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Non-iterative computational model for fiber-reinforced elastomeric isolators

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ABSTRACT

In this paper, time history analyses are carried out on a structure seismically isolated with fiber-reinforced elastomeric isolators (FREIs). The lateral response of the isolators is simulated using two modeling techniques, the *Backbone Curve* model, which combines a dashpot with a nonlinear elastic spring, and a new proposed model, named *Pivot-Elastic*. This proposed model combines a bilinear pivot hysteretic model with a nonlinear elastic spring. In contrast to other numerical models that have been previously used for FREIs (e.g., Backbone Curve and modified bilinear models), the proposed Pivot-Elastic model is non-iterative and determination of the model parameters does not require fitting over the entire experimentally obtained hysteresis loops. The Pivot-Elastic model can be easily assembled using a combination of elements readily available in commercially available structural analysis software, which would facilitate its implementation in engineering practice. The accuracy of the proposed model is evaluated using test results from a previous shake table study. The peak response values of the isolated structure predicted by the Pivot-Elastic and the Backbone Curve models are compared with experimentally obtained values. Findings confirm the ability of the proposed Pivot-Elastic model to accurately predict the seismic response of structures isolated with FREIs.

1. Introduction

Steel-reinforced elastomeric isolators (SREIs) are the most common type of seismic isolation device in use. They are composed of elastomeric layers interleaved by reinforcing steel shims. The application of SREIs in North America is almost entirely limited to high importance or historical buildings, or those housing sensitive or valuable contents. For smaller projects (e.g., residential buildings), it is not economically viable to employ traditional seismic isolation technology. Various alternative, low-cost seismic isolation systems using rubber have been investigated over the years [1–13].

Kelly [2] suggested that by reducing the weight and cost of elastomeric isolators, seismic isolation could be extended to typical (normal importance) housing and commercial buildings. By eliminating the thick top and bottom steel connecting plates and using fiber material instead of steel for the reinforcing layers, the weight of the isolators can be significantly reduced. Unlike SREIs, which utilize a hot vulcanization manufacturing process, Toopchi-Nezhad et al. [7] suggested that fiber-reinforced elastomeric isolators (FREIs) can be manufactured using cold vulcanization, which has the potential to reduce the high manufacturing costs associated with SREIs. An additional advantage of FREIs is the ability to manufacture large pads and cut individual isolators from the pads to the desired size [2,9].

FREIs can be installed with no bonding or fastening to the upper and lower supports in an unbonded application (Fig. 1). Shear forces are transferred from the isolator to the superstructure and substructure through friction along the support surfaces. Due to the absence of the thick end plates and flexibility of fiber reinforcement layers, unbonded fiber reinforced elastomeric isolators (U-FREIs) undergo a unique rollover deformation when subjected to lateral loading. This rollover is shown to increase the seismic isolating efficiency by reducing the effective lateral stiffness of the isolators [14,15]. Additionally, when FREIs are unbonded this results in a reduced stress demand on the isolator [15]. U-FREIs have been shown [6,7] to provide a higher level of energy dissipation compared to conventional SREI. Experimental studies [3,6,7,9,10] have confirmed that U-FREIs are viable.

The unbonded application, which provides SU-FREI with its desirable characteristics, does introduce limitations in comparison to bonded or partially bonded isolators [12]. SU-FREI are unable to resist tensile forces, and as such are not suitable for situations where overturning may occur or where large vertical ground accel-

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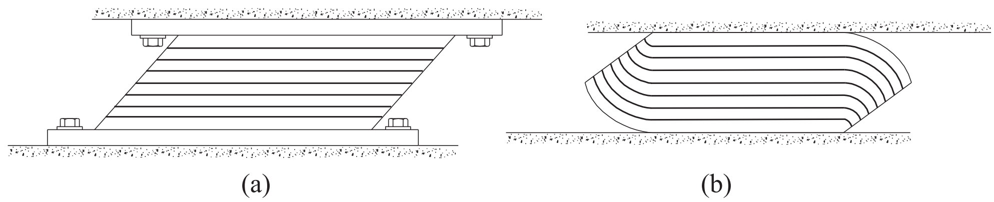

Fig. 1. FREI in (a) bonded application, (b) unbonded application.

erations are anticipated. In addition, under certain loading conditions SU-FREI could potentially experience slip as they rely on friction to transfer horizontal forces, which could result in permanent displacements [16].

The lateral load-displacement relationship of stable unbonded fiber reinforced elastomeric isolators (SU-FREIs) can be divided into three different regions: an initial linear region; a softening region, where the effective stiffness reduces due to the rollover; and a subsequent stiffening region, where the effective stiffness increases due to the contact of the originally vertical faces of the isolator with the upper and lower supports [17]. Results from lateral cyclic tests conducted on SU-FREIs [3,6,7,18,19,20] have shown that both the effective stiffness and equivalent viscous damping vary nonlinearly with displacement. As such, modeling an isolation system composed of SU-FREIs with such complex load-displacement characteristics is challenging. It is noted that in the remainder of this paper SU-FREIs are simply referred to as FREIs.

In order to analyze the response of structures seismically isolated with FREIs, a model that accurately simulates both the stiffness and damping characteristics of the isolators is required. Toopchi-Nezhad et al. [21] used a combination of a nonlinear elastic spring with a dashpot connected in parallel (hereinafter referred to as the *Backbone Curve model*) to model the response of FREIs and carried out time history analysis. Toopchi-Nezhad et al. [22] used two models to simulate the lateral response of FREIs, a modified bilinear model and a 10-parameter rate-dependent model based on a set of equations proposed by Hwang et al. [23]. Love et al. [24] employed a modified form of the linearized Bouc-Wen model to model a base isolation system comprised of FREIs. In all these modeling techniques, a separate set of model parameters were calculated based on the hysteresis loops of the isolator at different displacement amplitudes, since it was not possible to accurately match the variation in the values of the effective stiffness and damping ratio of the FREI with a single set of model parameters. As a result, the time history analysis using such models is iterative. In addition, determination of the model parameters requires curve fitting over entire hysteresis loops. A simplified model that accurately simulates the response of FREIs and requires no iterations is needed to facilitate the analysis and design of structures isolated with this type of isolator.

In this study, a computational model to simulate the lateral response of FREIs is proposed. The proposed model, hereinafter referred to as the *Pivot-Elastic model*, is non-iterative and can be employed in commercially available structural analysis programs, such as SAP2000 [25]. In addition, in contrast to existing FREI models, determination of the parameters of the Pivot-Elastic model does not require fitting over entire hysteresis loops; rather, only the effective stiffness and damping ratio need to be considered. Furthermore, compared with previously employed models, the total number of the parameters of the Pivot-Elastic model is considerably less. For example, the modified bilinear and 10-parameter models used by Toopchi-Nezhad et al. [22] required a total of 18 and 60 parameters, respectively, whereas the total number of the parameters needed for the Pivot-Elastic model is six.

The Pivot-Elastic model is a combination of two elements: a plasticity model with bilinear pivot hysteresis [26] and a nonlinear elastic spring. These two elements connected in parallel can simulate the variation in the values of the effective stiffness and damping ratio of FREIs. Two series of time history analyses are carried out, one using the Backbone Curve model and one using the proposed Pivot-Elastic model, and the results are compared with the results from a previous shake-table study [8] carried out on a two-story steel moment frame structure isolated with FREIs. Results of the time history analyses confirm the ability of the proposed model to accurately predict the seismic response of structures isolated with FREIs.

2. Modeling FREIs

2.1. Bilinear model

In an effort to simplify the inelastic analysis of seismically isolated bridges, the AASHTO Guide Specifications for Seismic Isolation Design [27] introduced the concept of an equivalent linear system, using an effective period and effective damping ratio, to describe the dynamic behavior of the most common isolation systems at the time, namely the lead plug system and the friction pendulum system, both of which can be modeled by bilinear hysteresis [28]. While the validity of using an effective period and effective damping ratio to accurately describe the seismic response of bilinear hysteretic systems has been challenged by various studies (e.g., [29–31]), these linear parameters remain important design parameters and are present in current seismic isolation design code provisions. Fig. 2 shows the definition of the bilinear model, where u_y is the yield displacement, and K_1 and K_2 are the first and second stiffness values, respectively. The effective (secant) stiffness of the bilinear system, $K_{\mathrm{eff}}^{\mathrm{bi}}$, at displacement u can be calculated using

$$K_{\mathrm{eff}}^{\mathrm{bi}} = \begin{cases} K_1 & u < u_y \\ K_2 + \frac{u_y}{u}(K_1 - K_2) & u \geqslant u_y \end{cases} \tag{1}$$

The energy dissipated per cycle, $E_{\mathrm{h}}^{\mathrm{bi}}$, for $u \geqslant u_y$ can be obtained by

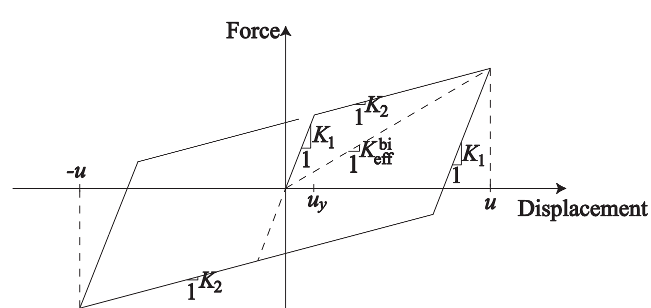

Fig. 2. Bilinear model.