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A consistent omnidirectional nonlinear hysteretic response model for triple friction pendulum bearings

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Abstract

Seismic isolation systems have found widespread use in the design of essential facilities such as hospitals, which have to meet higher performance requirements. Base isolators can significantly reduce seismic demands and protect both the structure and its contents. Among them, the so-called Triple Friction Pendulum (TFP) bearings arguably offer the highest performance. There are several simplified models available to simulate the behavior of TFP bearings, and most of these models only offer uniaxial responses. However, in seismic response simulations, the determination of coupled biaxial lateral responses is often necessary. In such cases, the typical approach is to use two uncoupled macroelements that represent the uniaxial lateral response of a TFP bearing in two lateral directions. Such a modeling approach will produce errors in both the direction and amplitude of the restoring force of the TFP, and the accuracy of the simulation results will highly depend on the chosen orientation of the two uncoupled macroelements. We propose a methodology herein that is based on classical plasticity, which takes any uniaxial backbone curve (along with its elastic unloading and re-loading rules) and produces an omnidirectional model that consistently produces coupled biaxial responses in any arbitrary direction. The idea is to use as many nested yield surfaces of classical plasticity as needed to produce a given uniaxial backbone curve and to use this model to produce the biaxial restoring forces of the TFP consistently. The proposed methodology is implemented in MATLAB, and a representative omnidirectional TFP model is validated using data from large-scale experiments conducted at UC Berkeley in 2011.

Keywords: triple friction pendulum; multi-surface plasticity; nonlinear hysteretic responses

1. Introduction

Base isolation systems are among the most commonly employed devices around the world for reducing the destructive energy that earthquake-induced ground motions impart onto a superstructure through its mass. This class of seismic protection devices is based on the simple notion of separating the ground motions from those of the superstructure as much as possible. There are many subclasses of base isolation systems, which are typically used in performance-critical facilities, such as hospitals, transportation structures, and energy, water, and information hubs.

In general, there are multiple categories of the base isolation device; this paper will focus on the friction pendulum device, especially the Triple Friction Pendulum (TFP) system. Triple friction pendulum (TFP) bearings are among state-of-the-art technology in isolation devices and arguably offer the highest performance. TFP bearings rely on friction to dissipate seismic energy and exhibit highly nonlinear/hysteretic responses.

The unidirectional behavior of TFP bearings has been well studied by Fenz and Constantinou [1], and Morgan and Mahin [2]. It is captured simply by taking the equilibrium of each stage to find the force-deformation relationship. There are other simplified models available to simulate the behavior of TFP bearings, and most of these models only offer uniaxial responses. However, in seismic response simulations—especially those involving potentially damaging events—biaxial lateral responses are often required. In such cases, the typical approach is to use two uncoupled macroelements that represent the uniaxial lateral response of a TFP bearing in two lateral directions. The use of two uncoupled macroelements in two orthogonal directions will produce various errors. For example, both the direction and the amplitude of the resultant reaction will be incorrect in general, and will depend on the chosen orientation of the macroelement-i.e., the same displacement history will produce different reaction force histories for different macroelement assembly orientations. In fact, if the reacting medium has a theoretical limit strength, it will be possible to produce a resultant force that is larger than that limit, even when each macroelement used in that calculation obeys that said limit.

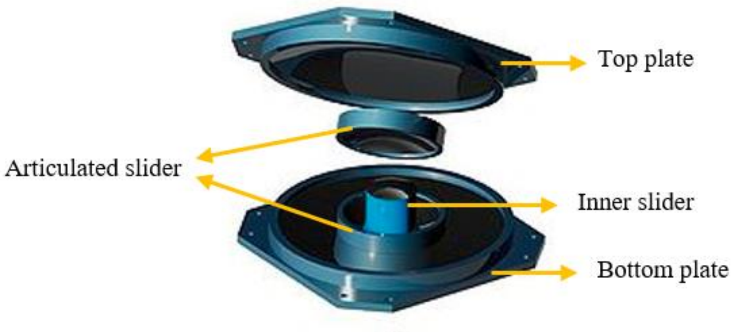

Fig. 1 – Triple Friction Pendulum Bearing 3D isometric view

2 An omnidirectional modeling approach for the hysteretic response of TFP bearings

2.1 Methodology

The difficulty, as mentioned above, is not unique to TFP. It is, in fact, typically the norm to devise and use uniaxial hysteretic models wherein there is no inherent physical reason (or expectation) that the actual response will remain uniaxial throughout the loading history. We propose a methodology rooted in classical plasticity [3], which takes any uniaxial backbone curve (along with its elastic unloading and re-loading rules) and produces a biaxial model that will consistently reproduce the original uniaxial response in any arbitrary direction. The idea is to use as many nested yield surfaces—and hardening rules that govern their motions and interactions (in stress/force space)—as needed to produce a given smooth uniaxial backbone curve. If the

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bi-axial multi-surface model can be calibrated to achieve this feat, then it will produce results that are consistent with the original uniaxial backbone curve for arbitrary loading histories. It goes without saying that perhaps the multiaxial response of such a model should be calibrated using actual multiaxial testing data. Regardless, the multiaxial multi-surface plasticity model—henceforth referred to as the omnidirectional model—will always produce more accurate results than two uncoupled uniaxial models.

The particular multi-surface plasticity framework adopted here is due to Montáns [4][5], who aimed at describing the Masing behavior of various materials. Montáns was able to describe the multiaxial nonlinear hardening function in a relatively simple way. Therefore, his formulation is highly suitable for modeling the hysteretic behavior of TFP bearings. In the implicit multi-surface plasticity algorithm that we implemented, the active surface is determined iteratively at each time step, and the Newton-Rapson method is used for determining the consistency parameter. The stresses and the state variables that govern the evolution of nested yield surfaces are updated after that. Since the radii and the hardening parameters of each yield surface are different, this multi-surface plasticity model can easily represent multi-stage hardening behavior. Therefore, the omnidirectional model has been implemented as a framework in MATLAB.

2.2 Verification of the omnidirectional model

Based on Montáns's multi-surface plasticity model, a uniaxial proportional loading test has been conducted. There are eight nested surfaces in total, and the shear strain is prescribed. We conduct a similar test to verify our implementation since not all of the test input variables are given explicitly in Montáns's paper. All the input variables are listed in Table 1, Fig.2, and Fig.3 show the loading protocol and strain-stress relationship. From these results, one can see that although the behavior is not necessarily identical to that by TFP bearings, trends are very similar, and the model can present different tangent stiffness in different stages. As such, the multi-surface plasticity framework will be used to devise an omnidirectional macroelement model that can mimic the hysteretic responses of TFP bearings under general multiaxial loading cycles.

Table 1 – Input variables of the uniaxial loading protocol

Number of surfaces i	The radius of each surface: r^i	Kinematic hardening modulus: H^i
1	6	50000
2	10	46154
3	15	18043
4	25	6674
5	40	1798
6	70	254
7	100	004
8	120	0.01
Poisson's ratio $\nu = 0.3$		
Shear modulus: $G = 30000$		

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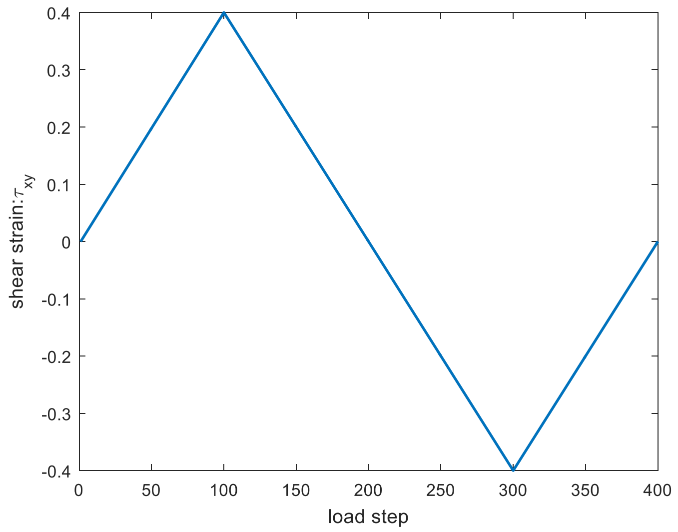

Fig. 2 – The displacement loading protocol

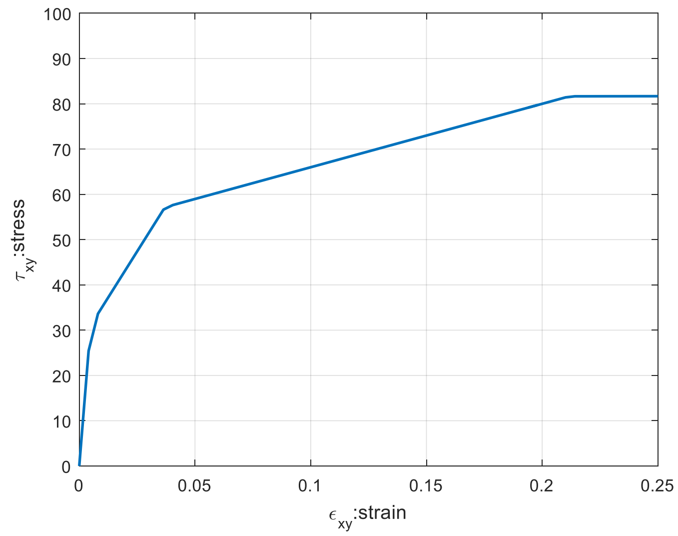

Fig. 3 – Stress-strain relationship

3 Validating the omnidirectional multi-surface and continuum FE models

3.1 Experimental setup

In 2011, both controlled and uncontrolled displacement experiments of the TFP bearing were conducted at the UC, Berkeley, aimed at characterizing the bidirectional behavior of TFP bearings (Becker and Mahin [6][7]). A simple rigid superstructure sat on four identical TFP bearings. The lateral displacement of the superstructure was constrained, while horizontal displacement histories were imposed at the bottom of the bearing using a shake table (Fig.4). The maximum lateral displacement was ±5 inches. The raw data is available on Designsafe, after post-processing, we obtain the displacement and normalized shear force history of the TFP bearings.

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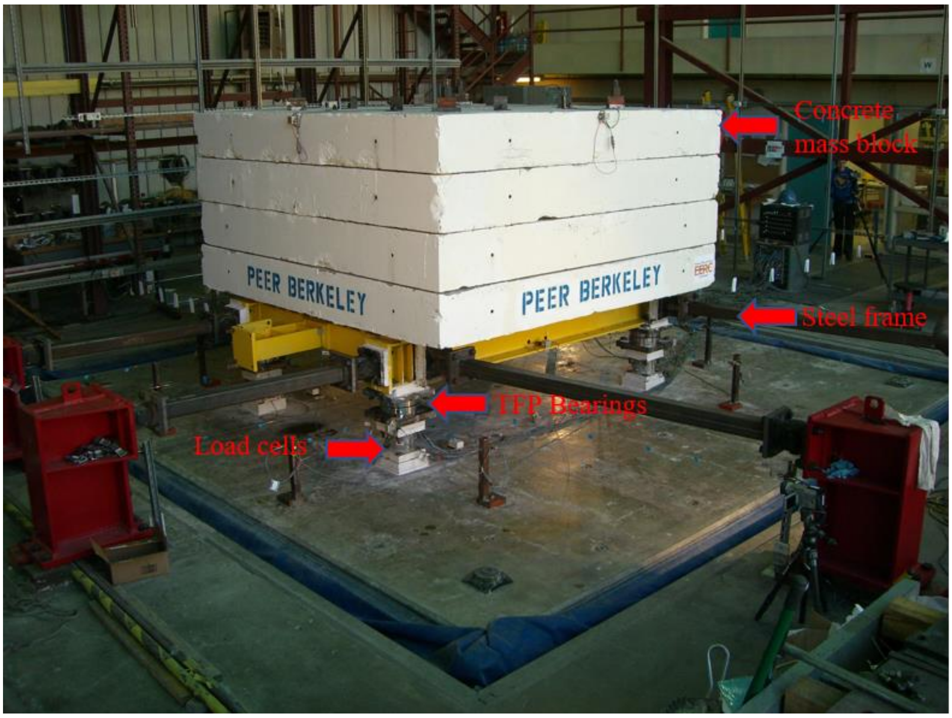

Fig. 4 – Rigid block set up at the UC Berkeley PEER Earthquake Simulator (adapted from [7])

Based on the TFP geometry shown in Fig.5, we could obtain the uniaxial backbone curve then calibrate the parameters of the omnidirectional model. In order to simplify the calculation, we propose to use three yield surfaces omnidirectional model instead of more yield surfaces. Table 2 shows the input parameters.

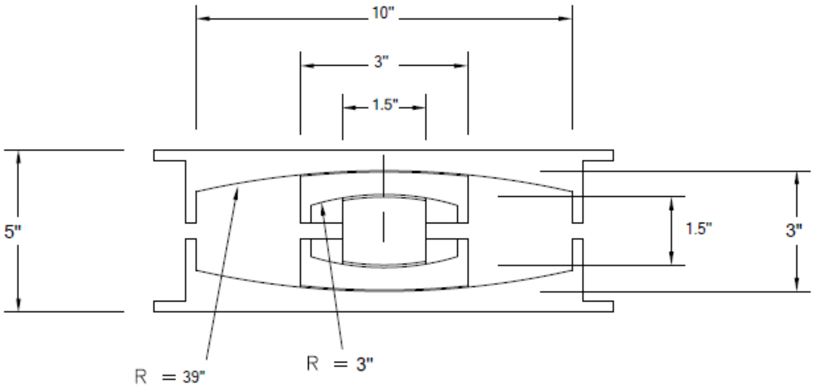

Fig. 5 – Section view of the TFP bearing

Table 2 – Input variables of the uniaxial loading protocol

Number of surfaces i	The radius of each surface: r^i (1e-3)	Kinematic hardening modulus: H^i (1e-3)
1	93	383

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2	164	17
3	264	6
Poisson's ratio $\nu = 0.3$		
Shear modulus: $G = 0.1765$		

3.2 Comparison of experimental and numerical results

Due to the length limit of this paper, only three representative experiments—namely, uniaxial controlled-displacement, biaxial controlled-displacement, and biaxial uncontrolled-displacement tests— are selected for examining the omnidirectional model in the present study.

3.2.1 Uniaxial controlled-displacement sine-wave orbits

The displacement loading protocol and the hysteresis diagram of the experiment and the numerical model for this loading case are shown in Fig.6. These results indicate that the omnidirectional macroelement model captures the hysteretic response well.

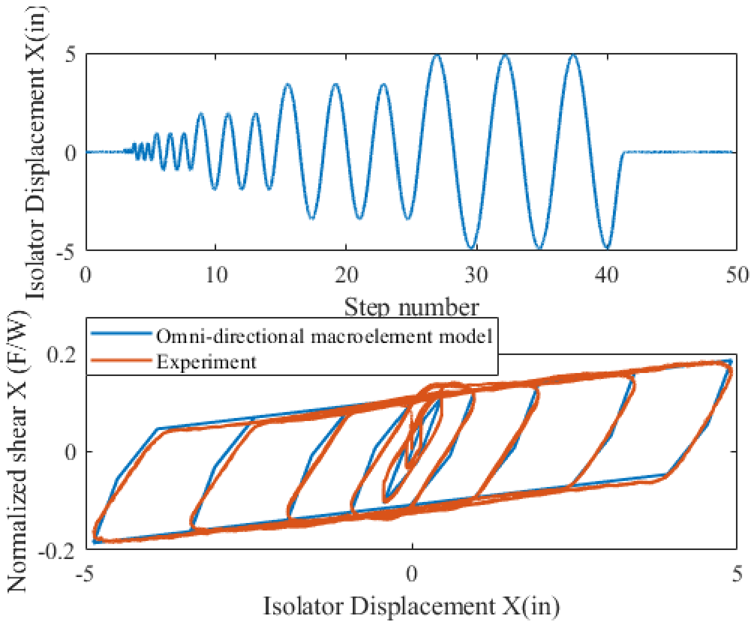

Fig. 6 – Controlled-displacement sine-wave orbits and experimental and numerical hysteresis loops

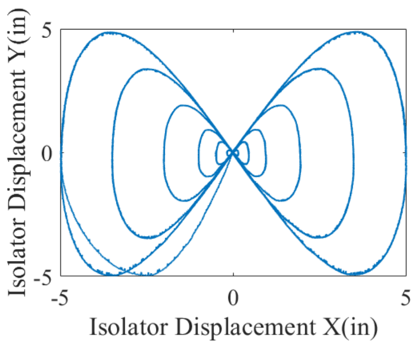

Fig. 7 – Controlled-displacement eight displacement orbit

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3.2.2 Biderictional controlled-displacement eight-shape orbits

The performance of the omnidirectional macroelement model for this loading protocol is also reasonable. The numerical model predicts the peak shear force relatively accurately, which indicates that the algorithm is robust. A discrepancy happens, however, during the unloading and reloading process when the omnidirectional model hardens more than what's observed in the experiment. Nevertheless, this discrepancy can be reduced by adjusting the model parameters through a formal optimization procedure, which will be attempted in a future study.

3.2.3 Bidirectional uncontrolled-displacement orbit

Predicting the hystereses of TFP bearings under earthquake loading protocol is arguably a challenging task, and the omnidirectional macroelement model appears to capture the coupled bi-axial response reasonably well. On the other hand, while the numerical model matches the peak shear force in the X-direction and generates a lower shear force in the Y-direction. Adjusting the model parameters may mitigate this issue, but the discrepancy may also be due in part to measurement and data processing inaccuracies.

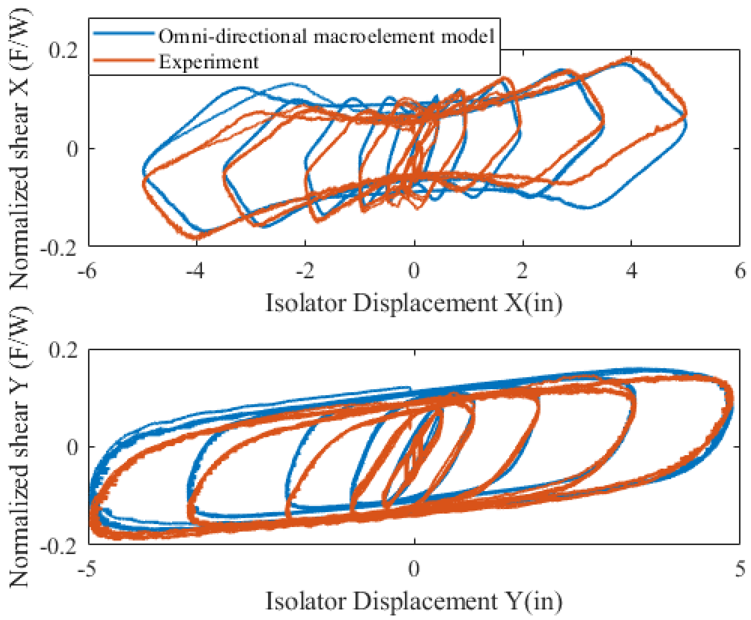

Fig. 8 – Experimental and numerical hystereses for the figure eights displacement orbit

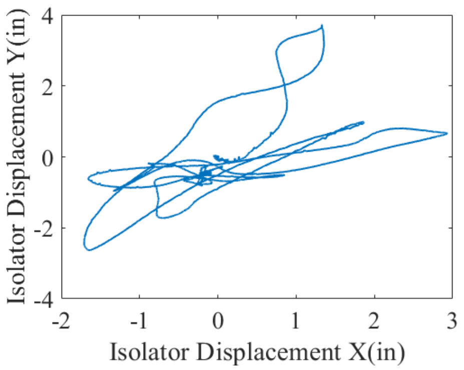

Fig. 9 – Uncontrolled-displacement orbits from the Northridge earthquake Newhall record

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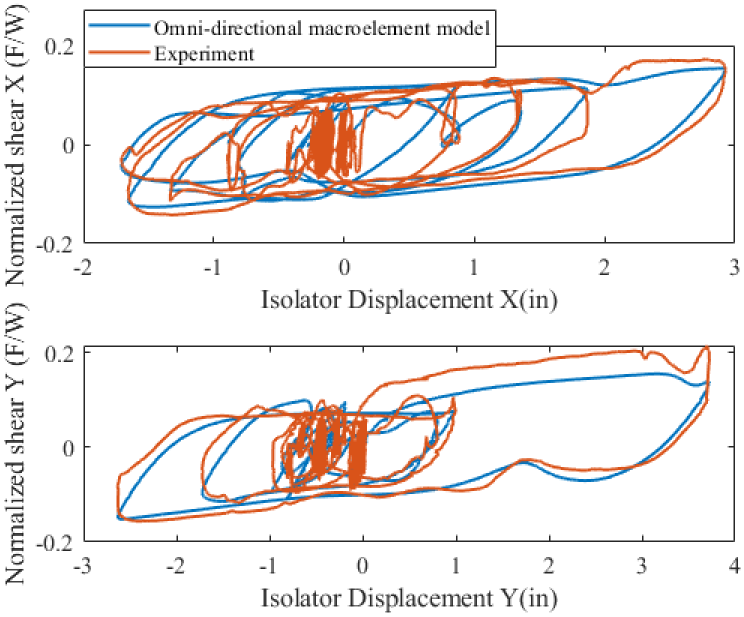

Fig. 10 – Experimental and numerical hystereses for the Northridge earthquake Newhall record

4. Conclusions

An omnidirectional macroelement modeling methodology based on multi-surface plasticity was proposed and implemented in MATLAB. Validation results obtained using experimental data from full-scale TFP bearings indicated that the proposed approach is accurate and robust. The proposed omnidirectional macroelement model development methodology is adequately general, in that it can easily be adapted/applied to other isolator types such as quintuple friction pendulum systems, and other coupled bi-axial reaction (e.g., soil-pile interaction) problems.

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