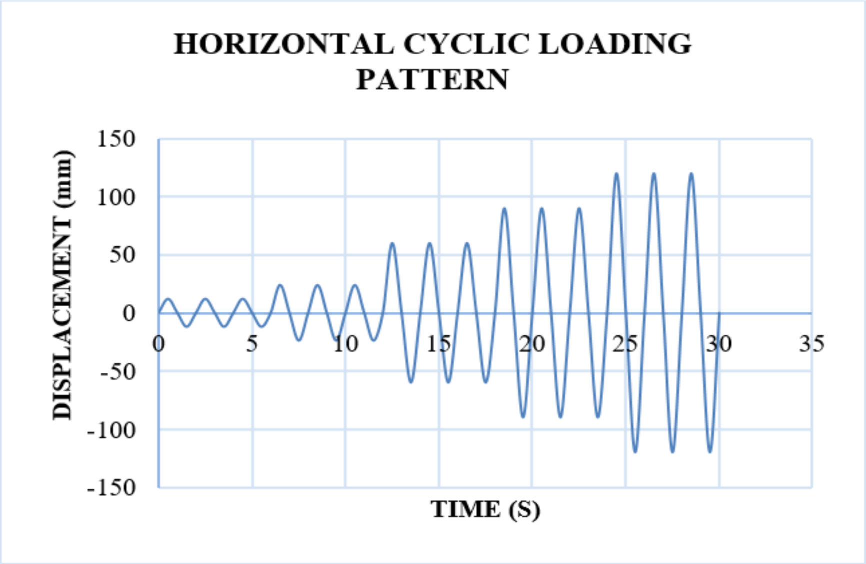


Figure 4. Horizontal cyclic loading pattern

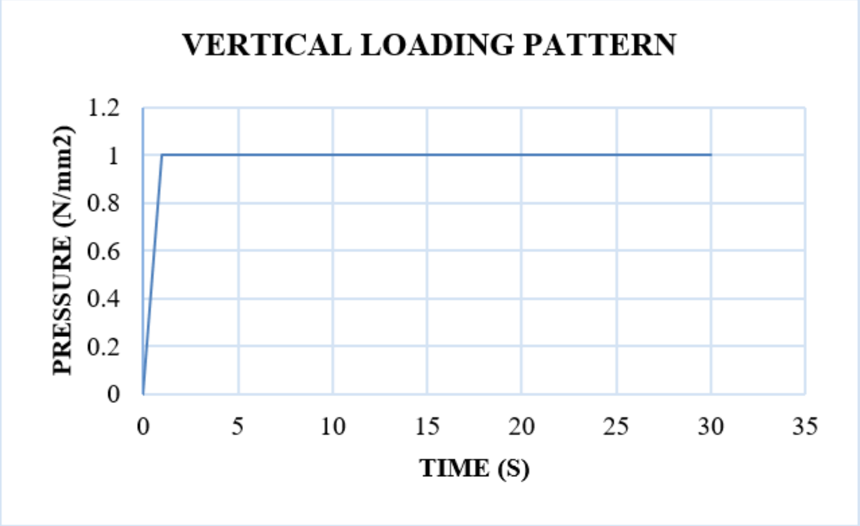


Figure 5. Vertical loading pattern

2.4. Evaluation of Low-Cost FREI's Vertical Stiffness, Horizontal Stiffness, and Damping Ratio

Based on the low-cost FREI hysteresis loops, the formulas used to determine the ratio of equivalent viscous damping and horizontally effective stiffness are as follows [21]:

$$k_{heff} = \frac{F_{max} - F_{min}}{\Delta_{max} - \Delta_{min}} \tag{1}$$

$$\Delta_{max} = \frac{\Delta_{maxa} - \Delta_{mina}}{2} \tag{2}$$

$$W_s = \frac{1}{2}\ k_{eff}\ \Delta_{max}^2 \tag{3}$$

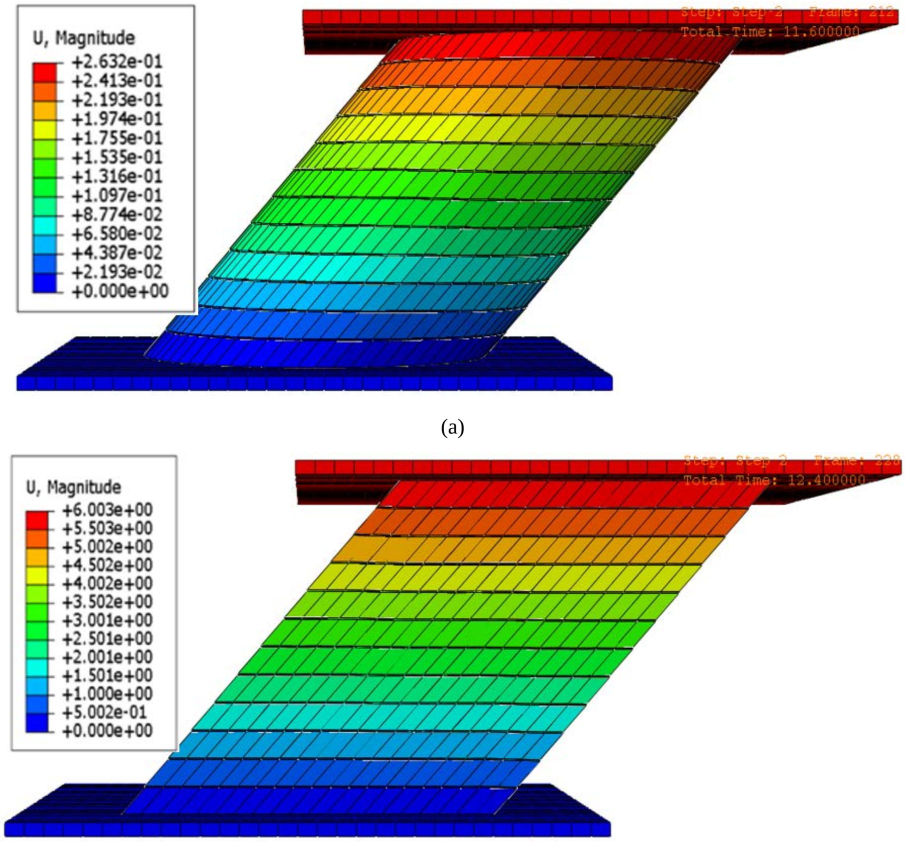
$$\xi = \frac{W_d}{4\pi W_s} \tag{4}$$

Hysteresis loop parameters include F_{max} denotes the highest lateral force, F_{min} denotes the lowest lateral force, Δ_{max} denotes the highest lateral displacement, Δ_{min} denotes the minimum lateral displacement, ξ is the ratio of equivalent viscous damping, k_{heff} is horizontally effective stiffness. The ratio of equivalent damping FREI and effective horizontal stiffness will be tested using cyclic displacement with 100% total rubber thickness as an amplitude.

3. Results and Discussion

3.1. Stiffness and Damping BFREI with Shape Variation

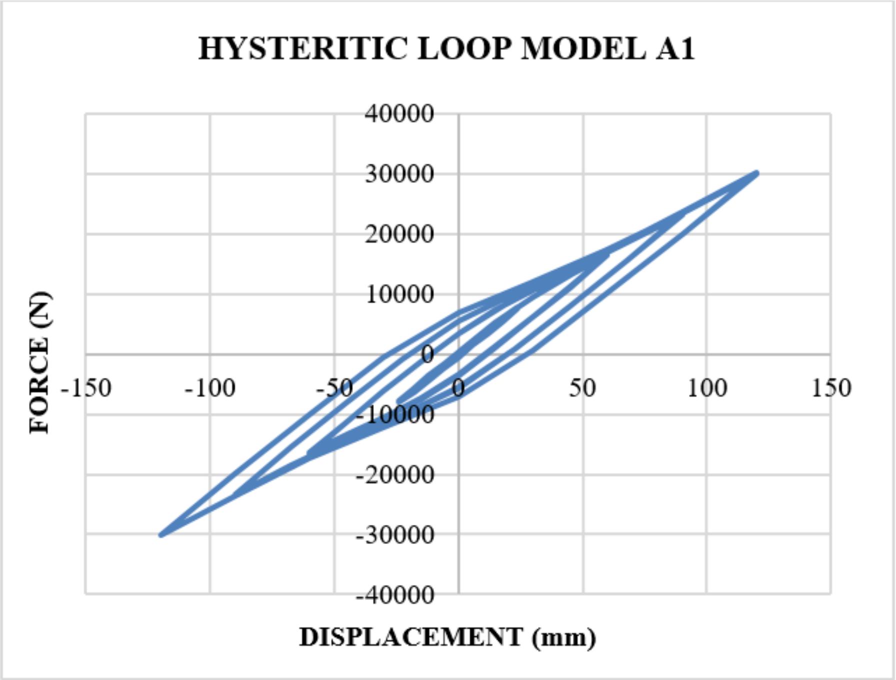
The results of the low-cost FREI modeling with bonded boundary conditions (BFREI) will be explained from the modeling illustration on ABAQUS given in Figure 6, followed by the Hysteretic plot the recapitulation and the hysterical plot of the mechanical behavior in the form of stiffness and damping values presented in Figure 7 and Table 7.



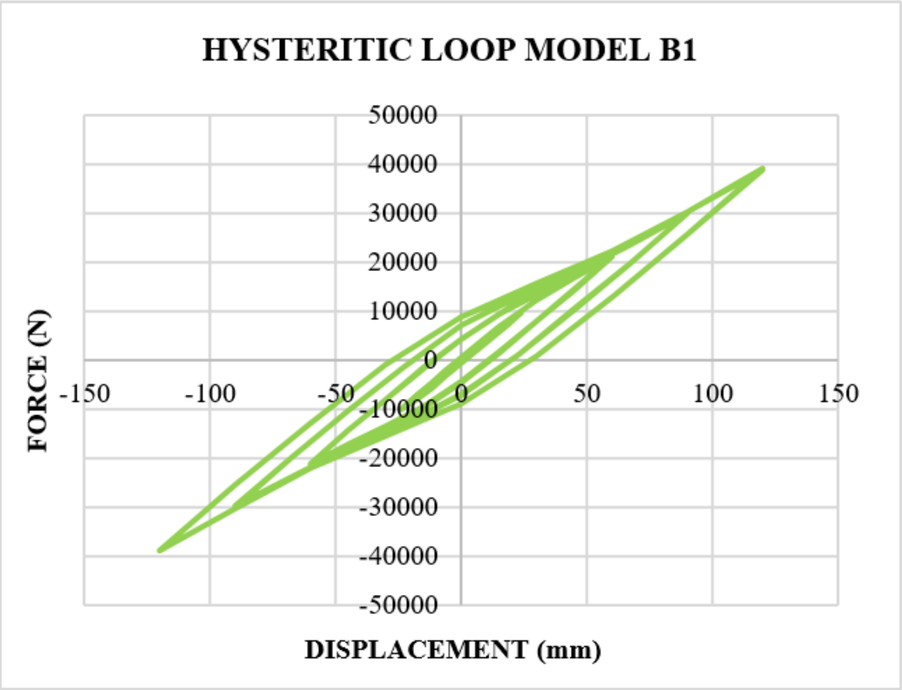
(a)

(b)

Figure 6. Results of Displacements from ABAQUS: (a) Model A1; (b) Model B1



(a)



(b)

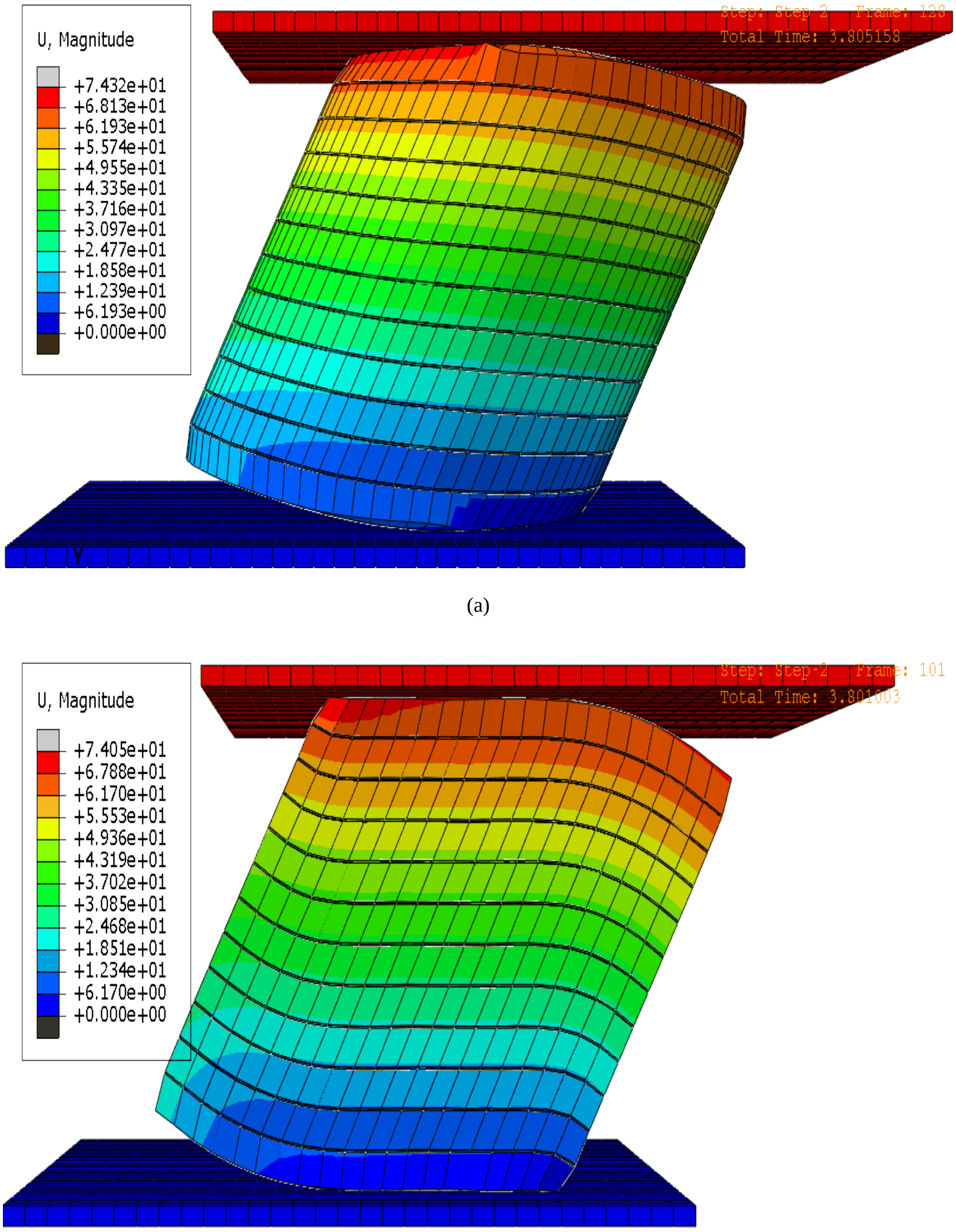
Figure 7. Results of Hysteretic Loops: (a) Model A1; (b) Model B1

Table 7. Comparison of the hysteresis model A1 and B1-derived vertical, horizontal, and equivalent damping ratio (BFREI) with shape variation

Model	Loop	Kv (N/mm)	K_{heef} (N/mm)	ξ (%)
Model A1	LOOP 1 (10% t_r)	31901.02	333.952	0.35%
	LOOP 2 (20% t_r)	31163.3	327.2612	2.58%
	LOOP 3 (50% t_r)	26377.23	275.0709	8.01%
	LOOP 4 (75% t_r)	24825.45	258.6892	8.13%
	LOOP 5 (100% t_r)	24034.75	250.4135	7.76%
Model B1	LOOP 1 (10% t_r)	40798.44	427.0913	0.35%
	LOOP 2 (20% t_r)	39896.76	418.9778	2.57%
	LOOP 3 (50% t_r)	33771.69	352.1825	7.98%
	LOOP 4 (75% t_r)	31918.88	332.6043	8.07%
	LOOP 5 (100% t_r)	31126.95	324.3058	7.66%

3.2. Stiffness and Damping UFREI with Shape Variation

The results of the FREI modeling with unbonded boundary conditions (UFREI) will be explained from the modeling illustration on ABAQUS presented in Figure 8, followed by the Hysteretic plot and the recapitulation of the mechanical behavior in the form of stiffness and damping values presented in Figure 9 and Table 8.



(a)

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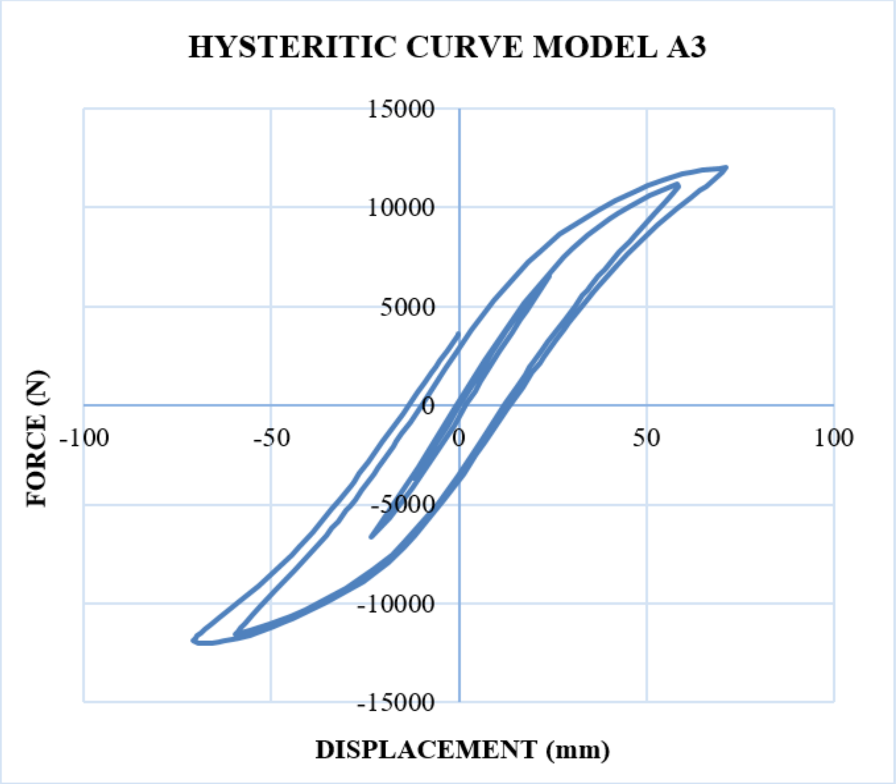
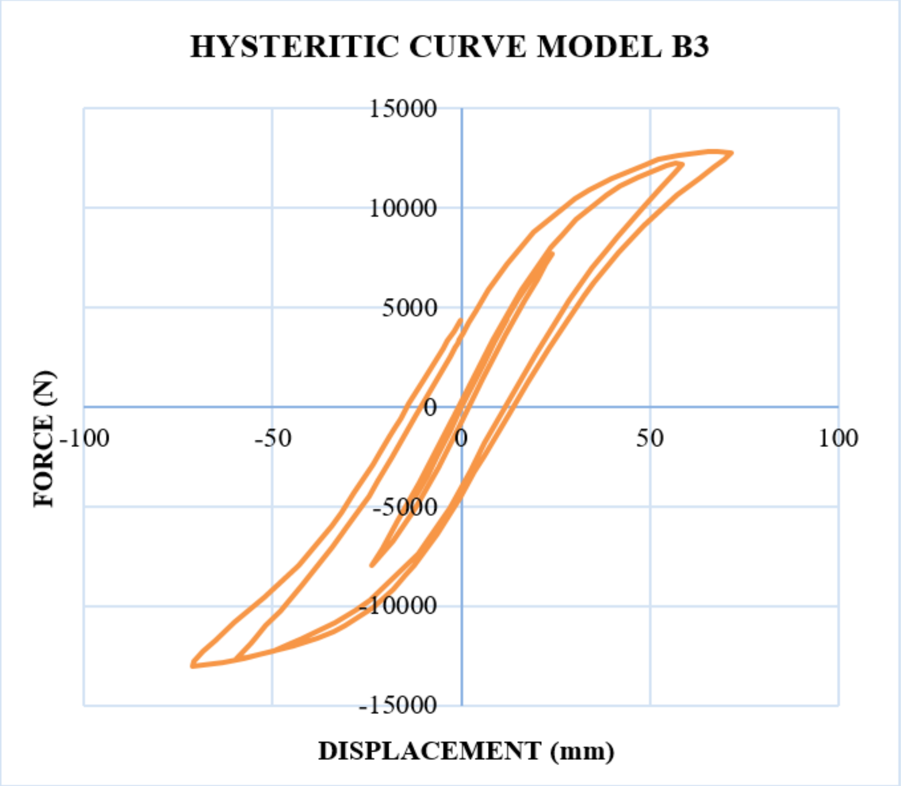
Figure 8. Results of Displacement from ABAQUS: (a) Model A2; (b) Model B2



(a)



(b)

Figure 9. Results of Hysteretic Loop Model A2 and B2

Table 8. Comparison of the hysteresis model A2 and B2-derived vertical, horizontal, and equivalent damping ratio (UFREI) with shape variation

Model	Loop	Kv (N/mm)	K_{heef} (N/mm)	ξ (%)
Model A2	LOOP 1 (10% t_r)	28978.40	303.49	0.70%
	LOOP 2 (20% t_r)	26038.68	278.31	2.92%
	LOOP 3 (50% t_r)	18077.65	191.24	11.01%
	LOOP 4 (60% t_r)	16218.11	168.37	11.51%
Model B2	LOOP 1 (10% t_r)	35387.61	371.38	0.71%
	LOOP 2 (20% t_r)	30843.33	329.52	3.31%
	LOOP 3 (50% t_r)	19932.38	210.14	11.54%
	LOOP 4 (60% t_r)	17114.17	180.52	12.55%

Based on the results of the low-cost FREI modeling with bonded or unbonded boundary conditions from variations in rounded and rectangular shapes, as shown by the FREI hysteric curve on ABAQUS in Figures 7 and 9, results are obtained with variations in shape that further increase the value of the isolators surface area, causing a further increase in loop area and horizontal forces, resulting in low-cost base isolator modifications. How much of a hysterical curve is produced by the region's low seismic forces depends significantly on the geometry of the surface area. In comparison to a low-cost circular FREI, a low-cost rectangular FREI is more resistant to seismic forces. Considering Tables 7 and 8, the investigation of vertical and horizontal stiffness with shape variations leads to the conclusion that an increase in base isolator surface area, both at UFREI and BFREI, directly correlates with a greater value for vertical and horizontal stiffness. Finally, the region on low-cost FREI may be included, which could increase the damping ratio value.

4. Conclusions

1. Kelly and Takhirov [9] proposed developing FREI instead of steel shim to reduce weight and cost. Two adjustments were made in this study: (1) the use of flax fiber as a replacement for reinforcing isolators and (2) developing innovations to reduce the application of glue in bonding steel plates with rubber in UFREI.
2. The horizontal and vertical stiffness of the FREI with a rectangular shape is greater than that of the FREI with a round shape in both BFREI and UFREI, as shown in Table 7 and Table 8.
3. Instead of high horizontal stiffness, a building needs high vertical stiffness to support its load and prevent movement. It is ideal for low-cost FREI in low-rise buildings.
4. In seismic energy dissipation, both FREI with rectangular and round shapes have no significant effect on earthquake energy dissipation, as shown by the damping value in Table 7 and Table 8. However, when compared to the bond pattern, particularly bonded and unbounded, the damping value of UFREI is greater than BFREI in both circular and square shapes.
5. The mechanical effects of the FEA model demonstrate that the damping value of UFREI is higher than the damping value of BFREI, suggesting that a great deal needs to be conducted on the growth of isolators with unbonded connections. This represents an advancement in reducing the quantity of glue required on insulators, which will affect production costs later on. However, it also needs to be investigated in the manufacturing process and field practice because this UFREI can be used and functions effectively when used in construction projects.
6. Since fiber-reinforced insulators are an innovative form of elastomeric bearing, they need to be compared with conventional steel-based isolators in terms of performance and production costs. Steel reinforcement is more expensive than fiber reinforcement. However, when compared to steel reinforcement insulators, researchers and practitioners continue to work on developing fiber insulators in only a few instances.

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