VIBRATION MITIGATIONVIAPASSIVE TRANSLATIONAL TUNED MASS DAMPER

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Abstract - This study investigates the effectiveness of a newly developed passive translational tuned mass damper (PTTMD) to suppress the undesirable response of structures due to external excitations such as earthquakes.In vibration mitigation, tuned mass dampers (TMDs) are an effective and efficient solution which consists of a mass, spring, and dashpot. Typically, the design of TMD for mitigating is depending on theparticular mode of structural vibration (e.g. first mode). For implementing TMD, it is the fundamental concern to find out optimum parameter of TMD to minimize the structural vibration. Therefore, the main focus of this study is to establish optimum parameter (i.e. modal mass) for newly developed PTTMD. To this aim,atwo-storey three-dimensional symmetrical momentresistance steel frame (MRSF) were made. The PTTMD was placed on top of the steel frame and shake-table tests(i.e. dynamic tests) have executed by employing scaled El Centro 1940 earthquake. In order to verify the experimental results and to a deeper analysis of the results, a numerical response prediction model was developed in SAP2000 and the numerical simulation was done using time history analysis with and without PTTMD.The experimental and numerical predicted results showed that the response of the structure could be significantly reduced by using PTTMD. From this study, it has been found that the modal mass of 12.5% and 5% arethe best performer in terms of vibration mitigation for scaled El Centro of 20 sec and 25 sec, respectively.

Index terms - Passive translational tuned mass damper, Vibration mitigation, Momentresistance steel frame, Shake-table, Earthquake, Displacement.

I. INTRODUCTION

In recent years, proper design of both existing and new structure for the structural engineers is the major issue because of thedevastating impact of dynamic loads such as earthquake. In addition, the capability of the structure to absorb and dissipate energy which emerging from earthquake has to be enriched in pursuance of improving the structural resistance in seismically active regions. Strong earthquake not only damages the structures and infrastructures but also increase the potential risk in terms of human life and financial loss. In order to minimize those losses, various vibration controlling approaches have been implemented in term of adjusting rigidity, masses, damping, stiffness, and counter forces. Generally, vibration controlling system has classified as active, passive, hybrid or semi-active [1]-[6]. Among them, passive system is the simplest and cheapest solution for reducing structural attenuate vibration. The passive system can be adopted in many ways such as isolation, mass addition, improving stiffness, and tuning damping. Furthermore, tuning of damping employed by thetuned mass damper, tuned liquid damper, and tuned liquid column damper[7]. The notion of TMD was presented by Watts in 1883 and patented by Frahm in 1909[1], [8]-[9].

Centerpoint Tower in Sydney, John Hancock Tower in Boston, Citicorp Center in New York, CN Tower in Toronto, Chiba Port Tower in Japan, Taipei 101 in Taiwan,Burj Al Arab in UAE are the practical application of TMD and many more existing structures with TMD can be found in the literature [10]. Moreover, theperformance of TMD, which is installed on steel building (39-story and height 184.6 m) located at Incheon in Korea, evaluated in [11] using system identification[12]. The key feature of vibration control is to minimize vibrations which induced in mechanical and structural systems by varioustypes of excitation source[13]-[14]. Typically, TMD is implemented as alinear and passive device. In this study, the linear analysis is adopting to predict numerical simulations. However, few researchers showed that TMD is not effective against shorter duration of seismic load[5],[15].

It is aforesaid that numerous vibration control strategies have been developed and implemented in order to minimize astonishing response of structures. The efficacyof control depends on few things such as: the type of the structure, nature of the earthquake excitation, the type of control device, the control algorithm used, and the response quantity of interest. Therefore, it is become difficult to evaluate the relative adeptness of a scheme and simplify the effectiveness of the various controllers innovated by the researchers [16].

Several researchers have presented equations for optimum values of the parameters of TMD using different criteria. In most of the cases optimization has been done for the damping and frequency ratio based on the mass ratio. Firstly, Den Hartogin 1947 showed the equation for minimizing response with

TMD[2]. Later, Warbuton (1982) derive theequation for harmonic motion using Den Hartog approaches[17]. Many theoretical optimizations can be found in [18]-[22]. In this study, theoptimum equation for minimizing response is used which is presented by Tsai and Lin in 1993[23]. In addition, optimization of themodal mass of PTTMD executed both experimentally and numerically.

In order to investigate the efficacy of the newly developed TMD on structure, the response of the structure with and without TMD has been investigated by employing scaled El Centro 1940 earthquake data. The main objective of this study is to investigate the optimum modal mass to minimize the vibration of the structure against longer (25 sec) and shorter (20 sec) duration of seismic excitations.To this aim, the dynamic tests were performed with TMD and modal mass of 0, 5, 7.5, 10, 12.5, 15, and 17.5%.

II. THEORY OF TUNED MASS DAMPER

A. TMD attached to a MDOF system

Figure 1 shows passive translational TMD connected to a two degree of freedom structure. As shown in Figure 2, the TMD consist of a stand (for placing on top of the structure), rail (for moving wheel), and mass carrier (for tuning mass ratio). The most effective position of a TMD tuned to a particular mode of thefrequency of a structure is the storey that undergoes the largest deflection in that eigenmode[13]. To this aim, PTTMD has been placed at the top of the two-storey frame in this study.

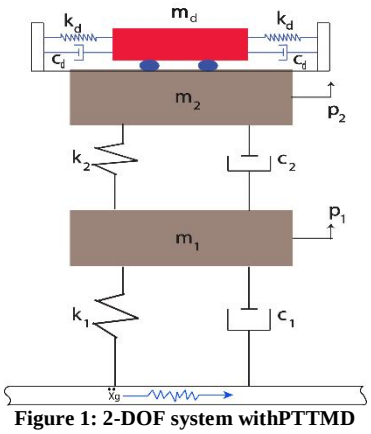


Figure 1: 2-DOF system withPTTMD

B. Equation of motion for PTTMD

For this study, a two-storey MRSF structure is considered, having across-section of thebeam and column 10 mm by 10 mm square bar and 1 mm steel plate as slab. In addition, there is a bracing (10 mm by 4 mm flat bar) to target thefirst mode of vibration to mitigate (see Figure 3).It is necessary to bring 2-DOF system into dynamical form for dynamic analysis. The governing equation of motion for the 2-DOF system as follows:

$$m_1\ddot{x}_1 + c_1\dot{x}_1 + k_1x_1 - k_2(x_2 - x_1) - c_2(\dot{x}_2 - \dot{x}_1) = -m_1\ddot{x}_g \quad (1)$$

$$m_2\ddot{x}_2 + c_2(\dot{x}_2 - \dot{x}_1) + k_2(x_2 - x_1) - k_dx_d - c_d\dot{x}_d = -m_2\ddot{x}_g \quad (2)$$

Here notation "d" means parameters related to the damper. The key step is to combine the equations (1) and (2) and express the resulting equation in a form similar to the SDOF case. This operation reduces the problem to an equivalent SDOF system. The approach followed here is based on transforming the original matrix equation to scalar modal equations. Introducing matrix notation, equations (1) and (2) are written as follows:

$$M\ddot{X} + C\dot{X} + KX = \begin{bmatrix} -m_1\ddot{x}_g \\ -m_2\ddot{x}_g \end{bmatrix} + \begin{bmatrix} 0 \\ k_dx_d + c_d\dot{x}_d \end{bmatrix} \quad (3)$$

where the displacement vector is ($X = \begin{bmatrix} x_1 \\ x_2 \end{bmatrix}$), mass matrix is ($M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix}$) and stiffness matrix is ($K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix}$).

B. Optimum parameters of the PTTMD using Tsai and Lin model

Optimal tuning parameters f and ξ_d determined by equations suggested by Tsai and Lin (1993)[23]

$$f = \left(\frac{\sqrt{1-.5\bar{m}}}{1+\bar{m}} + \sqrt{1-2\xi^2} - 1\right) - [2.375 - 1.034\sqrt{\bar{m}} - 0.426\bar{m}]\xi\sqrt{\bar{m}} - (3.730 - 16.903\sqrt{\bar{m}} + 20.496\bar{m})\xi^2\sqrt{\bar{m}} \quad (4)$$

$$\xi_d = \sqrt{\frac{3\bar{m}}{8(1+\bar{m})(1-.5\bar{m})}} + (.151\xi - .170\xi^2) + (.163\xi + 4.980\xi^2)\bar{m} \quad (5)$$

Tuning ratio fand $\xi_d$can be found from equation (4) and (5). Where TMD damping ratio, $\xi_d = \xi_{opt}$. The TMD stiffness is given by,

$$k_d = \bar{m} \times f_{opt}^2 \times K_1 \quad (6a)$$

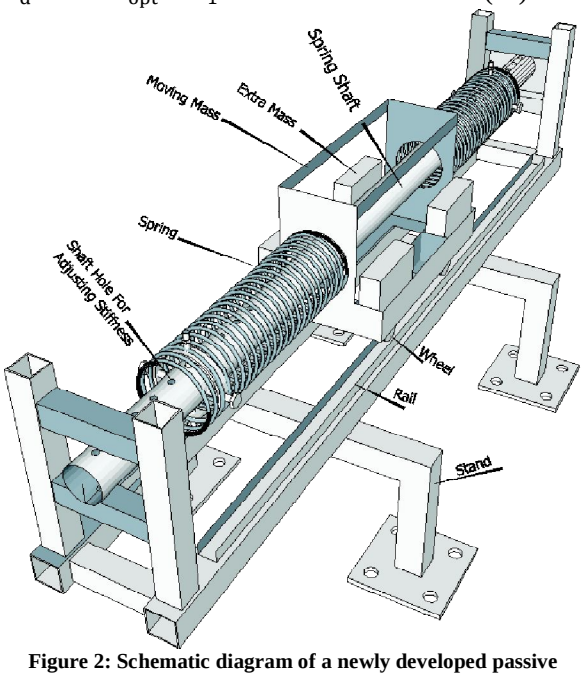


Figure 2: Schematic diagram of a newly developed passive translational TMD



Figure 3: Experimental setup of a newly developed passive translational TMD

where $\bar{m}$ is the mass ratio, K_1 means the kineticequivalent stiffness of structure for 1st mode. While the mass of TMD is estimated as

$$m_d = \bar{m} \times M_1 \quad (6b)$$

where $M_1$is the kinetic equivalent mass of structure for 1st mode.

III. RESULTS AND DISCUSSION

In this study,a two-storey MRSF structure is examined to investigate the effectiveness of the newly developed passive translational tuned mass damper (PTTMD) system in reducing structural responses due to seismic excitation. The most commonly used earthquake record in vibration control is selected in this study to evaluate the performance of each control techniques using PTTMD. Particularly scaled El Centro 1940 was employed in this study (see ref. [6] for scaling details).The elastic acceleration response spectra of El Centro earthquake is plotted in Figure 4(a). Original data El Centro was scaled down by a scale factor 3.68 as well as modified into a two-different time history such as 20 and 25 sec, respectively. Scale El Centro 1940 data are depicted in Fig. 4(b-c).

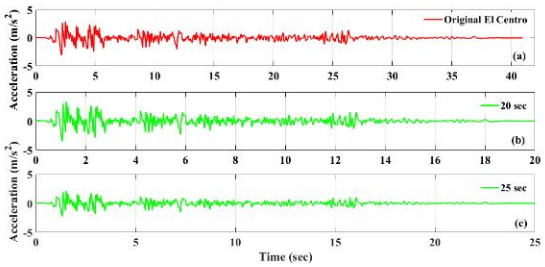


Figure 4: Input excitations: (a) original El Centro, (b) scale data for 20 sec and (c) scale data for 25 sec

As mentioned earlier that the TMD is normally designed for aparticular mode of vibration or frequency, additional 35 kg mass added on each floor for obtaining targeting frequency. In order to attain the aforesaid goal of this study, a numerical model was developed in SAP2000 for predicting identical experimental response. The comparison between experimental response versus numerical response of uncontrolled (i.e. without TMD) and controlled (i.e. with TMD and modal mass of 5%) are presented in Figures 5 and 6, respectively. To illustrate, experimental observation is presented by red solid line and numerical simulation is shown by adashed black line. From these figures,it can be observed that the numerical predicted displacements are very close to the experimental observation, which is very important to validate the experimental setup and to draw a conclusion.Due to page limitation, the comparison of experimental results with numerical prediction are not presented for the modal mass of 7.5, 10, 12.5, 15 and 17.5%. But a quite good agreement between experimental and numerical responses were observed.Similar way, the evolution of displacements are also not presented for the modal mass of 7.5, 10, 12.5, 15 and 17.5%.

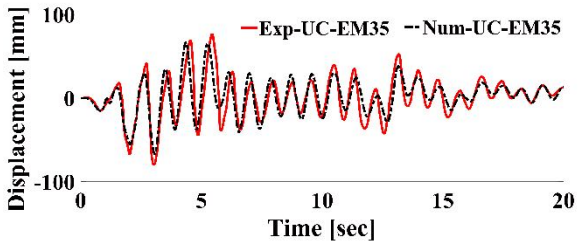


Figure 5: Comparison between experimental (Exp) observation and numerical (Num) simulationwithout PTTMD for 20 sec.

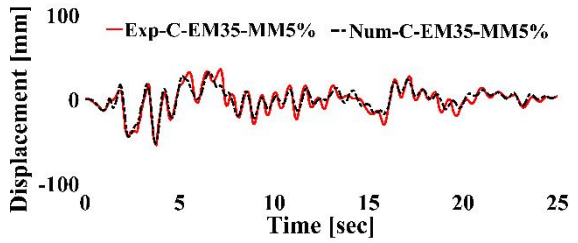


Figure 6: Evaluation of displacement measured in theexperimentand numerical simulation as a function of time with PTTMD andmodal mass of 5% for 25 sec.

Note: EM35 = 35 kg on its each floor, UC = uncontrolled structure (i.e. without TMD), C = Controlled structure (i.e. with TMD), MM = Modal Mass.

In order to deeper investigate the effect of modal mass on the structural response, Figures 7 and 8 were plotted for the modal mass of 0, 5, 10, and 15% for the duration of 20 and 25 sec, respectively.

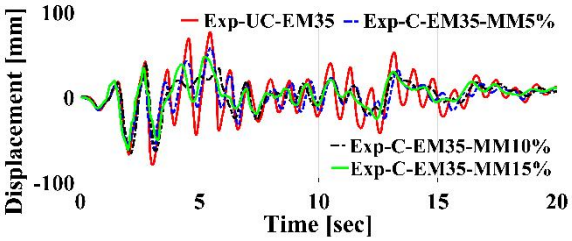


Figure 7: Comparison between uncontrolled (UC, MM = 0%) and controlled (C, MM = 5, 10, and 15%) structure for 20 sec.

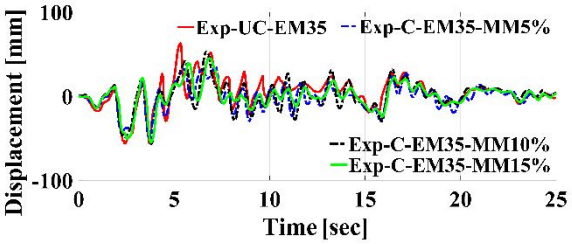


Figure 8: Comparison between uncontrolled (UC) and controlled (C) structure for 25 sec.

In Figures 7 and 8, the solid red line represents the response for uncontrolled (UC, MM = 0%), while dashed blue, dashed-dotted black, and solid light green line represent the response for controlled (C) with modal mass of 5, 10, and 15%, respectively. In general, TMD is not effective for ashorter duration (20 sec) of seismic load but PTTMD shows better performance for 20 sec rather than the 25 sec in this study. It is quite clear that the uncontrolled structure vibrates more than the controlled structures. Structure with modal mass of 10 and 15% revealed superior vibration reduction capability for 20 sec. On the other hand, structure with modal mass 5% mitigated thehighest amplitude for 25 sec.

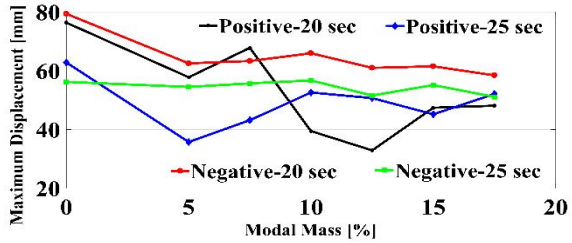


Figure 9:Positive and negative peak displacements as a function of % of MM for 20 and 25 sec.

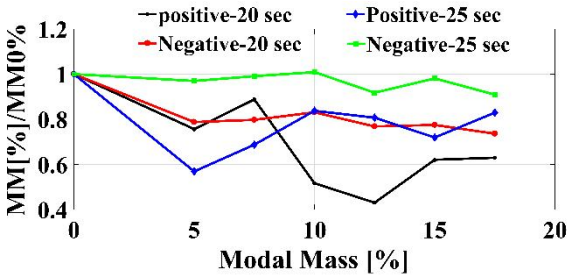


Figure 10:Normalized positive and negative peak displacements as a function of % of MM for 20 and 25 sec.

In order to find out the optimize modal mass, the positive and negative peak and normalized displacement of structures are plotted in Figures 9 and 10, respectively. From these two figures, it can be stated that the efficacy of TMD might be increased with the increased of modal mass. Nonetheless, in this study, it has found that in several cases of the MRSF with PTTMD are strugglingwith the resonant anddetuning effects. For example, in terms of positive displacement, responses do not reduce while themodal mass of 7.5-17.5 for 25 sec and modal mass of 15-17.5 for 20 sec is applied. While interestingly,continuous decreasing trend of displacementwas observed with the increasing modal mass for both 20 and 25 sec. It is found that up to 12.5% of modal mass for 20 sec and 5% of modal mass for 25 sec could be suitably used to mitigate displacement for studied MRSF structure.

CONCLUSION

This study investigates the optimumparameter (i.e., modal mass) of a newly developed PTTMD both experimentally and numerically. To do this end, firstly, a PTTMD was designed and developed. In a second stage, the aforementioned PTTMD was employed into a two-storied frame. In order to verify the efficacy of the newly developed PTTMD response of structure without TMD was considered named “uncontrolled (UC)” case. While the response of the structures with TMD was named as “controlled (C)”. The outcome of this study can be summarized as follows:

a) The amplitudes of displacement and drift are found to be higher when the structure is acted upon by dynamic conditions without PTTMD.
b) By assigning PTTMD to structure, the structure is going to more stable as the values of displacement and drift are reduced.
c) A quite good agreement between experimental and numerical results was found.
d) From the analysis and observations of the graphs, it is found that up to 12.5% of modal mass for 20 sec and 5% of modal mass for 25 sec could be suitably used to mitigate displacement for studied MRSF structure.

Even though the proposed test setup and the results showed that the PTTMD is effective to mitigate the vibration of the steel structures, further experimental tests need to be carried out to draw strong conclusions. To this aim, further investigations are currently underway by the authors to figure out the other parameters such as stiffness, damping in order to obtain the minimum vibration of the steel structures as well as concrete structures.

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