MODELLING OF TRIPLE FRICTION PENDULUM BEARING IN SAP2000

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ABSTRACT

Until recently there were no applicable hysteresis rules or nonlinear elements available in structural analysis software that can be used to exactly model triple Friction Pendulum bearings for response-history analysis. And to model TFP bearings, Series models composed of nonlinear elements were proposed to simulate the behavior of TFP bearings in analysis software [1]. However, the behavior of the triple Friction Pendulum bearing is not exactly that of a series arrangement of single concave Friction Pendulum bearings, though it is similar. But recently, CSI released newer versions of SAP2000 that has a direct link element of TFP bearings. This paper describes how to enter the input parameters of TFP bearing. Recommendations are made for modeling in SAP2000 and are illustrated through analysis of a simple high-rise seismically isolated structure.

KEYWORDS: Triple friction pendulum bearing, modeling, SAP2000, seismic isolation, base isolation.

I. INTRODUCTION

Seismic isolation is the separation of the structure from the harmful motions of the ground by providing flexibility and energy dissipation capability through the insertion of the isolated so called isolators between the foundation and the building structure [2]. Unlike the conventional design approach, which is based upon an increased resistance (strengthening) of the structures, the seismic isolation concept is aimed at a significant reduction of dynamic loads induced by the earthquake at the base of the structures themselves [3]. In an effort to create a more adaptable bearing with smoother transitions, Earthquake Protective Systems developed the triple friction pendulum (TFP) bearing. Triple friction pendulum (TFP) bearings are ideal earthquake protection technologies for use in performance-based design because they can be designed to achieve multiple performance objectives corresponding to different levels of ground shaking. TFP bearings can limit structure displacement during a design basis (or maximum considered) earthquake, while the still effectively isolating the structure under the service level earthquake, reducing seismic demands on the structure and its non-structural components.

The bearing has four stacked spherical sliding surfaces, two of which are identical, leaving three distinct pendulum mechanisms. As motion occurs on all four sliding surfaces, the TFP bearing allows for the same displacement capacity with a bearing that is less than half as large in diameter as the single friction pendulum bearing. The special purpose software programs used for structural analysis of base-isolated structures such as SAP2000 models elastomeric bearings as a two-node discrete element with stiffness in each of the six principal directions represented by linear or nonlinear springs between the two nodes. Analytical expressions for force and stiffness can be used to define a spring in any direction. Usually, Series models composed of nonlinear elements were proposed to simulate the behavior of TFP bearings in analysis software that can be used to exactly model TFP bearings. But since the latest version of SAP2000 provided a direct element for the TFP bearing, then this paper is to estimate the input parameters of TFP bearing in SAP2000.

II. STRUCTURAL MODEL

A sample model of (25*15) m 10-story building was created with columns and beams sections of IPE300 and slab sections of 0.2m width concrete slab



Figure 2 2D view of the SAP2000 model

1 TFP isolator

To create the isolator model, a sample TFP bearing carrying vertical load of 250 ton assumed with the following properties:

Geometric Properties 1.1 $R_1 = R_4 = 2235 mm$, $R_2 = R_3 = 406 mm$ $h_1 = h_4 = 102mm$, $h_2 = h_3 = 76m$ $R_{1eff} = R4_{eff} = R_1 - h_1 = 2235 - 102 = 2133 \text{ mm}$ $R_{2eff} = R_{3eff} = R_2 - h_2 = 406 - 76 = 330 \text{ mm}$ $d_1^* = d_4^* = d_1$. $R_{1eff}/R_1 = 356*2133/2235 = 339.8 \text{mm}$ (Actual displacement capacity) $d_2^* = d_3^* = d_2$. $R_{2eff}/R_2 = 51*330/406 = 41.5$ mm (Actual displacement capacity) **1.2** Calculating frictional properties of the bearing Bearing pressure at surfaces 1 and 4: $P=250 / (\pi x 203^2) = 0.00193 t / mm^2 = 2.8 Ksi$ (unit converted due to next eqn units) 3-cycle friction $\mu \approx 0.122-0.01P$ [1] $= 0.122 - (0.01 \times 2.8) = 0.094$ Adjust for high velocity $(-0.015) \approx 0.079$ (lower bound friction) 1st-cycle friction $\mu \approx 1.2 \times 0.079 = 0.095$ Lower bound $\mu_1 = \mu_4 = 0.079$ Upper bound $\mu_1 = \mu_4 = 0.095$ Bearing pressure at surfaces 2 and 3: $P=250 / (\pi x 152^2) = 0.0034 t / mm^2 = 4.996 Ksi$ 3-cycle friction $\mu \approx 0.122-0.01P$ = 0.122 - (0.01 * 4.996) = 0.072;Adjust for high velocity $(-0.005) \approx 0.067$ (lower bound friction) 1st-cycle friction $\mu \approx 1.2 \times 0.067 = 0.081$ Lower bound $\mu_2 = \mu_3 = 0.067$ Upper bound $\mu_2 = \mu_3 = 0.081$ μ = force at zero displacement divided by the normal load $\mu = \mu_1 - ((\mu_1 - \mu_2) R_{2eff} / R_{1eff})$ Lower bound $\mu = 0.079$ - ((0.079-0.067)*(330/2133)) = 0.077 Upper bound $\mu = 0.095$ - ((0.095-0.081)*(330/2133)) = 0.093

Geom	etric Properties	Fricti	onal Properties
Property	value	Property	value
$R_{1eff} = R_{4eff} mm$	2133	$\mu_1 = \mu_4$ Lower bound	0.079
$R_{2eff} = R_{3eff} mm$	330	$\mu_2 = \mu_3$ Lower bound	0.067
$d_1^* = d_4^* mm$	339.8	μLower bound	0.077
$\mathbf{d_2}^* = \mathbf{d_3}^* \mathbf{mm}$	41.5	$\mu_1 = \mu_4$ Upper bound	0.095
		$\mu_2 = \mu_3$ Upper bound	0.081
		u Upper r bound	0.093

TABLE 1: Summary of Isolation Bearing Properties



Figure 3 Geometric properties of the TFP bearing

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1.3 Calculating D _D (upper bound analysis):						
\mathbf{S}_{d}	μ	μ_1	D_y	F _{d1}	W	#bearing
0.3395	0.093	0.095	0.00462	0.114822	250	24
			Σ	688.9311	6000	
1) Let the disp	placement be	D_{D}			0.0469	m
2) Effective st	tiffness: Q _d =	μ. ΣW			558	ton
	$K_D = \Sigma F_D /$	D _D			14689.36	ton/m
	$K_{eff} = K_{D+}$	Q_d/D_D			26587.02	ton/m
3) Effective p	eriod:		(Eq.17.5-2,	ASCE 7-10)		
$T_{eff} =$	$= 2\pi \sqrt{\frac{\Sigma}{(K_{ef})}}$	$\frac{W}{f}(g)$			0.953369	sec

4) Effective damping:

(Eq.17.8-7, ASCE 7-10)

$$\beta_D = \frac{E}{2\pi K_{eff} D_D^2} = \frac{4\mu \Sigma W (D_D - D_y)}{2\pi K_{eff} D_D^2} \qquad 0.25672$$

5) Damping reduction factor:

$$\beta = (\frac{\beta_{eff}}{0.05})^{0.3}$$
1.633604

6)

$$D'_{D} = rac{S_{D1} \cdot T_{eff}^{2}}{4\pi^{2} \cdot \beta}g$$

0.0469 m

2 Calculating Sap2000 link/support property data (upper bound):

2.1 Main properties

2.1.1 Determination of bearing (rotational inertia 1):

It had been considered that the isolator is a cylinder with diameter $\Phi = 0.305$ m with height h= 0.32 m (total height of the bearing)

Then cross section area $a = 0.0731 \text{ m}^2$

$$K_{eff} = \frac{W}{R_{1eff}} + \frac{\mu W}{D_D} = K_{eff} = \frac{250}{2.133} + \frac{0.093 * 250}{0.0496} = 585.956 \text{ ton/m}$$
$$I = \frac{K_{eff} \cdot h^3}{12E} = \frac{585.956 * (0.32)^3}{12 * 1E^7} = 1.6 E^{-7} m^4$$

Note that young's modulus E was assumed = $1*10^7$ equal to half of actual steel modulus as the bearing is not a solid piece of metal.

2.1.2 Determination of bearing Mass:

 $\begin{array}{l} D_{m\text{-max}} = 0.0496 \text{ m} \\ D_{TM} = 1.15^* \ D_{m\text{-max}} & (17.5.3.5, \text{ ASCE 7-10}) \\ = 1.15^* 0.0496 = 0.05704 \text{ m} \\ D = 2 \ D_{TM} = 0.11408 \text{ m} \text{ Sub.in FP bearing size/weight correlation} \\ W = 0.241 D^2 \text{-} \ 0.0564 D & (D \ \text{ft}) \quad [4] \\ For \ D = 0.11408 \text{ mm} \quad W = 0.005648 \text{ton} \quad \boxed{M = 0.000576 \text{ ton.sec}^2/\text{m}} \end{array}$





Link/Support	t Type	Triple Pendu	ulum Isolator 🛛 👻	
Property N	ame	TFP	Se	et Default Name
Property Not	tes		h	Modify/Show
Total Mass an	id Weigh	nt		
Mass	[0.000576	Rotational Inertia 1	0.0000016
Weight	[0.	Rotational Inertia 2	0.
				•
Factors For L Property is [Property is [ine, Are Defined Defined	a and Solid Spr for This Length for This Area In	Rotational Inertia 3 ings In a Line Spring Area and Solid Springs	0. 1. 1.
Factors For L Property is [Property is [Directional Pro	ine, Are Defined Defined operties	a and Solid Spr for This Length for This Area In	Rotational Inertia 3 ings In a Line Spring Area and Solid Springs	0. 1. 1. P-Delta Parameters
Factors For L Property is D Property is D Directional Pro Direction	ine, Are Defined Defined operties Fixed	a and Solid Spr for This Length for This Area In NonLinear	Rotational Inertia 3 ings In a Line Spring Area and Solid Springs Properties	0. 1. 1. P-Delta Parameters Advanced
Factors For L Property is D Property is D Directional Pro Direction	ine, Are Defined Defined operties Fixed	a and Solid Spr for This Length for This Area In NonLinear	Rotational Inertia 3 ings In a Line Spring Area and Solid Springs Properties Modify/Show for U1	0. 1. 1. P-Delta Parameters Advanced
Factors For L Property is D Property is D Directional Pro Direction V U1	ine, Are Defined Defined Operties Fixed	a and Solid Spr for This Length for This Area In NonLinear	Rotational Inertia 3 ings In a Line Spring Area and Solid Springs Properties Modify/Show for U1 Modify/Show for U2	0. 1. 1. P-Delta Parameters Advanced
Factors For L Property is D Property is D Directional Pro Direction V U1 V U2 V U2 V U3	ine, Are Defined Defined Defined Fixed	a and Solid Spr for This Length for This Area In NonLinear V V	Rotational Inertia 3 ings In a Line Spring Area and Solid Springs Properties Modify/Show for U1 Modify/Show for U2	0. 1. 1. P-Delta Parameters Advanced
Factors For L Property is D Directional Pro Direction V U1 V U2 V U2 V U3 R1	ine, Are Defined 1 Defined 1 Define 1	a and Solid Spr for This Length for This Area In NonLinear	Rotational Inertia 3 ings In a Line Spring Area and Solid Springs Properties Modify/Show for U1 Modify/Show for U2 Modify/Show for U3 Modify/Show for U3	0. 1. 1. P-Delta Parameters Advanced
Factors For L Property is D Directional Pro Direction V U1 V U2 V U2 V U3 R1 R2	ine, Are Defined 1 Defined 1 Define 1	a and Solid Spr for This Length for This Area In NonLinear V V	Rotational Inertia 3 ings In a Line Spring Area and Solid Springs Properties Modify/Show for U1 Modify/Show for U2 Modify/Show for U3 Modify/Show for R1	0. 1. 1. P-Delta Parameters Advanced

Figure 5 SAP2000 Link Main Properties

2.2 Directional properties (U1):

As mentioned we considered the isolator as a cylinder with $\Phi = 0.305$ m, h=0.32 m Then, effective stiffness = A*E/L = 0.0731* 1E⁷/ 0.32 = 2284375 ton/m Effective damping from the D_D calculation = 25.67%

Identification		
Property Name	TFP	
Direction	U1	
Туре	Triple Pe	ndulum Isolator
NonLinear	Yes	
Properties Used For Lines	ar Analysis Ca	ses
Effective Stiffness		2284375
Effective Damping		0.2567
Properties Used For Nonli	inear Analysis	Cases
Stiffness		2284375
Damping Coefficient		0.2567
		Concert

Figure 6 SAP2000 Link propertes in dir. U1

2.3 Directional properties (U2, 3):

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Determination of linear properties:
2.3.1
Effective stiffness (calculated in section 3.3) = 585.956 ton/m
Effective damping (calculated in section 3.3) = 25.67%
Height for outer surface = h_1 = h_4 = 0.102 \text{ m}
Height for inner surface = h_2 = h_3 = 0.076m
        Determination of nonlinear properties:
2.3.2
Stiffness = \mu.W/Dy
Dy=(\mu_1-\mu_2) R_{2eff} = (0.095-0.081)*0.33 = 0.00462m
Stiffness of outer surface = 0.095 \times 250/.00462 = 5140.693 ton/m
Stiffness of inner surface = 0.081*250/.00462= 4383.117 ton/m
Friction co. Slaw = \mu_1 for outer surface = 0.095
                  = \mu_2 for inner surface = 0.081
Friction co. Fast = 2\mu_1 for outer surface = 2*0.095=0.19
                 = 2\mu_2 for inner surface = 2*0.081 = 0.162
Rate parameter = Friction co. Slaw / Friction co. Fast = 0.5
Radius of sliding surface: For outer = R_{1eff}= 2.133 m
                           For inner = R_{2eff} = 0.33 m
Stop distance: For outer surface u^{**} = 2Dy + 2d_1^*
                                     = (2*0.00462) + (2*0.3398) = 0.68884 \text{ m}
               For inner surface = 2Dy = 2*0.00462 = 0.00924 m
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Property Name				
rioporty ridino	TFP	Туре		Triple Pendulum
Direction	U2; U3	NonLine	NonLinear	
near Properties				
Effective Stiffness - U2	585.956	Effective Stiffness - U3		585.956
Effective Damping - U2	0.2567	Effective	Effective Damping - U3	
hear Deformation Location				
Distance from End-J - U2	0.	Distance	e from End-J - U3	0.
eight and Symmetry of Slidi	ng Surfaces			
Height for Outer Surface	0.102	Outer Bottom	Outer Bottom Surface is Symmetric to C	
Height for Inner Surface	0.070	✓ Inner Bottom Surface is Symmetric f		
-	0.076	√ Inner Bottom	Surface is Symmet	ric to Inner Top Surface
onlinear Properties for Dire	ctions U2 and U3	[√] Inner Bottom	Surface is Symmet	ric to Inner Top Surface
onlinear Properties for Dire	ctions U2 and U3 Outer Top	Outer Bottom	Surface is Symmet	Inner Bottom
onlinear Properties for Dire Stiffness	ctions U2 and U3 Outer Top 5140.693	Outer Bottom	Surface is Symmet Inner Top 4383.117	Inner Bottom 4383.117
onlinear Properties for Dire Stiffness Friction Coefficient, Slow	ctions U2 and U3 Outer Top 5140.693 0.095	✓ Inner Bottom Outer Bottom 5140.693 0.095 0.095	Surface is Symmet Inner Top 4383.117 0.081	Inner Bottom 4383.117 0.081
onlinear Properties for Dire Stiffness Friction Coefficient, Slow Friction Coefficient, Fast	ctions U2 and U3 Outer Top 5140.693 0.095 0.19	Outer Bottom 5140.693 0.095 0.19	Surface is Symmet Inner Top 4383.117 0.081 0.162	Inner Top Surface
onlinear Properties for Dire Stiffness Friction Coefficient, Slow Friction Coefficient, Fast Rate Parameter	ctions U2 and U3 Outer Top 5140.693 0.095 0.19 0.5	✓ Inner Bottom 0uter Bottom 5140.693 0.095 0.19 0.5 0.5	Surface is Symmet Inner Top 4383.117 0.081 0.162 0.5	ric to Inner Top Surface Inner Bottom 4383.117 0.081 0.162 0.5
onlinear Properties for Dire Stiffness Friction Coefficient, Slow Friction Coefficient, Fast Rate Parameter Radius of Sliding Surface	ctions U2 and U3 Outer Top 5140.693 0.095 0.19 0.5 2.133	Outer Bottom 5140.693 0.095 0.19 0.5 2.133	Surface is Symmet Inner Top 4383.117 0.081 0.162 0.5 0.33	ric to Inner Top Surface Inner Bottom 4383.117 0.081 0.162 0.5 0.33
onlinear Properties for Dire Stiffness Friction Coefficient, Slow Friction Coefficient, Fast Rate Parameter Radius of Sliding Surface Stop Distance	ctions U2 and U3 Outer Top 5140.693 0.095 0.19 0.5 2.133 0.68884	Outer Bottom 5140.693 0.095 0.19 0.5 2.133 0.68884	Surface is Symmet Inner Top 4383.117 0.081 0.162 0.5 0.33 0.00924	ric to Inner Top Surface Inner Bottom 4383.117 0.081 0.162 0.5 0.33 0.00924

Figure 7 SAP2000 Link propertes in dir. U2,3

3 Analysis

A modal response spectrum analysis was performed to check the model

Table 2: Check drifts:

Floor	drift
1	0.000213
2	0.005796
3	0.005268
4	0.004769
5	0.004229
6	0.003643
7	0.003012
8	0.002334
9	0.001609
10	0.000834

StepType	Period	SumUX	SumUY	SumRZ
Mode1	11.63388	0	0.943872	0
Mode2	4.911323	0	0.943872	0.928305
Mode3	3.65751	0	0.990241	0.928305
Mode4	3.464683	0.927456	0.990241	0.928305
Mode5	2.093332	0.927456	0.996964	0.928305
Mode6	1.561331	0.927456	0.996964	0.984615
Mode7	1.468379	0.927456	0.998605	0.984615
Mode8	1.144701	0.927456	0.999145	0.984615
Mode9	1.103375	0.984977	0.999145	0.984615
Mode10	0.953785	0.984977	0.999356	0.984615

TABLE 3: Modal Participating Mass Ratios

III. CONCLUSION

For modeling Triple Friction Pendulum bearing in past versions of SAP2000, it usually modeled as a series of friction bearing trying to be close to the actual behavior of the isolator. But after using the new feature of Triple Friction Pendulum Bearings, It is finally noted that new versions of SAP2000 16.0 and later versions are more sufficient for analysis of base-isolated structures with triple friction pendulum bearings as these versions has an actual model of TFP bearing, So we can get results with actual behavior of the isolator. For future work, I recommend using version 16.0 and later versions in modeling of triple friction pendulum bearings.

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Khloud El-Bayoumi, A researcher in Mansoura University. Holding BCs in civil engineering from Mansoura University 2010 and currently attending the Master's study with a thesis title "dynamic analysis of high rise seismically isolated buildings" and about to finish it soon. I'm interested in studying the behavior of seismic isolated buildings.

