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PRELIMINARY STUDY ON DISPLACEMENT-BASED DESIGN FOR SEISMIC RETROFIT OF EXISTING BUILDINGS USING TUNED MASS DAMPER

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ABSTRACT

According to the equivalent linear system, this paper presents a preliminary displacement-based design (DBD) procedure for seismic retrofit of existing buildings using tuned mass damper (TMD) under the specified seismic loading. The design method is primarily controlling the roof displacement of the building, and this method uses the nonlinear pushover analysis in the design procedure. The concept of optimum design for the TMD would be used in the design procedure. The design results are compared with those computed from the dynamic inelastic time history analyses. It is shown from nonlinear time history analyses that the maximum nonlinear responses of the retrofitted building with TMD can be reasonably captured by the presented method.

Keywords: tuned mass damper, displacement-based design, seismic retrofit design

1. INTRODUCTION

The purpose of this study is to confer the displacement-based design (DBD) method for seismic retrofit of existing buildings using tuned mass damper. The design method is primarily controlling the displacement, and this method replaces the nonlinear time history analysis by the nonlinear pushover analysis in the design procedure. This method predicts the maximum response of the nonlinear structure by using the equivalent linear system. There are many references that discuss the evaluation of equivalent linear system. Nevertheless, this study calculates the equivalent linear system by using the average energy method and proposes the displacement-based design method for seismic retrofit of existing multi-story buildings using tuned mass damper. In addition, the DBD method considers the effect of multiple modes. This study, first studies the simulation of TMD by using SAP2000N and PISA3D nonlinear analysis program and then proposes the DBD method for seismic retrofit of existing multi-story buildings using tuned mass damper. The design results are compared with those calculated from nonlinear time history analysis and then summaries some conclusions.

2. SIMULATION OF THE TUNED MASS DAMPER

In the figure 1, the mechanics of the tuned mass damper are included the stiffness and the damping devices which are in parallel connection. The stiffness may be linear or nonlinear, and the damping may also be linear or nonlinear. The motion equations of the multi-story building equipped with TMD are as follows:

$$\begin{aligned} &[M][\ddot{y}]+[C][\dot{y}]+K[y]=-[M][L]\ddot{u}_g+[P] \\ &m\ddot{z}+c\dot{z}+kz=-m(\ddot{y}_N+\ddot{u}_g) \end{aligned} \qquad (1)$$

where

$[P]=[0,....0,c\dot{z}+kz]^T$, m=mass of the TMD, c=damping of the TMD, k=stiffness of the TMD, $\ddot{y}_N$=acceleration of the roof, $\ddot{u}_g$=the ground motion, $[M]$=mass matrix of the structure, $[C]$=damping matrix of the structure, $[K]$=stiffness matrix of the structure, $[y]$=story displacement of the structure.

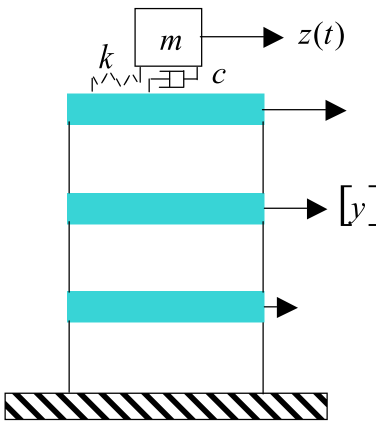
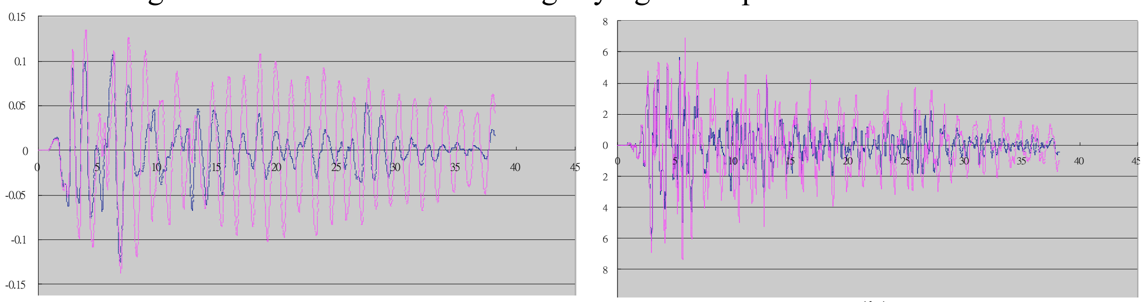


Figure 1 The structure equipped with TMD

The simulation of the TMD by using the 3D nonlinear analysis programs can be combined with the stiffness and damping link elements. The stiffness and damping link elements are connected parallel to each other. The stiffness and damping parameters may be input linear or nonlinear according to the practice application

The accuracy of the analysis results simulated from 3D nonlinear analysis programs such as SAP2000N and PISA3D would be studied by using an analytical example. A plane six stories and two-bay steel frame would be selected as the analytical example. The section of columns for the base frame is H300x300x10x15mm, and beams for the base frame is H200x200x8x12mm. The story high is 2.6m and the distance of one bay is 6m. The story mass is 10 ton. The TMD is installed at the roof of the base frame. These analysis results would be compared with those from the numerical calculation of state space analysis.

It can be found that the simulate results by using SAP2000N and PISA3D nonlinear analysis programs are rather consistence with the numerical calculation from the state space analysis. Figure 2 show the analytical results of roof displacement and roof acceleration for the base frame with and without TMD. The vertical coordinate of figure 2(a) represents the roof displacement (m), while the horizontal coordinate represents the time (sec). In addition, the vertical coordinate of figure 2(b) represents the roof acceleration (m/s^2), while the horizontal coordinate represents the time (sec). The reduction responses in the figure 2(a) and 2(b) are both corresponding to the base frame with TMD. Therefore, it can obtain the large reduction responses by equipping with the combination of simple mechanics which should be correctly designed. In another word, the stiffness and damping should be designed according to the optimum design method. A bad design of TMD would result in magnifying the response of the base frame.



(a) (b)

Figure 2 Reduction of the response for frame with TMD

3. DISPLACEMENT-BASED DESIGN

Based on the equivalent linear system method, this study proposes the displacement-based design for seismic retrofit of the existing multi-story buildings equipped with TMD. The design object is the control of the displacement. The design procedure would repeat the steps until the design displacement being satisfied the object criteria. The nonlinear static analysis and simple linear dynamics analysis will substitute for nonlinear time history dynamics analysis. Finally, the design results will be compared with the result calculated from nonlinear time history dynamics analysis. The design procedure is as shown in figure 3. The key steps for the design method are the TMD optimum design and evaluation of the equivalent linear system. There are many references that discuss the optimum design of linear stiffness TMD for the linear elastic structures. [Tsai et al., 1993] But, the references about optimum design method of TMD for the nonlinear structures are less. In this study, the design of linear stiffness TMD for the nonlinear structures would be used in the DBD procedure. The optimum design method of TMD which contains nonlinear stiffness would be study in the future. The determination of the equivalent linear system would be determined as equation 2 and 3. [Chen, 2003] The equivalent damping ratio ξ_e is determined from the contribution of the structural inelasticity, damper force, and inherence damping ratio of the structure. The TMD would be simulated as the equivalent frame under the nonlinear pushover analysis.

$$T_e = 2\pi\sqrt{\frac{M_e}{K_e}} \quad (2)$$

$$\xi_e = \xi_{e(inelasticity)} + \xi_{e(damper)} + \xi_{e(inherence)} \quad (3)$$

Where T_e is the equivalent period, M_e is the equivalent mass, K_e is the equivalent stiffness, ξ_e is the equivalent damping ratio, $\xi_{e(inelasticity)}$ is the damping ratio contributed from the inelasticity of the structure, $\xi_{e(damper)}$ is the damping ratio contributed from the damper force, $\xi_{e(inherence)}$ is the inherence damping ratio of the structure.

When performing the nonlinear pushover analysis, the lateral story forces distribution $[F]$ are proportional to the equation 4. The equivalent mode shape $[\bar{\phi}]$ is calculated from equation 5.

$$[F] = [K][\bar{\phi}] \quad (4)$$

$$[\bar{\phi}] = \Gamma_1 S_d(\omega_1, \xi_1)[\phi]_1 + \Gamma_2 S_d(\omega_2, \xi_2)[\phi_2] \quad (5)$$

In which $[K]$ is the stiffness matrix of the structure with TMD, ω_i is the frequency corresponding to the ith mode of the structure with TMD, ξ_i is the damping ratio corresponding to the ith mode of the structure with TMD, $[\phi_i]$ is the mode shape corresponding to the ith mode of structure with TMD, Γ_i is the partition factor corresponding to the ith mode of structure with TMD, S_d is the displacement determined from the spectrum.

According to the equivalent linear system, the maximum nonlinear roof displacement of the structure with TMD would be calculated from the elastic response spectrum corresponding to the equivalent period T_e and equivalent damping ratio ξ_e. As shows in figure 4, the maximum nonlinear roof displacement of the structure with TMD u_{roof} can be evaluated as follows:

$$u_{roof} = \bar{\Gamma} S_d(T_e, \xi_e) \quad (6)$$

Where $\bar{\Gamma} = \frac{[\bar{\phi}][M][1]}{[\bar{\phi}][M][\bar{\phi}]}$

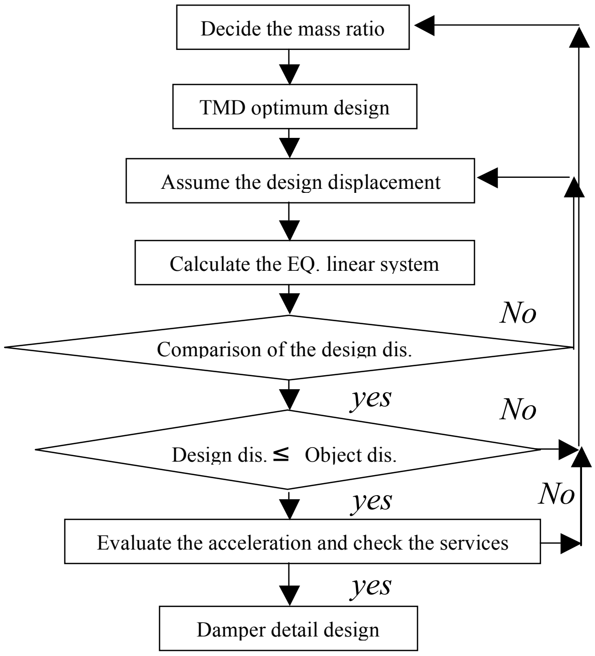


Figure 3 DBD design procedure

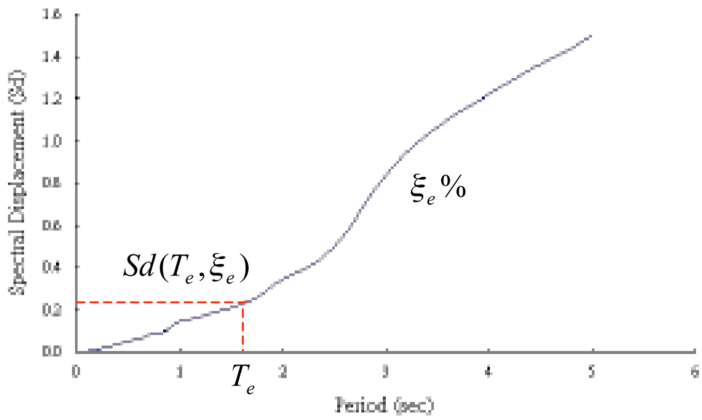


Figure 4 Elastic displacement response spectrum

It is interesting to demonstrate the design procedure by using one analytical example. The existing 3-story steel frame from the National Center for Research on Earthquake Engineering in Taiwan is selected as the base frame. The distance of the short direction is 3m and the long direction is 4.5m. The story high is 3m. The mass of 1st and 2nd floor is 11209kg, 3rd floor is 10910kg. The section of the columns are H200x204x12x12mm, the beams are H200x150x6x9mm. The design earthquake record is type II artificial history from Taiwan's seismic design provision with peak ground acceleration equaling to 0.5g. The object roof displacement of the retrofitted frame is 20cm (drift angle=2.2%).

The final parameters of linear stiffness TMD calculated from the design procedure are summarized as table 1. The TMD mass ratio μ equals to 1%.

Table1 Final TMD design results

	Mass (KN-s^2/m)	Stiffness (KN/m)	Damping (KN-s/m)
TMD	0.596	24.94	0.6605

The fundamental dynamics characteristics of the frame with TMD are summarized as table2. In addition, in order to verify the accuracy of the final design results, the nonlinear time history dynamics analysis is performed to check the maximum roof displacement of the retrofitted frame with TMD. In table3, it shows that the maximum roof displacement of the retrofitted frame with TMD conforms accurately the design displacement.

Table2 Fundamental dynamics characteristics of frame with the TMD

	Period (sec)	Modal Mass (KN-s^2/m)	Partition Factor	Mode Shape			
				TMD	3rd story	2nd story	1st story
1st Mode	1.0365	59.7189	0.4925	8.216	1	0.724	0.316
2nd Mode	0.8696	30.0887	0.7604	-4.045	1	0.760	0.344
EQ. Mode	0.9532	21.6207	1.1996	1.692	1	0.743	0.331

Table3 Comparison between DBD and time history analysis

	EQ. Period T_e (sec)	Damping Ratio $\xi_{e(inelasticity)}$	Damping Ratio $\xi_{e(damper)}$	Damping Ratio $\xi_{e(inherence)}$	Maximum roof dis. (m)
EQ. Mode	1.052	0.097	0.0033	0.02	0.2
	Nonlinear Time History Analysis				0.218

4. CONCLUSIONS

The proposed DBD procedure for the seismic retrofit of existing building equipped with TMD is simple and available. It is shown from nonlinear time history analyses that the maximum nonlinear responses of the retrofitted building with TMD can be reasonably captured by the presented method. However, the optimum design of the TMD which contains nonlinear stiffness would be extended to research in the future. In addition, the experiment of structure with TMD should also be conducted to verify the proposed DBD method.

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