Enhancing Seismic Performance of Cable-Stayed Bridges using Tuned Mass Dampers

Mohammed F. Alshaer [1*], Amr Z. Elkady [2], Mohammed A. Sakr [3], Ayman A. Seleemah [3]

[1*]*MSc Student, Structural Engineering Department, Faculty of Engineering, Tanta University*
[2]*Ph.D. Assistant Professor, Structural Engineering Department, Faculty of Engineering, Tanta University*
[3]*Ph.D. Professor, Structural Engineering Department, Faculty of Engineering, Tanta University*
Emails: ***Mohammedalshaer@f-eng.tanta.edu.eg***

Abstract- Enhancing the seismic performance of cable stayed bridges (CSBs) gained increasing attention over the past few decades. The aim of this paper is to investigate how single tuned mass damper (TMD) can enhance the performance of CSB by comparing the performance of the CSB before and after incorporating the TMD under different excitation records. Finite element analysis has been performed and verified in order to assess the optimum value of TMD mass ratio. Results shows that, the presence of TMD leads to a noticeable improvement in different responses. Also, for mass ratio values between 0.25% and 0.5%, the bridge shows best performance.

Keywords: ***Cable-stayed bridges, Earthquakes, Tuned mass damper***.

I. INTRODUCTION

Over the last decades, a large number of CSBs have been constructed around the world. CSBs offer cost effective choice for carrying the loads in medium to large spans. CSBs are considered as flexible structures as, they have a very low damping ratio [1]. Hence, they are vulnerable to lateral dynamic forces. A major part of wind and earthquake energy can be dissipated by increasing the damping ratio in CSBs. TMDs are very popular, economical and robust in mitigating the dynamic response.
A main problem faced when employing a TMD that it is effective only over a narrow frequency bandwidth. If the frequency is not similar to the natural frequency of the bridge it can be incompetent and probably counterproductive depending on how it is tuned, it can make the structure's behavior worse [2]. Several studies considered using TMDs to enhance the behavior of bridges theoretically and experimentally under different kinds of vibrations. For example, Gu et al. (1998) [3] found that TMD can increase the critical flutter wind speed of long-span bridges significantly. Chen and Kareem (2003) [4] examined the efficiency of TMD in controlling self-excited motion caused by negative damping. Further, vortex-induced vibration was successfully controlled using TMD by Fujino and Yoshida (2002) [5] on a 10-span continuous steel box girder bridge. Elkady et al. (2017) [6] performed experiments on the scaled model of the Dongshuimen bridge using TMD-type counterweight for reducing the earthquake induced displacements at the central span of a CSB. Results indicated that the TMD had notable effect on reducing the vibration of the main deck and increasing the damping ratio of the bridge. Retrofitting CSBs to improve its seismic performance using TMDs was considered by Sun et al. (2020) [7] through retrofitting Chongqi steel box-girder bridge. Bridge consists of separate but adjacent twin six-span bridges. During construction of the bridge, vortex-induced vibration was observed, which caused concern about the performance of the bridge. TMDs were installed in the four middle spans of the bridge to control large vibrations. Results indicated effectiveness of the TMDs and their functioning under different wind conditions. Recently, a new passive damping device named pounding tuned mass damper (PTMD) was proposed for vibration control of flexible structures such as bridges. It consists of a tuned mass whose stroke is restrained by a pair of delimiters covered with viscoelastic materials. When the tuned mass impacts on the viscoelastic delimiter, large amounts of energy can be dissipated via collision. In early studies of the mass block is located in the middle of the two delimiters but, parametric studies revealed that the gap is the key parameter that influences the vibration control effectiveness. After that, Zhang et al. (2021) [8] proposed a new type damping device named asymmetric (PTMD) where two gaps of the APTMD can be set to different values. Results showed that, the APTMD is slightly better than the TMD and the PTMD. Although efforts have been made to study TMDs and its effect on the performance of CSBs, more attention needs to be paid to study CSBs under seismic excitations in the lateral direction, focusing on TMDs and its optimum parameters. This particular study is concerned with studying the effectiveness of using a passive TMD to enhance the energy dissipation of CSB in the lateral direction under seismic and white noise excitations by determining the optimum value of TMD mass ratio.

II. FINITE ELEMENT MODELLING

A. General

A Finite element model (FEM) for the reduced scale model (1:60) of Chongqing Dongshuimen Yangtze River Cable-stayed Bridge constructed by Ansari et al. (2016) [9] was employed for the research.

B. Description of the structural scaled model

The main bridge consists of two towers, single-cable plane, cable-stayed steel truss girder, with three spans of 222.5, 445, and 190.5 m, respectively. The scaled dimensions of the model are shown in Fig. (1-a). Deck and pylons were constructed of steel with yield strength of 235 MPa. The pylons bases were fixed and the moment of inertia for the two pylons were 132,248 mm4. The cross section of the deck is a hollow box and additional steel elements were attached to the deck at equal intervals to model the dead load as shown in Fig. (1-b) and Fig. (1-c). Steel piano wires with tensile strength of 2,500 MPa and diameter of 0.4 mm were used to simulate the cables. Fig. (1-d) shows a photo of the scaled bridge in the laboratory.

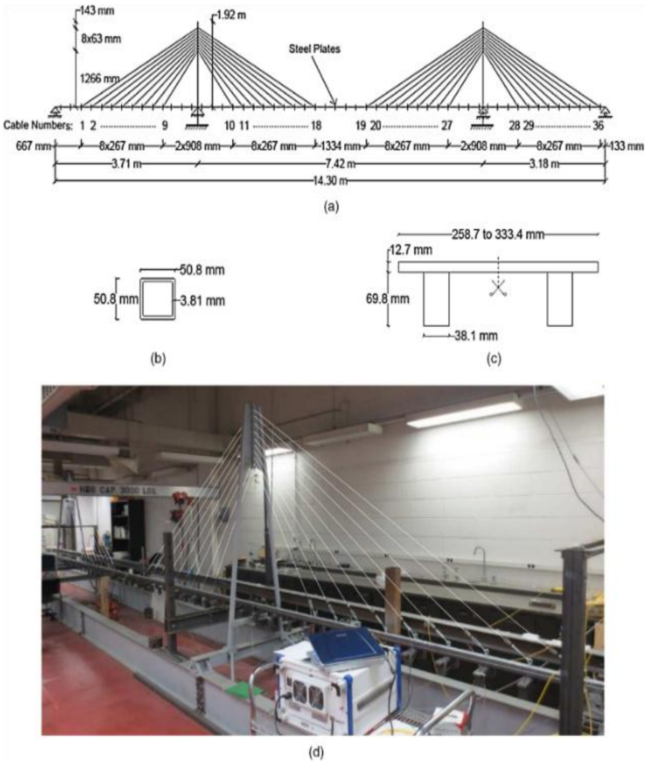

Fig. 1. Structural model: (a) side view; (b) cross-sectional view; (c) steel plates to consider the dead load; (d) photo of the model bridge.

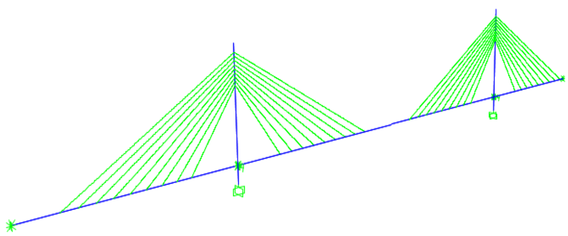

Fig. 2. Finite element model of the cable-stayed bridge

B. *Description of the finite element model*

A two-dimensional linear FEM was constructed. The support conditions, materials, and structural properties that were used in modeling are identical to the reduced-scale model, which are described earlier. Frame elements were used for modeling the pylons and deck, and the cables were modeled using cable elements. Fig. 2 shows the finite element model of the bridge.

C. *Verification*

Preliminary verification was done to ensure the ability of FEM to simulate the experimental work. The FEM results were compared with the experimental program performed earlier by Elkady et al. [6]. The experimental program was designed to evaluate the efficiency of using a single TMD to reduce the vibrations of the bridge. The weight of the random mass block used as a TMD in the experiment was 7.85 N and was concentrated in the mid-span of the steel box girder. TMD is modeled in the FEM using a spring-mass system, the spring is modeled as a linear two-joint link in which one joint is attached to the structure, and the other joint is free. Weight is then assigned to the free joint and linear damping is included directly in the linear link property. Damping ratio of the bridge when subjected to free vibration motion in two cases, with and without TMD was calculated from the experimental work as 6.05% and 0.557% for the two cases, respectively. These results were compared with the FEM results. The damping ratio of the bridge was calculated using the basic formula of a dynamic structure as 6.11% and 0.54% for the two cases, with and without TMD respectively. It is clear that, the comparison is satisfactory indicating the capability of the FEM to predict the actual behavior of the CSB with and without the TMD.

III. PARAMETRIC STUDY

Finite element analysis has been performed to assess the effect of changing the value of TMD mass ratio by comparing the performance of the CSB before and after incorporating the TMD under different excitation records. TMD is applied at the mid-span of the bridge and designed to control the first lateral mode of the bridge.

A. *TMD properties*

TMD mass ratio selected for this study ranges between 0.01% and 10% in order to the study the effect of varying TMD mass on the bridge. The optimum frequency ratio (η) and optimum damping ratio (ζ) between the TMD and the bridge modal properties were determined by applying the optimum tuning conditions given in Eq. (1) to (5) [10] [11].

$$m_{TMD} = \mu \, M_i \quad (1)$$

$$\eta = \frac{\sqrt{1-\frac{\mu}{2}}}{1+\mu} \quad (2)$$

$$\omega_{TMD} = \eta \, 2 \, \pi \, f_i \quad (3)$$

$$\zeta = \sqrt{\frac{\mu\,(1+\frac{3\mu}{4})}{4(1+\mu)(1-\frac{\mu}{2})}} \quad (4)$$

$$C_{TMD} = \zeta \, C_c \quad (5)$$

Fig. 3 provides information about the first two main lateral modes of vibration of the bridge. The TMD mass ratio (μ) is progressively increased from the initial 0.01% to 10% and TMD stiffness and damping are calculated as summarized in Table 1 and a model of TMD is shown in Fig. (4).

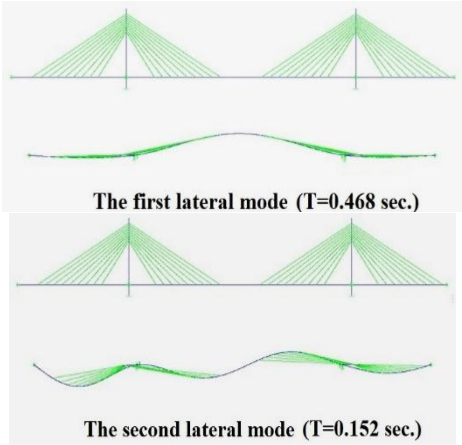

Fig. 3. First two main lateral modes of the bridge

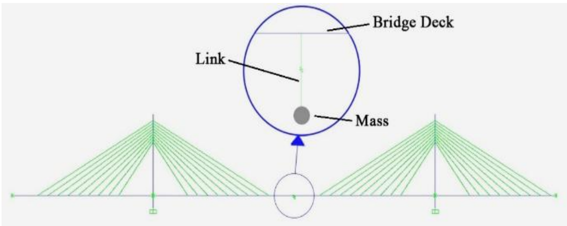

Fig. 4. Model of TMD used in analysis

Table 1. TMD properties calculated for each mass ratio (μ).

μ %	TMD weight (N)	K (N/ m)	C (N.s/m)
0.01	0.100	1.83	0.001
0.02	0.199	3.67	0.004
0.04	0.399	7.33	0.011
0.06	0.598	10.99	0.020
0.08	0.797	14.64	0.031
0.1	0.996	18.30	0.043
0.125	1.245	22.86	0.060
0.25	2.491	45.57	0.170
0.375	3.736	68.14	0.312
0.5	4.982	90.57	0.480
0.625	6.227	112.86	0.670
0.75	7.472	135.02	0.879
0.875	8.718	157.03	1.106
1	9.963	178.91	1.350
1.5	14.945	265.06	2.466
2	19.927	349.07	3.775
3	29.890	510.89	6.860
4	39.853	664.76	10.448
5	49.817	811.04	14.446
6	59.780	950.07	18.790
7	69.743	1082.19	23.430
8	79.707	1207.70	28.330
9	89.670	1326.90	33.458
10	99.633	1440.07	38.789

B. Types of Excitations applied to the bridge

Free vibration motion was applied to the bridge deck laterally to calculate the damping ratio. Then, the bridge was excited by an artificial white noise. Fig. 5 shows the acceleration time history for the white noise. Three seismic excitations were applied to the bridge as well. Excitations are presented in Table 2 and acceleration time histories are shown in Fig. 6.

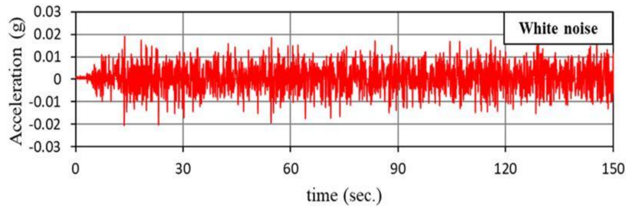

Fig. 5. Acceleration time history for White noise vibration

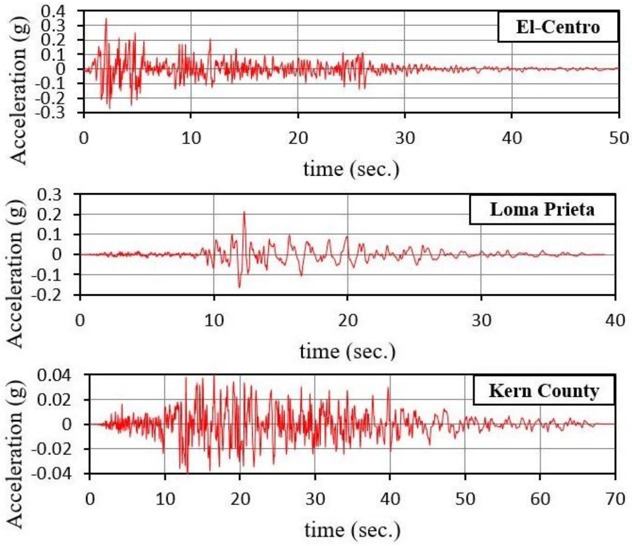

Fig. 6. Acceleration time history of El-Centro, Loma prieta and kern county earthquakes

Table 2. Seismic excitations applied to the bridge

Earthquake	Station	Date	PGA (g)
El-Centro	Imperial Valley	1940	0.348
Loma Prieta	Emeryville; Pacific Park #2	1989	0.214
Kern County	LA - Hollywood Stor FF	1952	0.042

C. Structural responses obtained from FEM

Following responses are obtained for each analysis case in order to evaluate bridge performance:

-Maximum deck displacement at the mid-span ($U_{d,max}$).

-Maximum bending moment of the deck at the mid-span in the lateral direction ($M_{d,max}$).

-Maximum base shear at the fixed support of the left tower in the lateral direction, ($R_{t,max}$).

-Maximum bending moment at the deck level of left tower in the lateral direction, ($M_{t,max}$).

IV. RESULTS AND DISCUSSION

The lateral displacement of the deck under the influence of free vibration motion are plotted in Fig.7. Damping ratios of the bridge were calculated using the basic formula of a structural dynamics [11] then plotted against the mass ratio of TMD (μ%) in Fig. 8. Curve shows an immediate improvement in damping ratio at low (μ) values then it decreases gradually. Figures (9-16) show structural responses obtained from FEM plotted against the mass ratio of the TMD.

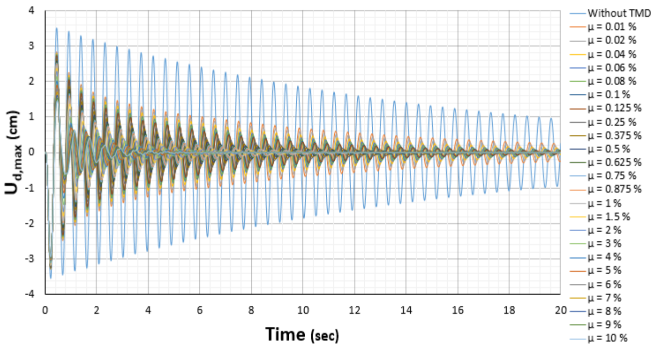

Fig. 7. Time history of the lateral displacement at mid-span deck

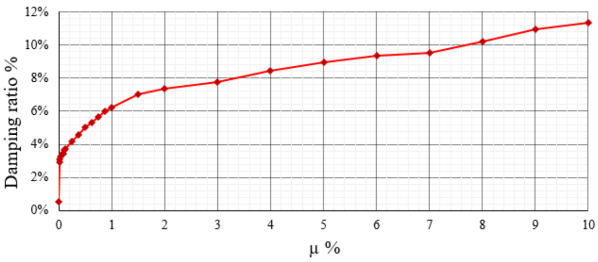

Fig 8 Damping ratio of the bridge calculated for different mass ratio

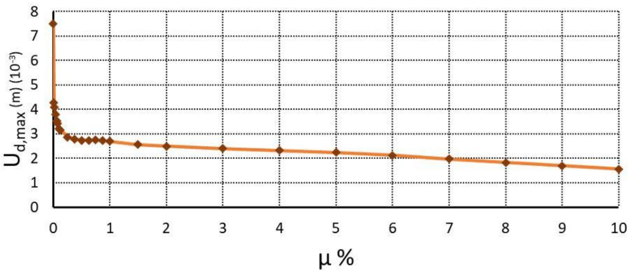

Fig. 9. $U_{d,max}$ resulted from the white noise vibration

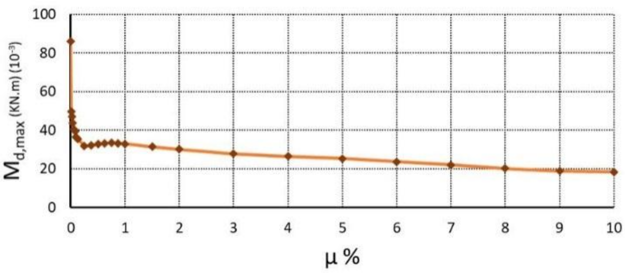

Fig. 10. $M_{d,max}$ resulted from the white noise vibration

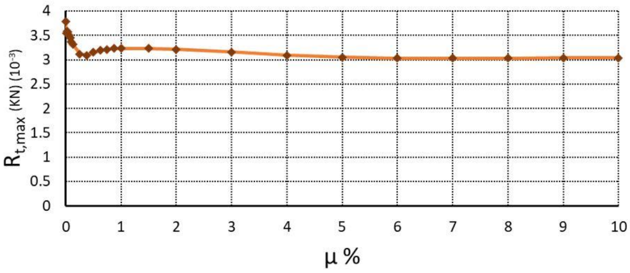

Fig. 11. $R_{t,max}$ resulted from the white noise vibration

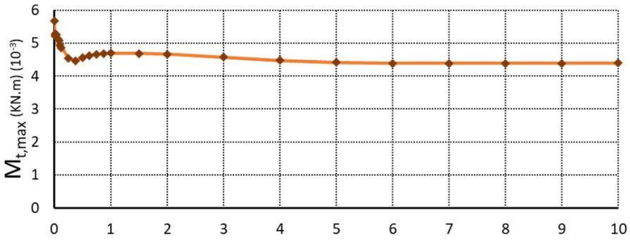

Fig. 12. $M_{t,max}$ resulted from the white noise vibration

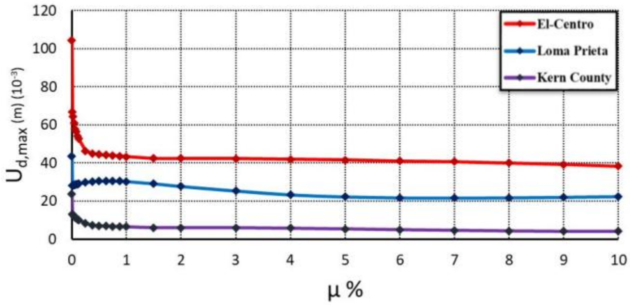

Fig. 13. $U_{d,max}$ resulted from seismic excitations

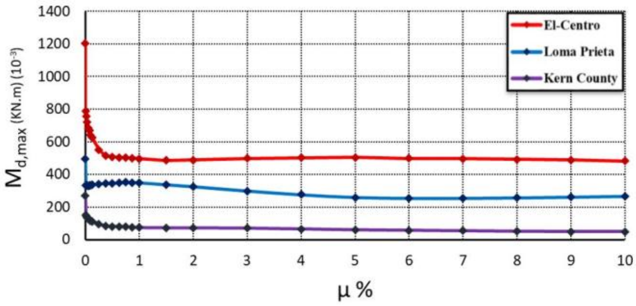

Fig. 14. $M_{d,max}$ resulted from seismic excitations

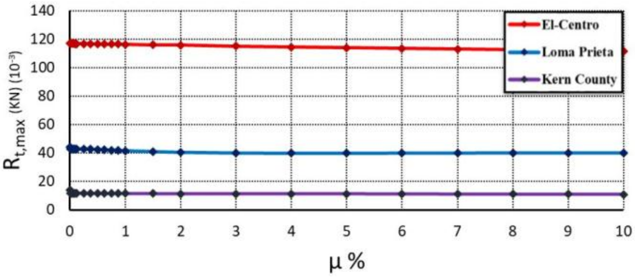

Fig. 15. $R_{t,max}$ resulted from seismic excitations

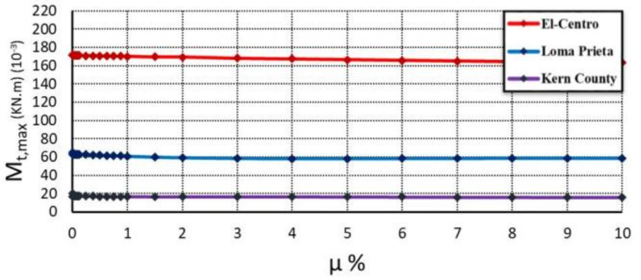

Fig. 16. $M_{t,max}$ resulted from seismic excitations

Results show that, the presence of TMD leads to a noticeable immediate improvement in different responses. For μ values between 0.25% and 0.5%, the bridge shows the best performance. Also, for μ > 1% the efficiency of using the TMD does not show significant increase that warrant the cost and difficulty of implementation which makes no need to increase the mass of TMD.

V. SUMMARY AND CONCLUSIONS

The purpose of this paper is to investigate effectiveness of using a passive TMD to enhance the energy dissipation of CSB in the lateral direction under different type of excitations.

A finite element model of Dongshuimen Cable-stayed Bridge was conducted and verified. Then, a single TMD was applied at the mid span of the bridge.

Different values of TMD mass ratio were studied under three seismic excitations and the white noise vibration. The damping ratio for each case was calculated. The results showed an immediate improvement in damping ratio at low (μ) values then it decreases gradually.

The structural responses extracted for each case were plotted against the mass ratio of the TMD and it was found that, for μ values between 0.25% and 0.5%, the bridge shows obvious improvement.

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