Performance Evaluation of a Newly Developed Translational Tuned Mass Damper

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Abstract—**A tuned mass damper (TMD) is a cost-effective tool for targeting the vibration mitigation of a particular mode of structures e.g. first mode of vibration. Structures like a tall building, large span bridges, and other slender structures tend to be easily excited to high amplitudes. In order to deal with the aforementioned issues, TMD could be a good option that can reduce extreme vibration very effectively. The main objective of this paper is to show the implementation of a newly developed TMD to reduce the amplitude of vibration for an excited structure. The TMD was designed such a way that its parameters such as spring stiffness, mass can be adjusted. By tuning the early mentioned parameters, its frequency also be changed to meet the requirements from the structure. In addition, this work investigates the effect of TMD by observing the dynamic response of a two-storey frame structure both experimentally and numerically. Finite element method has been used as a numerical tool to study the dynamic response of the steel frame-TMD system. The time-history (linear) analysis of the frame without (modal mass = 0%) and with TMD (modal mass = 5 and 15%) under earthquake load has carried out and the performances are evaluated and compared. It can be concluded that a significant reduction of response (i.e. displacement) is possible via the newly developed TMD. The maximum percentage of decrease in the displacement found to be reduced by 21% for the modal mass of 5% and 43% for the modal mass of 15%, respectively. Hence, it can be noted that newly developed TMD has potential to use in the real structure for vibration mitigation.**

Index Terms—**dynamic response, first mode of vibration, TMD, vibration mitigation, displacement**

I. Introduction

The vibration which generates due to dynamic loads such as seismic load, blast, gale load is becoming a great concern for the structural designers. For this reason, different vibration controlling method such as passive, active, semi-active, hybrid controls are adopted to reduce unwanted vibrations structural systems [1]-[6]. Typically, the goals of structural vibration control are as follows: (i) increasing flexibility, (ii) increasing safety levels, (iii) easier to monitor structures, and (iv) cost minimization [7]. Research progress and practical application of vibration controlling approaches are very inspiring in developed countries but unfortunately and wretchedly poor in developing countries including Bangladesh. Due to economic advantage, passive controlling approaches used immensely [8]. Out of a variety of passive control systems, TMD is widely implemented in tall building, bridges etc. Firstly, TMD was presented in order to absorb the energy of vibration as well as reduce the amplitude of vibration by Frahm [9]. In addition, Ormondroyd and Den Hartog [10] presented a theory for the TMD. And a detailed discussion of optimal tuning and damping parameters which was briefly described in Den Hartog's book on Mechanical Vibrations (1940) [2]. The early theory for TMD was appropriated only for an undamped single degree of freedom system (SDOF) to employ a sinusoidal force excitation. Many researchers investigated the theory for TMD which validated in damped SDOF system [11]. References [12]-[16] significantly contributed in the aforementioned cases.

The effectiveness of TMD in mitigating structural vibrations under different loads such as wind excitations [17], harmonic excitations [2] and human movements [18] have been validated. But, a topic of controversial discussion is the efficacy of TMDs in practical applications. Few researchers [19], [20] reported that TMDs is not effective for seismic vibration mitigation. On the other hand, references [21]-[24] completely disagreed with others. A TMD of offshore can reduce vibration and reduction in the peak displacement are about 0.27 times [25].

Vibration control is a comparatively new field in the

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structural engineering industry. Many researchers are doing research on it to find different controlling technology and for their optimum parameters. Optimization of mass ratio and inerter of TMD is a key feature of a TMD [28]-[29]. As passive control is comparatively economical with good performance, further study of this system has been chosen to research in this study.

Many successful applications of TMDs can be found around the globe such as: Centerpoint Tower in Sydney, John Hancock Tower in Boston, Citicorp Center in New York, CN Tower in Toronto, Chiba Port Tower in Japan, and Taipei 101 in Taiwan. Burj Al Arab, one of the world tallest high rise structure, is also build with TMD where 11 TMD placed in the different storey to control wind induced vibration [11], [26]-[27].

TMD is a cost effective strategy is necessary to suppress structural vibration by introducing additional damping. This damping mainly dependent on the mass ratio in a particular mode vibration. The mass ratio can be defined by the ratio of the damper mass to the effective modal mass of the building for a specific mode. Generally, TMDs weight is varied between 0.25%-1.0% of the building's weight in the fundamental mode [7].

In this study, a Tuned Mass Damper (TMD) is developed locally to observe its effect on structural response. A TMD is a passive damping system which utilizes a secondary mass attached to the main structure normally through spring and dashpot to reduce the dynamic response of the structure. The main advantages of TMD in this study are the stiffness and mass are adjustable. In order to investigate the effect of TMD on structure, the response of the structure with and without TMD is investigated employing seismic load in this study.

II. Design of the Tuned Mass Damper

A. Theoretical Background of TMD

A two degree of freedom (2-DOF) system is having a damper attached to mass 2 is considered here to introduce the key ideas. The governing equation of motion for the system shown in Fig. 1 as follows [1], [7]:

$$m_1\ddot{u}_1 + c_1\dot{u}_1 + k_1u_1 - k_2(u_2 - u_1) - c_2(\dot{u}_2 - \dot{u}_1) = -m_1\ddot{u}_g \quad (1)$$

$$m_2\ddot{u}_2 + c_2(\dot{u}_2 - \dot{u}_1) + k_2(u_2 - u_1) - k_du_d - c_d\dot{u}_d = -m_2\ddot{u}_g \quad (2)$$

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

$$M\ddot{U} + C\dot{U} + KU = \begin{bmatrix} -m_1\ddot{u}_g \\ -m_2\ddot{u}_g \end{bmatrix} + \begin{bmatrix} 0 \\ k_du_d + c_d\dot{u}_d \end{bmatrix} \quad (3)$$

Where $\ddot{U}$, $\dot{U}$ and U are the acceleration, velocity and displacement accordingly. And the displacement vector (U), mass matrix (M) and stiffness matrix (K) is given by

$$U = \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (4)$$

$$M = \begin{bmatrix} m_1 & 0 \\ 0 & m_2 \end{bmatrix} \quad (5)$$

$$K = \begin{bmatrix} k_1 + k_2 & -k_2 \\ -k_2 & k_2 \end{bmatrix} \quad (6)$$

Optimal tuning parameters f and ξ_d determined by equations suggested by Tsai and Lin (1993) [16]

$$f = \left(\frac{\sqrt{1-.5\bar{m}}}{1+\bar{m}} + \sqrt{1-2\xi^2} - 1\right) - \left[2.375 - 1.034\sqrt{\bar{m}} - 0.426\bar{m}\right]\xi\sqrt{\bar{m}} - \left(3.730 - 16.903\sqrt{\bar{m}} + 20.496\bar{m}\right)\xi^2\sqrt{\bar{m}} \quad (7)$$

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

Tuning ratio f can be found from in (7) and (8). Where TMD damping ratio, $\xi_d = \xi_{opt}$. The TMD stiffness is given by,

$$k_d = \bar{m} \times f_{opt}^2 \times K_1 \quad (9a)$$

where $\bar{m}$ is the mass ratio, K_1 means the Kinetic Equivalent Stiffness of Structure for 1st mode mass for TMD. And the mass of TMD is estimated as

$$m_d = \bar{m} \times M_1 \quad (9b)$$

where M_1 is the Kinetic Equivalent Mass of Structure for 1st mode

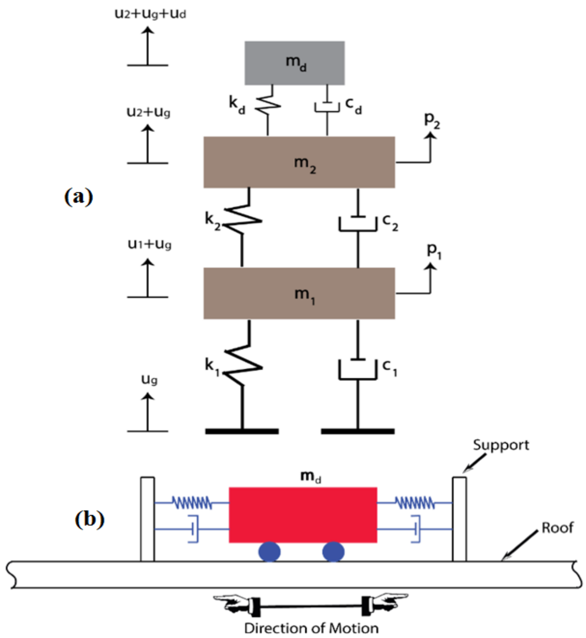


Figure 1. Schematic diagram: (a) 2-DOF system with TMD, (b) translational tuned mass damper.

B. Tuning

A TMD has three basic elements: mass, stiffness, and damping. So there are three forms of tuning required in the design of a TMD. The stiffness and mass of the TMD are selected to provide a TMD resonance frequency very close to the structure's resonance frequency. Tuning of mass and stiffness has been done by the above-mentioned equations (1-9). In this model provision of tuning of damping has not yet been implemented. The internal damping of TMD mainly comes from the friction of wheel to rail. This value has been evaluated by free vibration method of "moving mass" of TMD. In order to maintain expected stiffness, two types of spring have been used (see Table I).

C. Components of Designed TMD

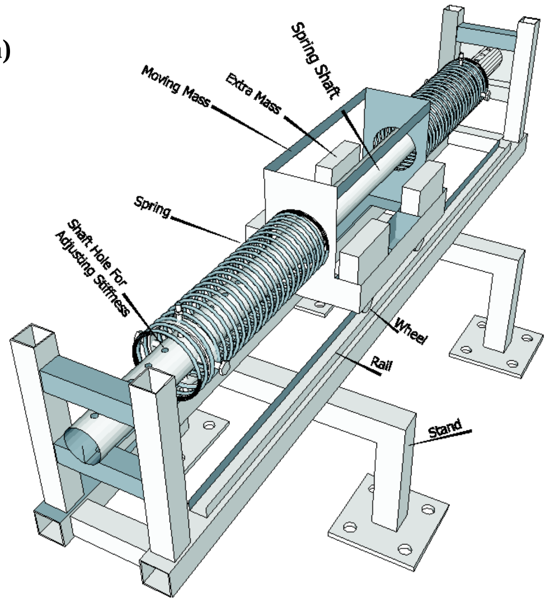
The TMD is shown in Figs. 1 and 2. It has broadly two components:

- Base structure: Though it is called part of TMD, actually it is part of the main structure. It holds the spring-mass system but it is integral with the main structure. Its self-weight is 8.83 kg. As a result, for providing 25 kg on the top floor, TMD + (25kg-8.83kg) 16.17kg has to be kept on. Base structure has different components, such as:
- Base frame: See Fig. 2
- Rail: The wheel of the mass carrier moves on it (See Fig. 2).
- Spring shaft: See Fig.2

TABLE I. DETAILS OF SPRINGS

Spring	Material	Wire Dia. (mm)	Outer Dia. (mm)	Free Length (mm)	Number of Active Coils (Nos)
Type-I	Carbon Valve, ASTM A230	2.34	62	215	22
Type-II		2.64	60	200	22

(a)



(b)

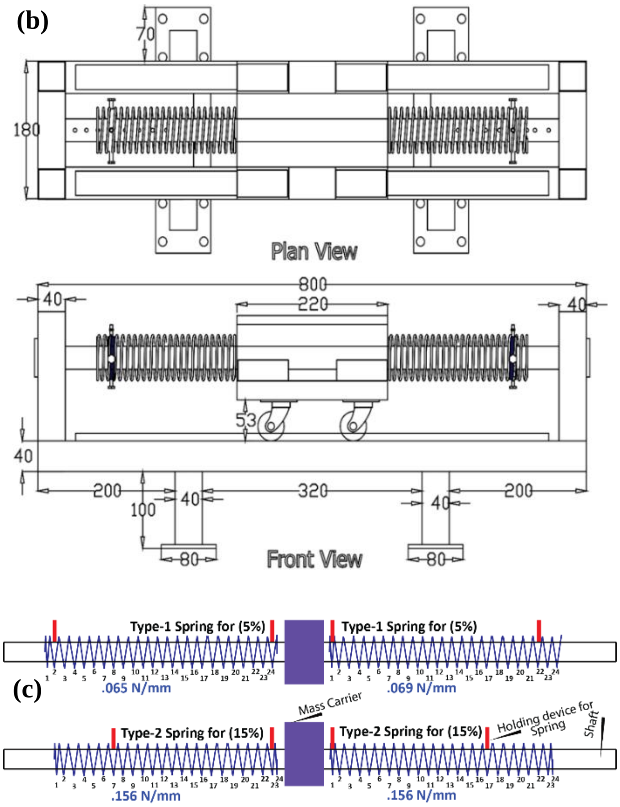


Figure 2. (a) Schematic diagram of Tuned Mass Damper, (b) dimensional details of TMD, and (c) spring adjustment for tuning.

- Spring: See Fig. 2
- Moving mass carrier and additional mass: The moving mass component (Fig. 2) has self-weight of 1.9 Kg. When it requires more mass, additional mass has to be provided (see Fig. 2).

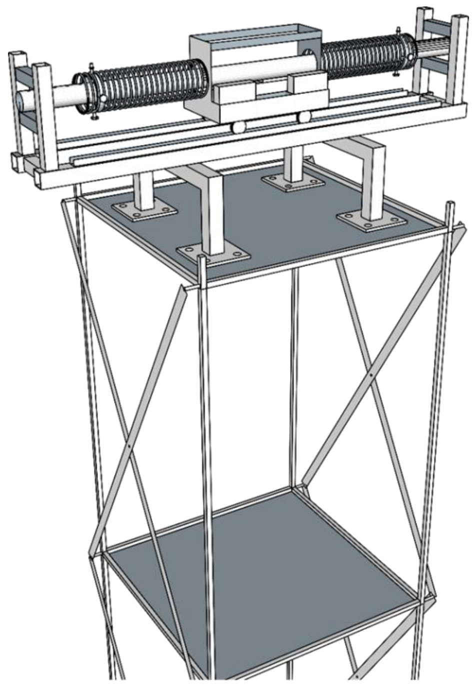


Figure 3. Schematic diagram of test setup with TMD.

III. Results and Discussion

The most commonly used earthquake record in vibration control is selected in this study to evaluate the performance of each control techniques using TMD. Particularly scaled El Centro 1940 was employed in this study [7]. The elastic acceleration response spectra of El Centro earthquake is plotted in Fig. 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 sec and 25 sec, respectively. Scale El Centro 1940 data are depicted in Fig. 4(b-c).

A. *Comparison of Experimental Observations Versus Numerical Responses*

To mitigate structural vibration of a steel frame, a comparison study is done by linear time history analysis employing scale El Centro 1940. Effect of extra mass are presented by Figs. 5 and 6. In these figures, solid and dotted line represent experimental and numerical responses, respectively. Green, red, black color display the result for uncontrolled (UC) structure where there are no additional masses, a structure with 25 kg (UC-EM25) and structure with 30 kg (UC-EM30), respectively. Figs. 5 and 6 present the response for 20 sec and 25 sec, correspondingly. It can be seen that the response is increasing with the mass intensity. Furthermore, it can be stated that both experimental observations and numerical simulations are agreed quite well.

Figs. 7 and 8 represent the comparison between the uncontrolled (UC) and controlled (C) structure for 20 sec and 25 sec, respectively. In Figs. 7 and 8, there are 8 lines where 4 solid lines show the experimental observation and 4 dotted lines show the responses of numerical simulations. The result for uncontrolled structure (no additional masses) and structure with 25 kg on each floor with TMD on the top floor with modal mass ratio of 0%, 5%, and 15% are indicating by green, red, black, and blue, respectively. From these figures, it can be observed that structure with TMD with 15% modal mass shows the better performance among others during 20 sec scaled El Centro Earthquake vice versa for 25 sec.

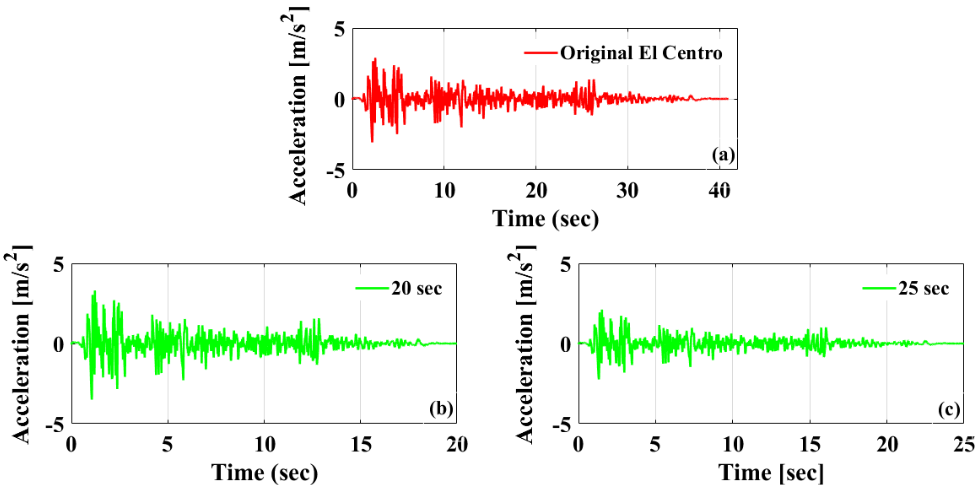


Figure 4. Input excitations: (a) original El Centro, (b) scale data for 20 sec, and (c) scale data for 25 sec.

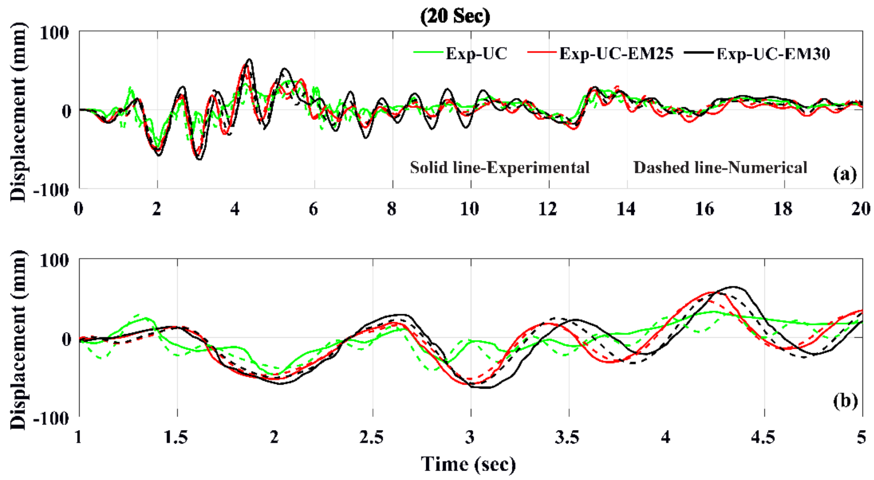


Figure 5. Verification of effect of extra masses in the uncontrolled (UC) structure for 20 sec: (a) full-time history and (b) zoomed view of 1-5sec.

In Figs. 9 and 10, there are 8 lines where 4 solid lines show the experimental observation and 4 dotted lines show the responses of numerical simulations, respectively. The result for UC structure (no additional masses) and structure with 30 kg on each floor with TMD on the top floor with modal mass of 0%, 5%, and 15% are indicating by green, red, black, and blue, respectively. From these figures, it has been found that the structure contains 30 kg on each floor with TMD with 15% modal mass shows the better performance among others during 20 sec scaled El Centro Earthquake vice versa for 25 sec.

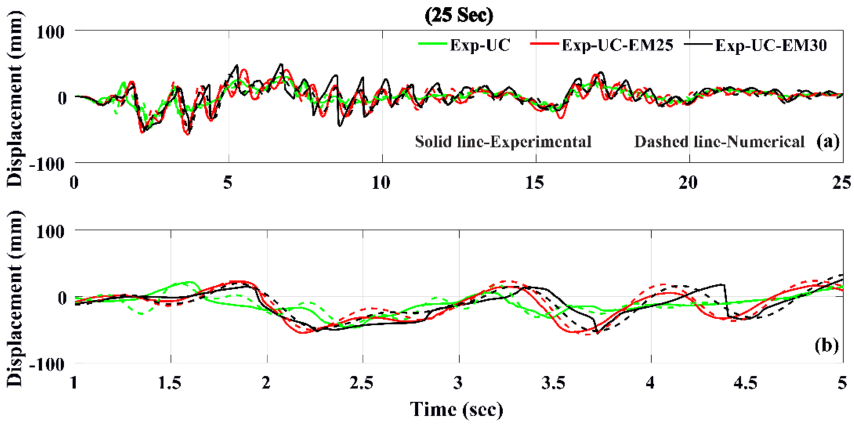


Figure 6. Verification of effect of extra masses in the uncontrolled (UC) structure for 25 sec: (a) full-time history and (b) zoomed view of 1-5sec.

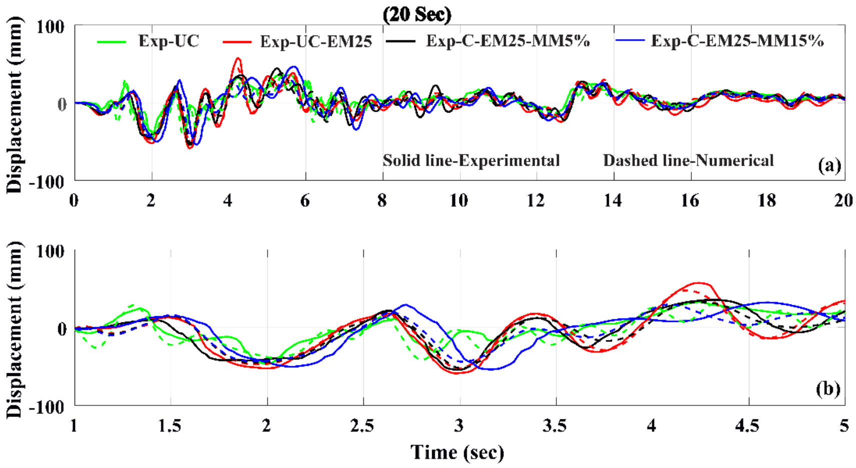


Figure 7. Comparison between uncontrolled (UC) and controlled (C) structure for 20 sec: (a) full-time history and (b) zoomed view of 1-5 sec.

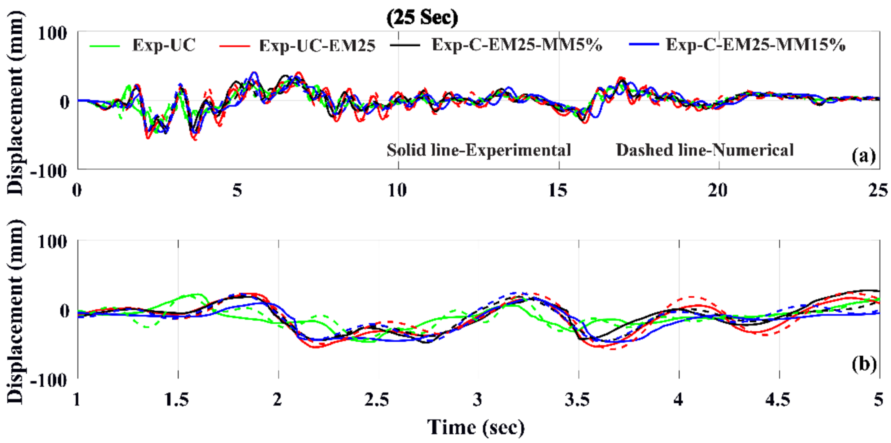


Figure 8. Comparison between uncontrolled (UC) and controlled (C) structure for 25 sec: (a) full-time history and (b) zoomed view of 1-5 sec.

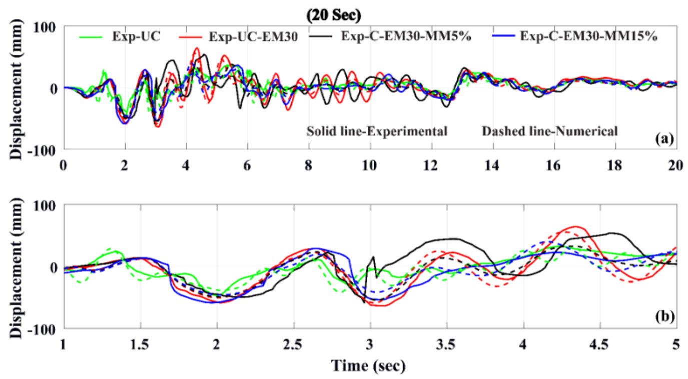


Figure 9. Comparison between uncontrolled (UC) and controlled (C) structure for 20 sec: (a) full-time history and (b) zoomed view of 1-5sec.

However, the percentage of reduction of peak values of the aforementioned figures are summarized in Table II. It can be seen that the uncontrolled (UC) response has been reduced significantly. And these results indicate that the studied TMD was efficiently tuned. It has been found that the maximum values were reduced around 43% for positive displacement and 12% for negative displacement, respectively, see Table II.

TABLE II. COMPARISON OF THE PEAK VALUES

Cases	Duration of scale El Centro (sec)	Modal Mass (%)	Max. (+) Reduction (%)	Min. (-) Reduction (%)
1	20s*	5	21.58	7.26
		15	16.66	7.73
2	25s*	5	13.08	10.39
		15	0.15	12.41
3	20s**	5	16.47	7.6
		15	43.19	8.33
4	25s**	5	16.25	12.77
		15	3.46	5.34
*25 kg on each floor, **30 kg on each floor				

IV. CONCLUSION

This study investigates the possibility of using a newly developed TMD both experimentally and numerically. To do this, firstly, a TMD was designed and developed. In a second stage, the aforementioned TMD was employed into a two-storied frame. In order to verify the efficacy of the newly developed TMD 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:

- The amplitudes of displacement and drift are found to be higher when the structure is acted upon by dynamic conditions without a damper.
- By assigning TMD to structure, the structure is going to be more stable as the values of displacement and drift are reduced.
- A quite good agreement between experimental and numerical results was found.
- From the analysis and observations of the graph, it can be concluded that the maximum percentage of decrease in the displacement found to be reduced by 21% for the modal mass of 5% and 43% for the modal mass of 15%, respectively.

Even though the proposed test setup and the results showed that the TMD is more effective to mitigate the vibration of the steel structure, 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 optimum amount of modal mass and the external mass on each floor to obtain the minimum vibration of the steel structures as well as concrete structures.

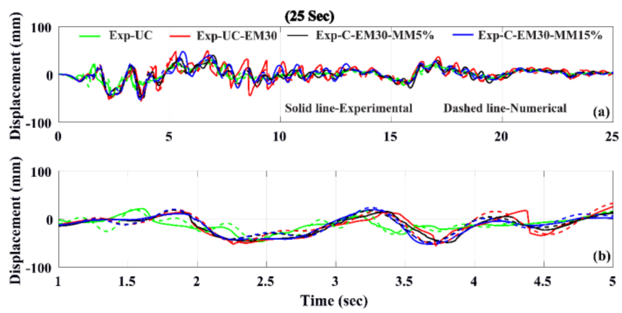


Figure 10. Comparison between uncontrolled (UC) and controlled (C) structure for 25 sec: (a) full-time history and (b) zoomed view of 1-5sec.

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