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 as there were no applicable hysteresis rules or nonlinear elements available in structural 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

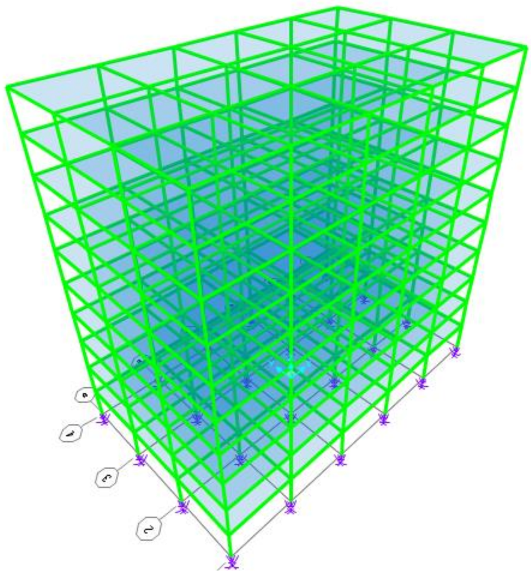

Figure 1 3D view of the SAP2000 model

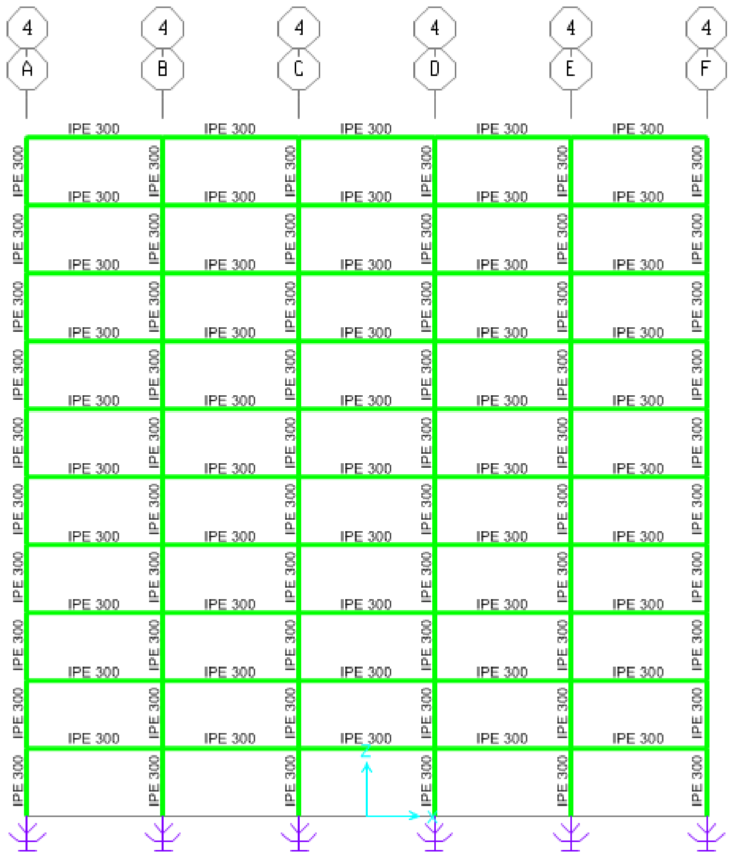

Figure 2 2D view of the SAP2000 model

1 TFP isolator

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

1.1 Geometric Properties

$R_1=R_4$ =2235mm, $R_2=R_3$= 406mm
$h_1= h_4$= 102mm, $h_2 =h_3$=76m
$R_{1eff}= R4_{eff} = R_1-h_1$= 2235 – 102=2133 mm
$R_{2eff} =R_{3eff} =R_2 -h_2$ = 406-76 = 330 mm
$d_1^* = d_4^*= d_1. R_{1eff}/R_1$ = 356*2133/2235= 339.8mm (Actual displacement capacity)
$d_2^* = d_3^*= d_2. R_{2eff}/R_2$ = 51*330/406 = 41.5mm (Actual displacement capacity)

1.2 Calculating frictional properties of the bearing

Bearing pressure at surfaces 1 and 4:
$P=250 / (\pi \, x203^2) = 0.00193$ t/mm^2 = 2.8 Ksi (unit converted due to next eq$_n$ units)
3-cycle friction $\mu\approx$ 0.122-0.01P [1]
= 0.122 – (0.01*2.8) = 0.094
Adjust for high velocity (-0.015) ≈ 0.079 (lower bound friction)
1st-cycle friction $\mu\approx$1.2x0.079 =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:
$P=250 / (\pi \, x152^2) = 0.0034$ 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) ≈ 0.067 (lower bound friction)
1st-cycle friction $\mu\approx$1.2x0.067 =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 μ = 0.079- ((0.079-0.067)*(330/2133)) = 0.077
Upper bound μ = 0.095- ((0.095-0.081)*(330/2133)) = 0.093

TABLE 1: Summary of Isolation Bearing Properties

Geometric Properties		Frictional 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	μ Lower bound	0.077
$d_2^*= d_3^*$ mm	41.5	$\mu_1 =\mu_4$ Upper bound	0.095
		$\mu_2 =\mu_3$ Upper bound	0.081
		μ Upper r bound	0.093

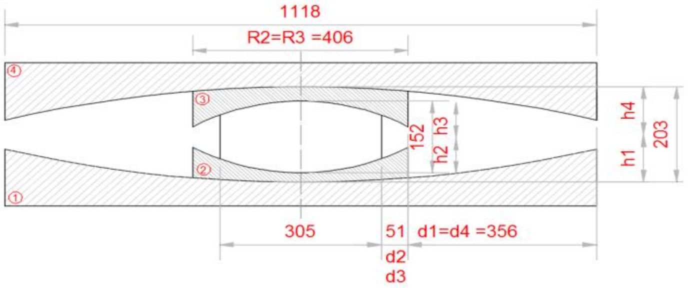

Figure 3 Geometric properties of the TFP bearing

1.3 Calculating D_D (upper bound analysis):

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 displacement be D_D	0.0469	m
2) Effective stiffness: $Q_d = \mu . \Sigma W$	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 period: (Eq.17.5-2, ASCE 7-10)

$$T_{eff} = 2\pi \sqrt{\frac{\Sigma W}{(K_{eff})(g)}}$$ 0.953369 sec

4) Effective damping: (Eq.17.8-7, ASCE 7-10)

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

5) Damping reduction factor:

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

6)

$$D'_D = \frac{S_{D1} \, . \, {T_{eff}}^2}{4\pi^2 . \beta} g$$ 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 Φ = 0.305 m with height h= 0.32 m (total height of the bearing)

Then cross section area a= 0.0731 m^2

$$K_{eff} = \frac{W}{R_{1eff}} + \frac{\mu W}{D_D} = K_{eff} = \frac{250}{2.133} + \frac{0.093 * 250}{0.0496} = 585.956 \, ton/m$$

$$I = \frac{K_{eff} . h^3}{12E} = \frac{585.956 * (0.32)^3}{12 * 1E^7} = 1.6 \, E^{-7} m^4$$

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:

D_{m-max} = 0.0496 m

D_{TM} = 1.15* D_{m-max} (17.5.3.5, ASCE 7-10)

= 1.15*0.0496 = 0.05704 m

D = 2 D_{TM} = 0.11408 m Sub.in FP bearing size/weight correlation

W = $0.241D^2$- 0.0564D (D ft) [4]

For D = 0.11408 mm W= 0.005648ton M= 0.000576 ton.sec^2/m

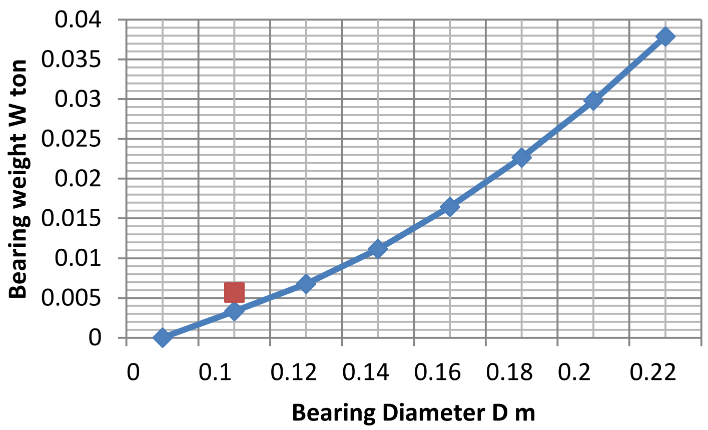

FIGURE 4 bearing mass/diameter curve

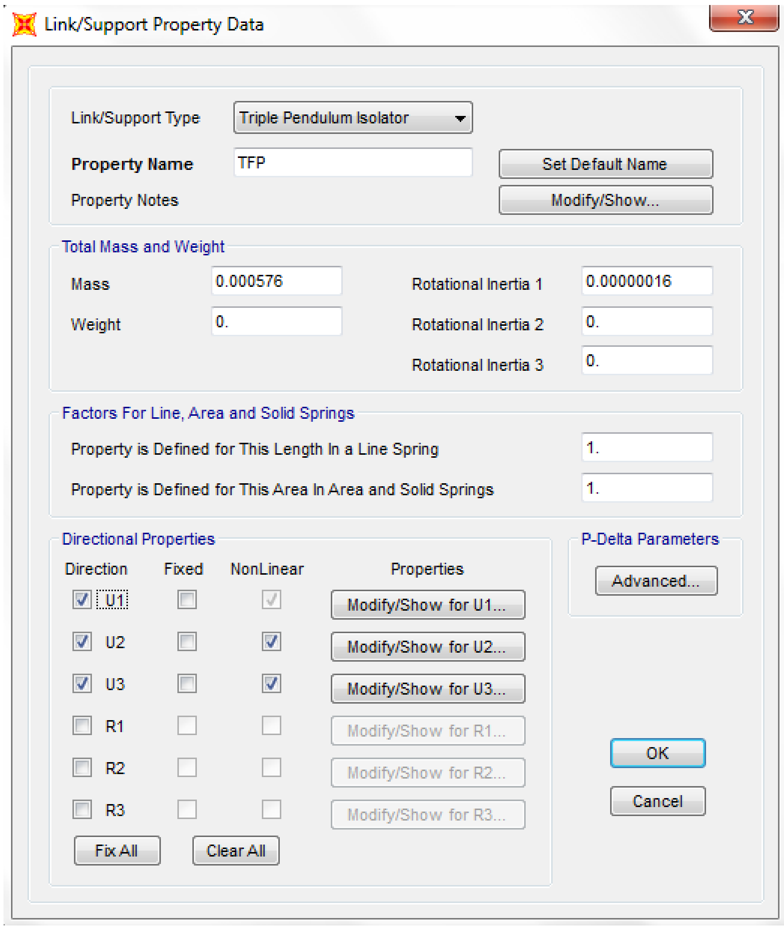

Figure 5 SAP2000 Link Main Properties

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* $1E^7$/ 0.32 = 2284375 ton/m
Effective damping from the D_D calculation = 25.67%

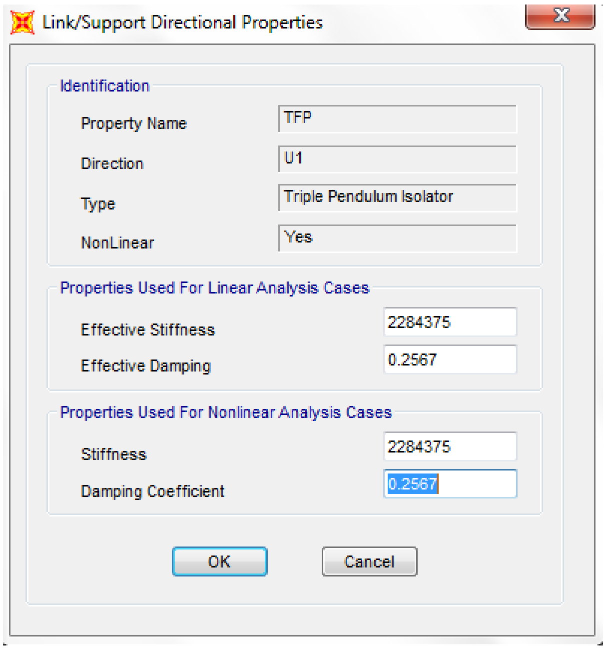

Figure 6 SAP2000 Link propertes in dir. U1

2.3 Directional properties (U2, 3):

2.3.1 Determination of linear properties:

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 m
Height for inner surface = h_2=h_3 = 0.076m

2.3.2 Determination of nonlinear properties:

Stiffness = μ.W/ Dy
Dy= (μ_1-μ_2) R_{2eff} = (0.095-0.081)*0.33 =0.00462m
Stiffness of outer surface = 0.095*250/.00462= 5140.693 ton/m
Stiffness of inner surface = 0.081*250/.00462= 4383.117 ton/m
Friction co. Slaw = μ_1 for outer surface = 0.095
= μ_2 for inner surface = 0.081
Friction co. Fast = 2μ_1 for outer surface = 2*0.095= 0.19
= 2μ_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 m
For inner surface = 2Dy = 2*0.00462 = 0.00924 m

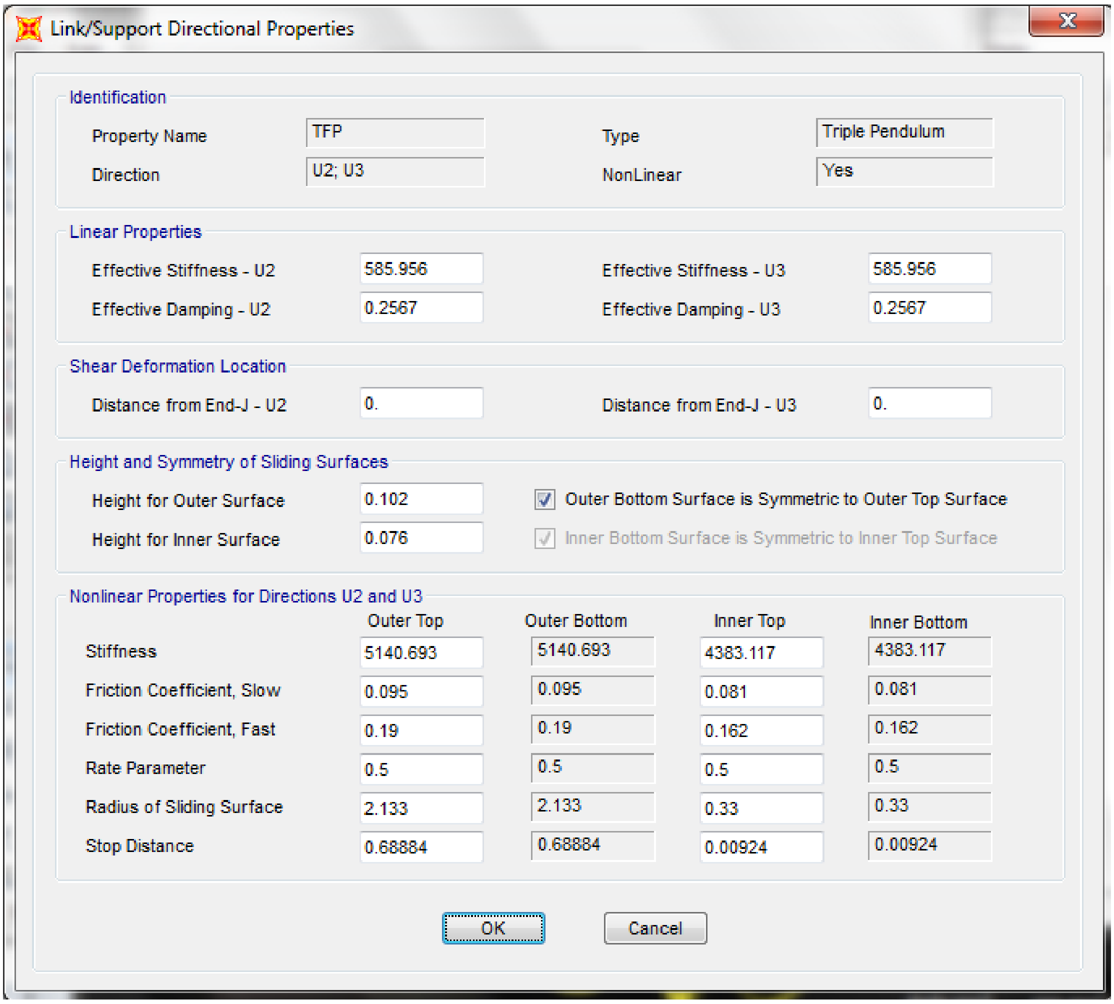

Figure 7 SAP2000 Link propertes in dir. U2,3

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

TABLE 3: Modal Participating Mass Ratios

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

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.