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FINITE ELEMENT ANALYSIS OF A RIGID BODY ISOLATED WITH HIGH-DAMPING UNBONDED FIBER-REINFORCED ELASTOMERIC ISOLATORS

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Abstract. Fiber-reinforced elastomeric isolators (FREIs) stand as a recent advancement in seismic isolation technology, primarily designed to alleviate manufacturing and production costs. Unlike conventional steel-reinforced elastomeric isolators (SREIs), FREIs incorporate fiber fabric layers instead of steel laminas for reinforcement. This substitution not only reduces costs but also results in a seismic device with good isolation properties. Of particular significance are unbonded fiber-reinforced elastomeric isolators (UFREIs) when employed without bonding or fastening between the superstructure and foundations. In such configurations, UFREIs exhibit noteworthy lateral deformation, displaying high damping properties and lower stiffness compared to their bonded counterparts in traditional applications. This study engages in a comprehensive exploration of the seismic isolation characteristics of high-damping UFREIs. Utilizing the Finite Element (FE) software Abaqus, a rigid body isolated by two UFREIs has been modeled and subjected to 2D non-linear time history analyses. The results, encompassing acceleration, displacements, and horizontal forces of the rigid body, have been compared to experimental findings from a prior study conducted by the authors (shake table tests). Beyond the commendable isolation properties of devices, the results validate the UFREI FE model as a suitable representation for understanding device behavior in future structural analyses. This validation is particularly crucial, given the possibility of developing a model based on simple laboratory material tests involving rubber and fiber.

1 INTRODUCTION

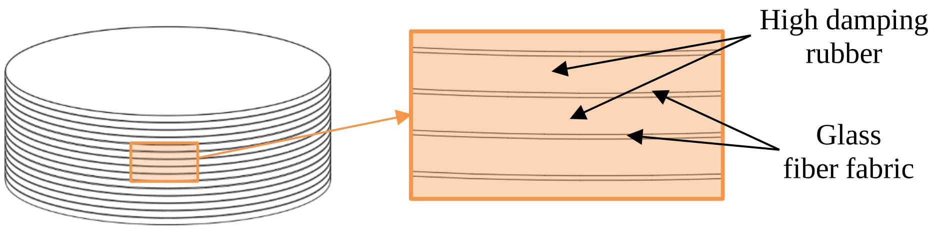
Fiber Reinforced Elastomeric Isolators (FREIs) have gained significant attention in recent years due to their ability to enhance the seismic performance of structures [1,2]. Unlike traditional steel-reinforced elastomeric isolators (SREIs), FREIs employ thin fiber layers as reinforcement. This distinction offers several advantages, such as simplified manufacturing processes, reduced weight of the isolators, and reduced costs. These characteristics make FREIs an attractive option for both upgrading existing structures and safeguarding new constructions in earthquake-prone regions, particularly in developing countries.

FREIs can be installed using various methods, including fully bonded [3][1], unbonded (UFREI) [4][5][6], and partially bonded (PBFREI) [7][8][9] configurations. UFREI is especially noteworthy because it functions without direct bonding or mechanical fastening to the structure. Instead, it relies on friction between the isolator and the contact surfaces to transmit shear loads. This friction-based mechanism, which allows for rollover lateral deformation, enhances damping while reducing horizontal stiffness, thus improving the overall seismic response compared to similar bonded systems [10]. These unique features have spurred significant research interest, leading to numerous studies on the behavior and seismic performance of UFREIs. Although the mechanical properties of UFREIs are well-documented through both numerical simulations and experimental studies, their application in actual structures remains an active area of exploration [11]. Numerical modeling is a particularly valuable approach for assessing the seismic performance of FREIs in structural applications, as it provides a cost-effective alternative to manufacturing and experimental testing.

In this paper, a numerical simulation of experimental shake table tests is performed in Abaqus [12]. A rigid body, isolated with two high-damping UFREIs, is subjected to unidirectional shake table tests. The time history analysis numerical results have been compared with the experimental ones to investigate the capacity of the finite element model (FEM), obtained from simple rubber material tests, to capture the lateral behavior of the device. This validation is crucial to determine if this tool can be used for future numerical structural applications.

2 HIGH-DAMPING FIBER-REINFORCED ELASTOMERIC ISOLATORS AND SHAKE TABLE TESTS

This study focused on seismic isolators specifically designed for the protection of low-rise masonry structures [13–16]. These are composed of alternating layers of high-damping rubber and glass fiber fabric. The isolators consist of high-damping rubber and glass fiber layers. The key geometric features and outcomes from the cyclic shear tests in terms of horizontal stiffness and damping ratios are presented in Table 1 and Table 2. The shear tests have been performed up to 200% of shear strain under a vertical pressure of 1.73 MPa. This vertical load was selected based on the conditions anticipated in the shake table tests to understand better the behavior of the isolators and the performance expectations. Further details on the experimental tests are available in [13].



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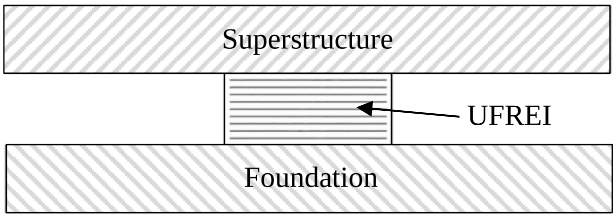

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Figure 1: High-damping UFREI: (a) design and (b) structural application.

Table 1: Geometrical characteristics of the high-damping UFREIs

Height	Base	Rubber thickness	Fiber thickness	n° rubber layers	n° fiber laminas	Total rubber thickness
[mm]	[mm]	[mm]	[mm]	[-]	[-]	[mm]
67.0	200	4	0.5	15	14	60

Table 2: UFREI cyclic shear test results

Shear strain	Horizontal stiffness	Damping ratio
[%]	[kN/mm]	[%]
25	0.52	10.70
50	0.41	9.97
75	0.34	9.85
100	0.29	9.84
150	0.24	10.80
200	0.23	11.60

Shake table experiments were carried out in the Applied Dynamics Laboratory at McMaster University using a rigid block composed of two concrete slabs. The dimensions of the block were 2.80 meters by 2.00 meters by 0.40 meters, and it weighed approximately 110 kN, as shown in Figure 2. Each UFREI experienced a vertical load of 1.73 MPa and was aligned centrally along the block, separated by 1.30 meters in the North-South axis, which was the primary direction of testing. The block underwent testing with four different seismic events from earthquake records of Iran: the Tabas earthquake of 1978, with a peak ground acceleration (PGA) of 0.85 g, the 1990 Manjil earthquake, with a PGA of 0.51g, the Bam earthquake of 2003, PGA of 0.81, and the 2017 Sarpol earthquake, with a PGA of 0.52 g. Due to constraints in the setup, each ground motion was compressed in time by a factor of two. The acceleration levels were gradually increased from 0.10 g PGA to their original values in increments of 0.10 g. This stepwise approach facilitated a thorough analysis of the responses of the UFREIs to various acceleration levels and helped maintain the safety of the test setup by enabling the detection of any potential slips or damages. Additional details on these experimental tests are described in [13]. In this study, not all test scenarios were executed numerically. Specifically, tests were selected at 0.20 g increments, starting at 0.10 g, and in the domain of stable response (i.e., no slip).

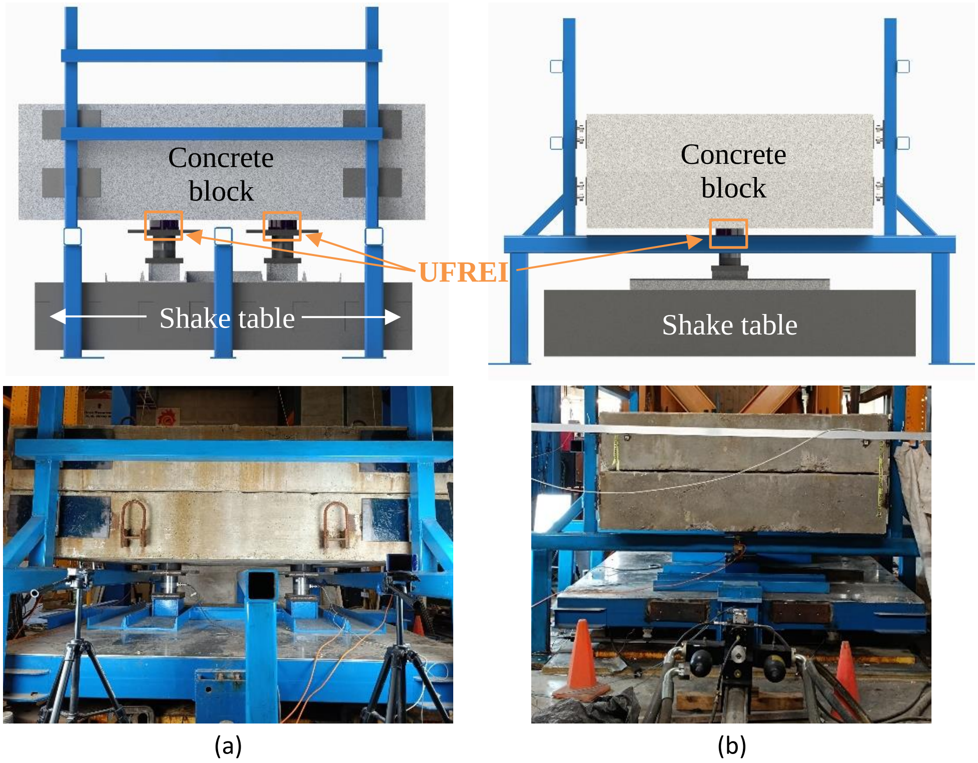


Figure 2: Shake table test setup: (a) north-south and (b) west-east views.

3 FINITE ELEMENT MODEL

The setup of the experimental shake table tests was recreated in Abaqus (Figure 3). For the isolators, the rubber material was modeled using Yeoh and Maxwell's hyperelastic and viscoelastic models using eight-node brick elements (C3D8RH). The glass fiber fabric layers embedded within the rubber [17] were modeled using a four-node doubly curved general-purpose shell, accommodating finite membrane strains. They were characterized by isotropic-elastic properties, with a Young's modulus of 1500 MPa and a Poisson's ratio of 0.2 [18]. An in-depth description of this modeling process is thoroughly detailed in earlier research [19].

The shake table was modeled as a rigid body using four-node 3D bilinear rigid quadrilateral mesh elements. The concrete blocks were modeled collectively as a single entity with a Young's modulus of 22000 MPa, a Poisson's ratio of 0.2, and a density of 2.50 x 10^{-9} tonne/mm^3. This setup maintained a vertical pressure of 1.73 MPa on the isolators. Since the tests were conducted in a unidirectional manner, the concrete block was restricted in the Y direction, and additional constraints were applied to the shake table in the Y and Z directions. The shake table's reference point (RP) received the acceleration time history inputs along the X-axis. The interactions between the isolators and both the rigid block and the shake table were simulated using penalty surface contact with a friction coefficient of 1, a standard value chosen to avoid slipping [20].

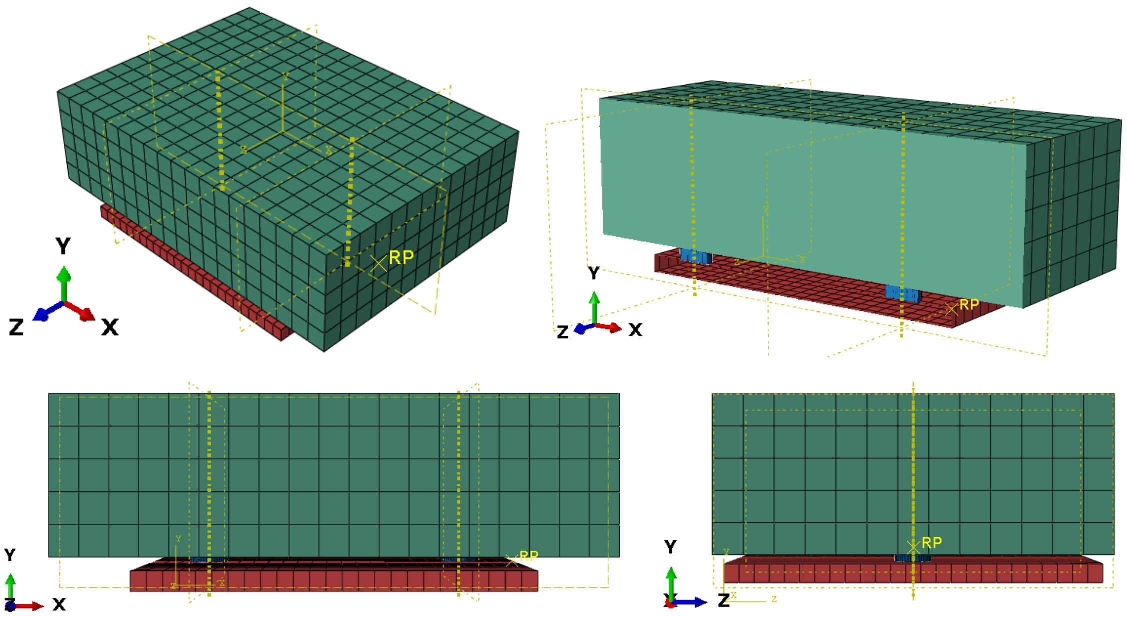
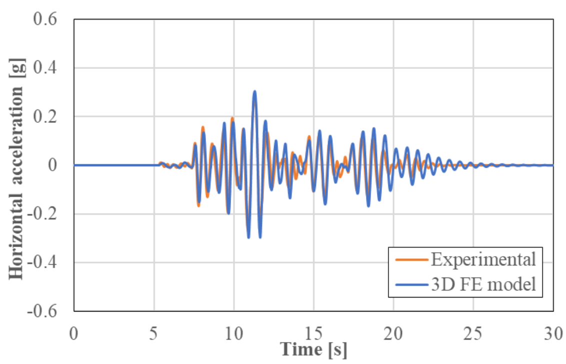


Figure 3: 3D FE model of the shake table setup.

4 NUMERICAL RESULTS AND DISCUSSION

The results from the non-linear time history analyses in the numerical model were compared with experimental data, focusing on the time histories of horizontal acceleration, displacement, and force. As an example, Figure 4 shows the time history of accelerations, displacements, and force for the Tabas 0.4 g ground motion test. Peak values from each earthquake record were identified for this comparison. Ratios of numerical model results to experimental data for each peak were computed. These results are summarized in Table 3. Additionally, the last row of the table displays the mean absolute error (MAE) percentage for all PGA amplitudes and ground motions examined.



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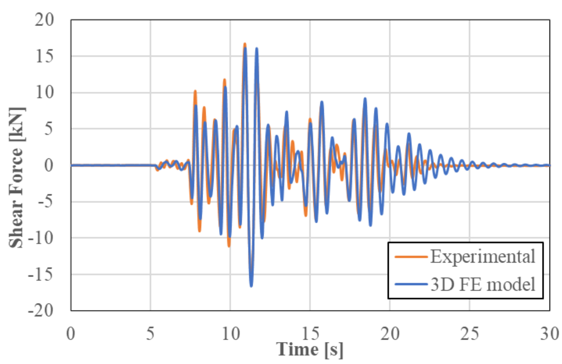

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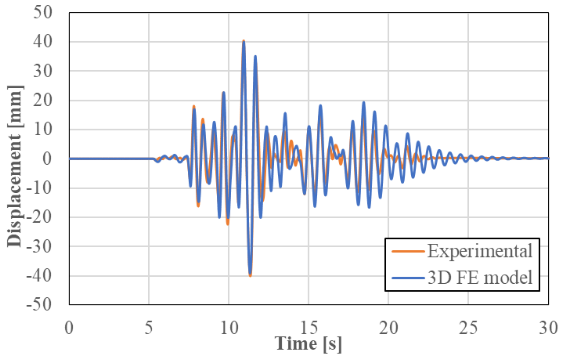

(c)

Figure 4: Non-linear time history results for the Tabas test at 0.40g: (a) comparison of the acceleration, (b) force, and (c) displacements.

Table 3: Model to experimental results ratio for peaks

Ground Motion	PGA (g)	Displacement	Horizontal force	Acceleration
Bam	0.11	1.42	1.10	1.17
	0.34	1.02	1.06	1.18
	0.40	0.97	1.13	1.17
Tavas	0.11	2.13	0.82	0.90
	0.39	1.04	1.00	1.07
	0.55	0.86	1.01	1.13
	0.66	1.01	1.18	1.23
Manjil	0.10	1.02	0.62	0.67
	0.25	1.51	0.83	1.14
	0.51	0.52	0.48	0.53
Sarpol	0.13	0.92	0.69	0.73
	0.27	1.20	0.96	1.16
	0.54	1.10	1.01	1.19
MAE [%]		24.46	16.08	20.08

The evaluation of the data showed that the highest MAE occurred in displacement measurements, reaching approximately 25%. The MAE for horizontal force was about 16%, while for acceleration, it was around 20%. Upon further inspection, the 3D FE model struggled to accurately simulate the behavior of the device at the smallest PGA amplitudes, typically associated with minimal shear strain, which was an anticipated outcome. As noted in prior studies, variations in the responses of the FE model, such as differences in stiffness and damping during low displacement cyclic shear tests, were observed [19]. Since the values at lower amplitudes are typically small, the resulting percentage errors can appear disproportionately large, potentially overstating the error's significance relative to the true scale of the measured values. To address this, a new MAE was computed, omitting the lowest PGA amplitudes from each set of ground motions. With this adjustment, the MAEs decreased to 11.77% for displacements, 8.62% for horizontal force, and 13.38% for accelerations, bringing them below the 15% threshold, which is generally considered acceptable in engineering practices.

5 CONCLUSIONS

This research evaluated the effectiveness of a 3D FE model, developed from simple material tests, in representing the seismic isolation performances of UFREIs. Specifically, shake table tests were simulated using Abaqus, and the resulting data, including displacement, horizontal forces, and acceleration time histories, were compared with experimental findings. The comparison focused on the peak values.

The results showed that the UFREI 3D FE model had difficulty accurately simulating behavior at lower peak ground acceleration (PGA) levels (PGA ≤ 0.13 g), which are typically associated with low shear strain. However, the FE model showed a strong correlation with experimental results at higher PGA amplitudes, confirming the potential of using this tool for predicting seismic performance in structural applications. Additionally, the ability of the model to function without requiring calibration from UFREI cyclic shear test data emphasizes its practical value, especially when specific experimental data is unavailable, a common scenario during preliminary research phases.

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