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Experimental Investigation of Tuned Liquid Damper Steel Structure Interactions

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ABSTRACT

Tuned liquid damper (TLD) is a type of tuned mass damper (TMD) where the mass is supplanted by a liquid (usually water). In this paper, performance of TLD that reduces the displacement and acceleration resulting from wind and earthquake lateral forces in tall buildings is studied. Experimental works have been conducted on three 10 stories steel building models with scale of 1/25 with and without water tanks. A dynamic ramp wave force with frequency of 1.5 Hz and amplitude of 2 mm is applied on each model using a horizontal shaking table. The results of the accelerometers and linear variable differential transformers (LVDTs) installed at the tenth floor of the models are recorded. It was found that the 8%, 15% and 11.5% weight of water tank to weights of structures can minimize the acceleration response and top floor displacement for the three tested models by 23 %, 48% and 18.2%, respectively. Also, the calculated damping ratio for model 2 is 1.9 %.

Keywords: Tuned liquid dampers, Sloshing, Shaking table, Vibration control, Earthquake response.

1. INTRODUCTION

Tuned liquid dampers (TLDs) are structural masses to diminish vibrations. TLD is a kind of tuned mass damper (TMD) where mass is supplanted by liquid. The sloshing of the fluid in TLD simulates the motion of the TMD. TLD includes a liquid-filled tank whose sloshing motion is tuned to the natural frequency of the structure. TLDs are often placed at the top of the structure. The liquid sloshing action of the TLD when the structure is subjected to outside excitation neutralizes and decreases the basic vibration.

Previous researchers had worked in using tuned liquid damper to be effective in the resistance of the lateral loads. Roshni and Ritzy [1] studied the performance of a new type of cost-effective TLD for relieving wind and earthquake induced vibrations in high-rise buildings. The effectiveness of TLD is evaluated based on the response reduction of the structure. They also studied various parameters that affect the performance of TLD.

David and Martin [2] summarized the gained experiences on the efficient design for building motion using TLDs in a residential project. A discussion on the potential advantages in terms of performance and cost of using an assistant damping system over the conventional methods was outlined.

Crowley and Porter.[3] presented analytical model for TLD systems with screens placed in various positions inside the water tank. The authors adopted a linearized wave water theory to analyze the fluid motion in the tank. A developed boundary-value problem in which homogeneous linear boundary conditions holding along the length of the screen were derived from a pair of model problems. One including an exact geometric description of a slatted screen to determine an inertia coefficient and the other using a quadratic drag law to determine an equivalent linear drag coefficient.

Chakraborty et al. [4] investigated the performance of tuned liquid column damper (TLCD) system of protection in mitigating seismic vibration effect of structures addressing the limiting effect of excessive TLCD displacement which may occur during strong motion period. They considered the natural limits of the hydraulic system due to possible excessive oscillation of liquid in the vertical column. A numerical study is made to clarify the effect of constraint condition on the optimum parameters of TLCD and its performance in seismic vibration mitigation.

Bhattacharjee et al. [5] studied the performance of unidirectional tuned liquid damper (TLD) that relies upon the motion of shallow liquid in a rigid tank for changing the dynamic characteristics of a structure and dissipating its vibration energy under harmonic excitation. The effect of various parameters which affect the structural response such as the ratio of water depth to tank length, the ratio of sloshing frequency to structural natural frequency and the ratio of excitation frequency to natural frequency of the structure were studied.

Maravani and Hamed [6] developed a numerical algorithm to solve both the small and large amplitude of excitations. In this algorithm, the fluid flow through the screen is fully resolved and it can consider the effect of the screen pattern on the performance of TLD. They conducted numerical investigation to study the effects of the slat screen pattern on the inherent damping and natural frequency of the TLD. The numerical results have been validated against experimental work and two new parameters termed as slat ratio (SR) and effective solidity ratio (Seff) are presented to imply the physical significance of screen pattern.

Kartha and Ritzy [7] studied the effectiveness of TLD in reducing seismic vibration of a two-storied building frame when it is subjected to horizontal excitations. Analytical study of the undamped frame was carried out using ANSYS program. The various parameters such as damper liquid depth and mass of liquid were studied.

Lotfollahi-Yaghin et al. [8] investigated the efficiency of tuned liquid damper in controlling the dynamic responses of offshore jacket-type platforms under earthquake excitation. This type of dampers consisting of several fluid-containing tanks which is installed on the top side of the platform. Hydrodynamic loads induced by the sloshing of the fluid inside the tank act as resistant forces against the vibration and can therefore control the structural response. They used the finite element–based program ANSYS to model a jacket-type platform having dimensions appropriate for the Persian Gulf climate. Then dynamic analysis was done using time-history approaches subjected to the records of El Centro, Kobe, and Tabas earthquakes. The tuned liquid dampers were optimally designed and after the verification of FE results, the dynamic responses of the jacket-type platforms with and without the tuned liquid damper system were compared.

Das and Choudhury [9] presented the evaluation of the applicability of flat bottom rectangular TLD to low-rise buildings using normal water and a sugar–water solution. It has been found that flat bottom rectangular TLD can satisfactorily control the vibration response of low-rise building model. Also, the higher density sugar–water solution gives better performance in reducing the structural response.

Chang and Mercan [10] studied a modified tuned liquid dampers (MTLD) structure system using Lu's analytical model and Real-Time Hybrid Simulation (RTHS). The capabilities of the analytical model were experimentally verified. It was found that MTLD can exhibit more efficiency than a traditional TLD in mitigating vibrations.

Kamgar et al. [11] investigated the effect of the soil–structure interaction on the response of a single-degree-of-freedom (SDOF) system (Nagasaki airport tower) that is controlled by a modified tuned liquid damper. The obtained results showed that the seismic design of the modified tuned liquid damper (MTLD) system can be more effective to reduce the structural responses during near-fault earthquake.

Dou et al. [12] developed a two-way coupling numerical model to investigate the nonlinear vibration of TLD and elastic supporting structural platform (SSP). Also, they verified the developed model by conducting experiments of TLD interaction with the SSP on a six-degree-of-freedom motion simulator. The bottom plate of the SSP was fixed to the motion simulator and subjected to sinusoidal excitation in the horizontal direction. Effects of TLD on suppressing the nonlinear vibration of SSP were investigated by varying TLD/SSP mass ratio and tuned frequency ratio to explore the coupling mechanism between TLD and SSP in terms of energy damping. The optimal values of the mass and frequency ratios for the coupled TLD-SSP system were proposed in order to achieve the minimum vibration of the platform caused by external loads.

As a part of a research program aiming to control seismic and wind vibrations for high-rise buildings in Egypt, this paper investigates the effectiveness of the TLD in control the vibrations of the building by using liquid (water) in a container at the top floor of the building structures. Experimental works have been conducted on three 10 stories steel building models with scale of 1/25 with and without water tanks. A dynamic ramp wave force with frequency of 1.5 Hz and amplitude of 2 mm is applied on each model using a horizontal shaking table.

2. EXPERIMENTAL PROGRAM

The experimental program investigates the effectiveness of TLD in reducing structural response against the seismic and wind lateral loads, as the liquid's sloshing reduces the structure vibration. The experimental program included testing three steel buildings consisting of 10 floors with a total height 180 cm for each model (Fig. 1). The fabricated steel models are subjected to a dynamic ramp wave force with a frequency of 1.5 Hz and an amplitude of 2 mm on each model using a horizontal shaking table. Every model will be tested in two conditions, one with TLD and the other without TLD.

2.1 Description of the tested steel buildings

Three steel structures buildings fabricated with square columns sections of 7mm x 7mm and spacing of 200 mm in the floor plan. The beams have rectangular sections of 2mm x 7mm and the plate thickness that simulate the floor plan is 1 mm. The model's geometrical data are given in Table 1. The fabricated steel models were scaled to 1/25 of the reinforced concrete buildings with dimensions aspect ratio 1/2, 2/3, and 1 to study the variable parameters. The kinematic scaling factors between the prototype and the models for different parameters are given in Table 2. The summary of the tested buildings and the test ID are shown in Table 3.

(a) Model 1 (b) Model 2 (c) Model 3

Figure 1. Fabricated steel structure models

Table 1. Geometrical data of the models

Item	Floor Plan Dimensions (mm)	Beams Direction	Aspect Ratio	Weight (Kg)
Model 1	450 x 850	Long direction	1/2	63
Model 2	850 x 1250	Long direction	2/3	133

Model 3	850 x 850	X-direction	1	87

Table 2. Kinematic scaling

Mass	1	Acceleration	1	Length	λ
Force	λ^3	Shear wave Velocity	$\lambda^{1/2}$	Stress	λ
Stiffness	λ^2	Time	$\lambda^{1/2}$	Strain	1
Modulus	λ	Frequency	$\lambda^{-1/2}$	EI	λ^5

where λ = (Original/scaled) dimension

Table 3. Design Summary of the tested steel buildings

	Test ID	Model No.	Aspect Ratio	Beams Directions	TLD Weight (Kg)	Weight TLD / Weight of structure
Without TLD	TLD0-M1-R1/2-BX	1	1/2	Long-Directions	0	0
	TLD0-M2-R2/3-BX	2	2/3	Long-Directions	0	0
	TLD0-M3-R1-BX	3	1	X-Directions	0	0
With TLD	TLD1-M1-R1/2-BX	1	1/2	Long-Directions	5	8%
	TLD1-M2-R2/3-BX	2	2/3	Long-Directions	20	15%
	TLD1-M3-R1-BX	3	1	X-Directions	10	11.5%

2.2 Description of the experimental setup

The experimental setup consisting of a shaking table with dimensions 1300 x 1700 x 25 mm connected to input dynamic loads machine as shown in Fig 2 which use fixed frequency loading protocol at a frequency of 1.5 Hz and an amplitude of 2 mm. Simulation for tuned liquid damper (TLD) is a tank with dimensions 440 mm x 220 x 110 mm that its empty weight is 0.5 kg, then the tank is filled with water to get 5 kg, 20 kg and 10 kg that will be used in the experimental protocol as shown in Fig. 3. There are six cases to be tested with ID shown in Table 3.

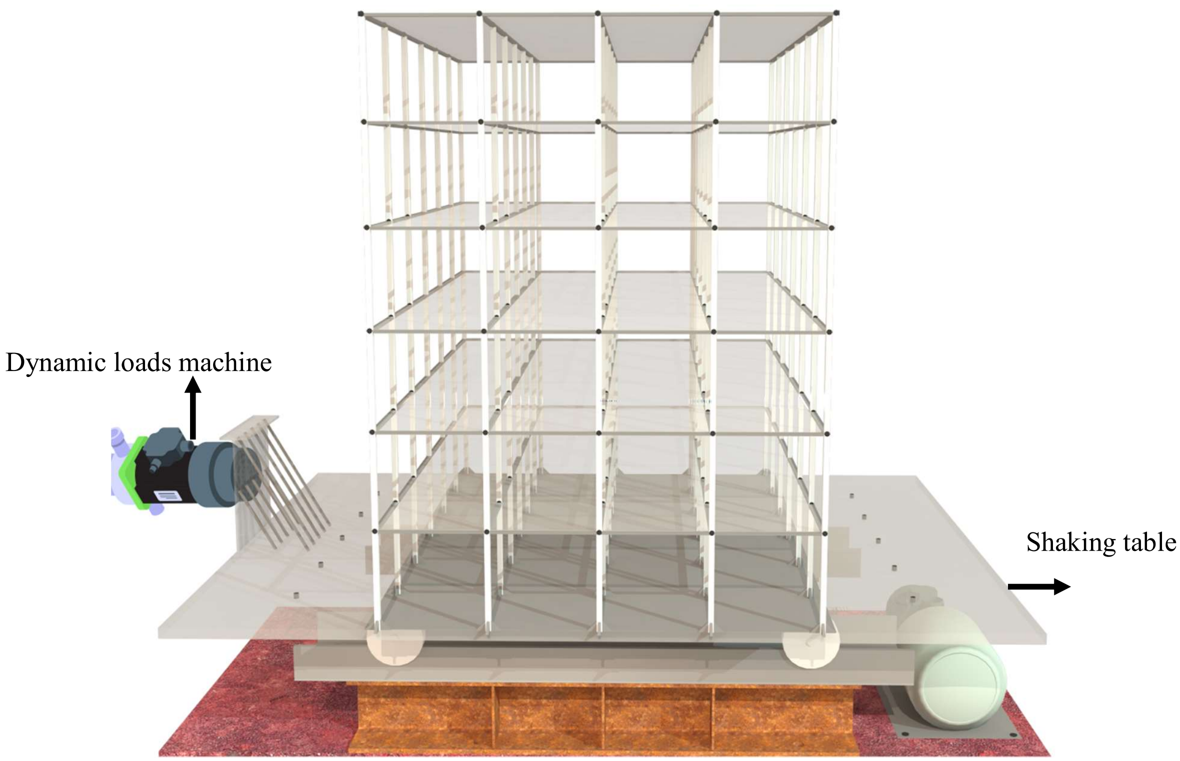


Figure 2. Description of the experimental setup

The displacements are measured using four linear variable differential transformers (LVDTs), two at the base plate and the other two at the top of the building model. The acceleration is measured using two accelerometers, one accelerometer is at the base of the building and the other at the top and are attached to the data acquisition system as shown in Fig. 3. The LVDTs and accelerometers are attached to the data acquisition system. The data acquisition system is connected to the vibration analyzer software to analyze the experimental data (Figs. 4 and 5).

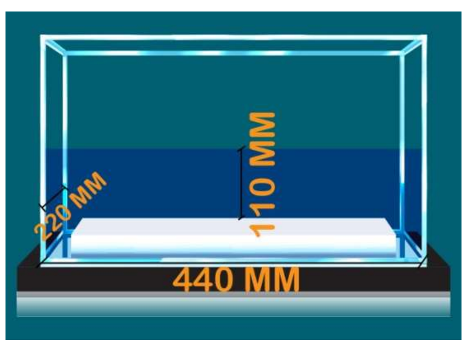
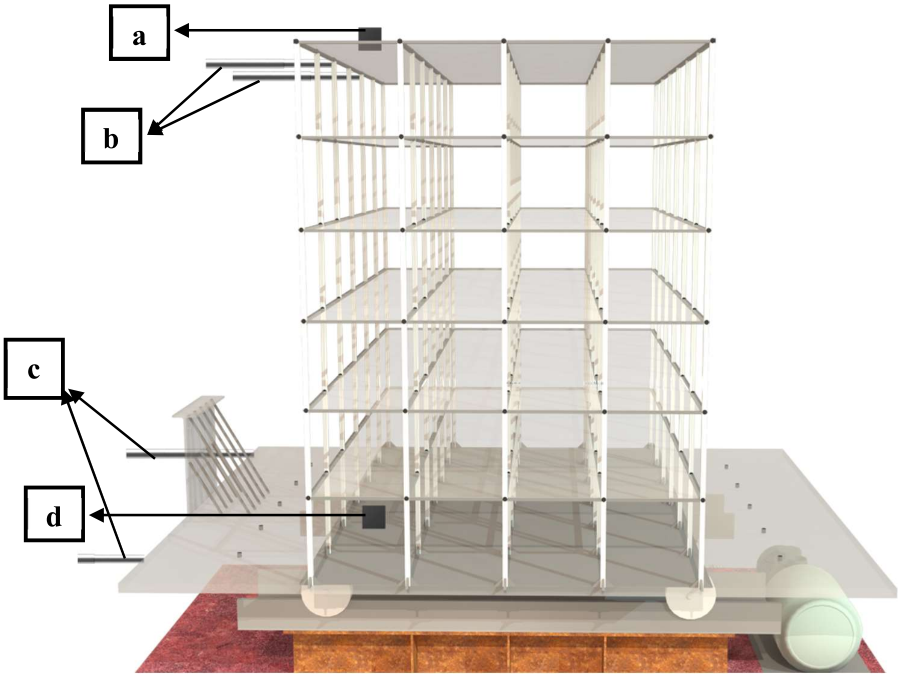
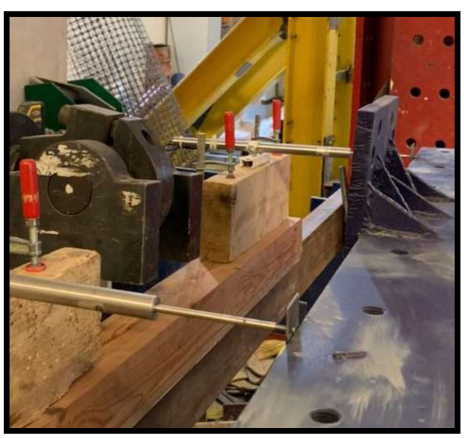


Figure 3. Dimensions of water tank (10 Kg)

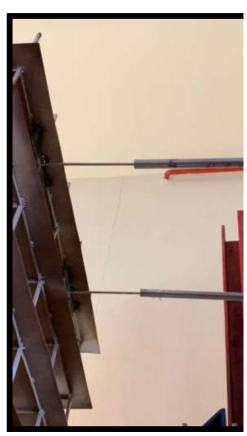


a: The accelerometer is at the top of the building
b: Two linear variable differential transformers at the top of building
c: Two linear variable differential transformers at the bottom of building
d: The accelerometer is at the base of the building

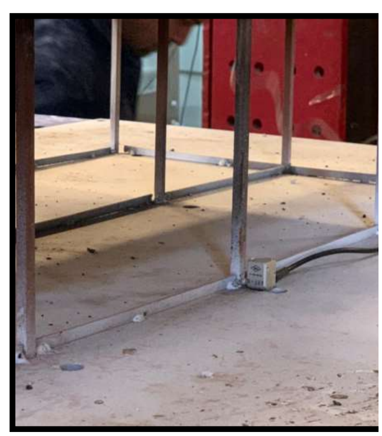
Figure 4. Measurement devices



LVDTs at the bottom

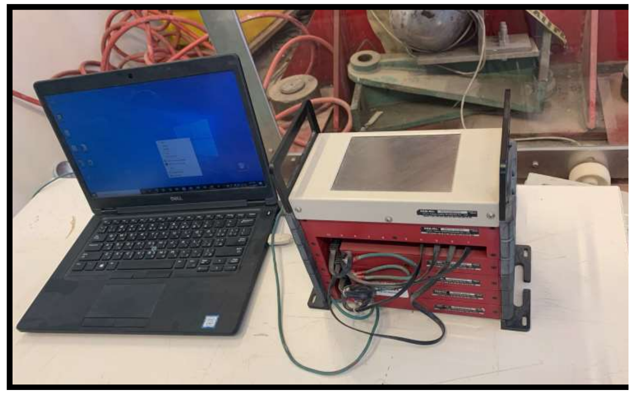


LVDTs at the top



Accelerometer at the bottom

Dynamic loads input machine



Data acquisition system

Figure 5. Experimental setup components

2.3 Loading protocol

The loading protocol is fixed during all the experimental works that is a dynamic ramp wave force with a frequency of 1.5 Hz and an amplitude of 2 mm by using dynamic loading machine and acting on the horizontal shaking table during the tested six cases as shown in Fig 6 that display the acceleration with time that recorded with the accelerometer which was tied to the shaking table. Figure 7 display the corresponding displacement with time which recorded from the bottom LVDTs tied to the shaking table.

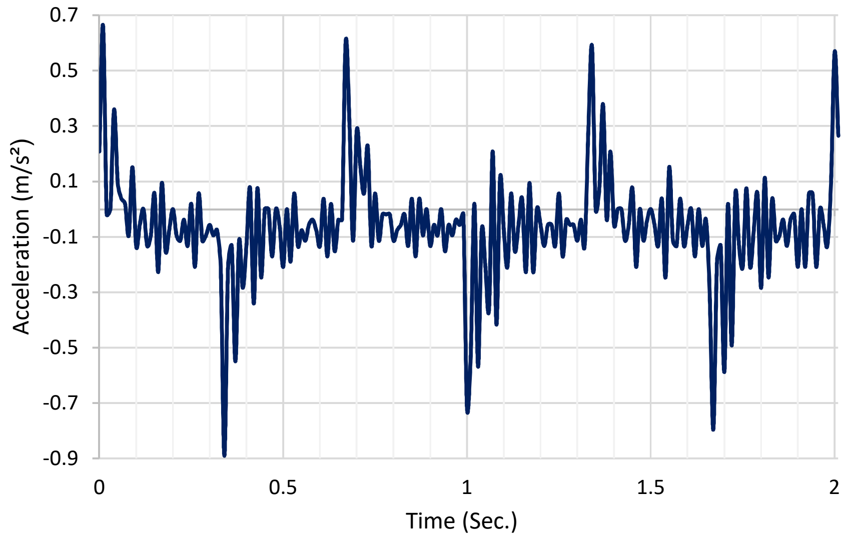


Figure 6. Loading protocol (Acceleration with Time)

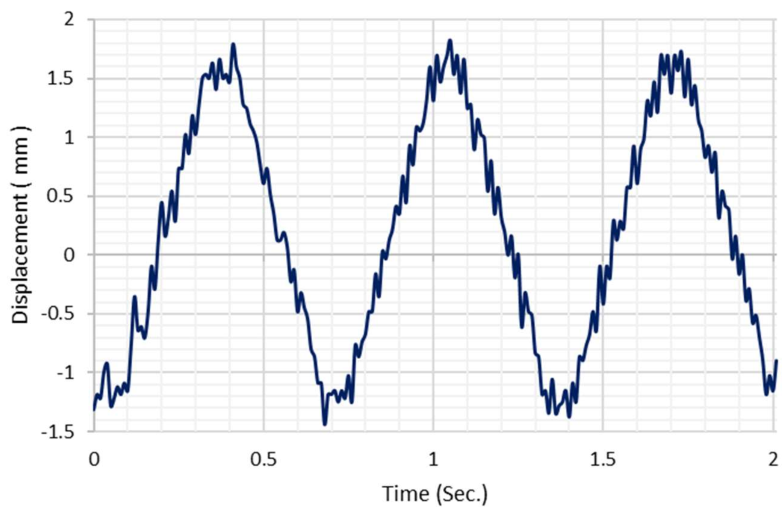


Figure 7. Loading Protocol (Displacement with Time)

3. RESULTS AND DISCUSSION

The main objective of the present analytical and experimental studies to investigate the effectiveness of TLD in reducing structural response against the seismic and wind lateral loads as the liquid's sloshing reduces the structure vibration. The experimental runs six cases with and without TLD.

3.1 Model 1: Comparison between the cases TLD0-M1-R1/2-BX and TLD1-M1-R1/2-BX

Figures 8 and 9 show the comparison between the acceleration and displacement at the top of the building that was recorded from the accelerometer and LVDTS, respectively and it is clear that the model TLD0-M1-R1/2-BX has acceleration at the top floor more that for the model TLD1-M1-R1/2-BX. Therefore, the existence of the TLD increases the resistance of the building against the lateral loads and decreases the acceleration of the building. The weight of TLD was 5 Kg which was 8% of the weight of the structure and percentage improvement of the behavior of the building against lateral loads is 23%. It is observed that, the existence of TLD and sloshing of water increased the damping factor of the model.

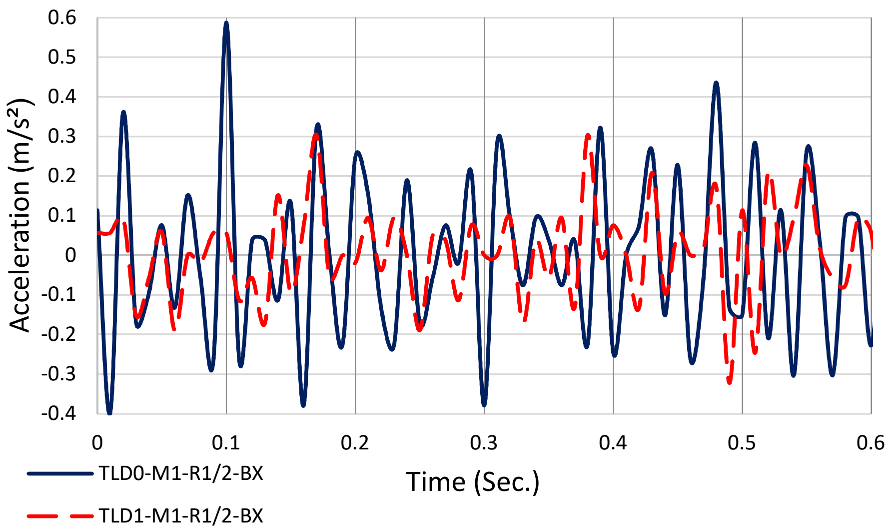


Figure 8. Comparison of acceleration at top for model 1

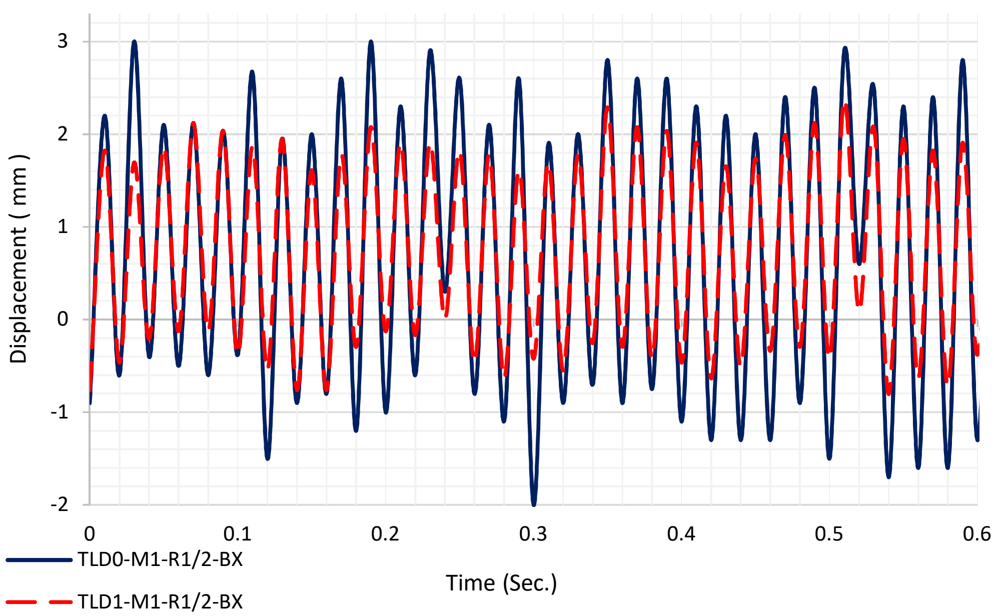


Figure 9. Comparison of top displacement for model 1

3.2 Model 2: Comparison between the cases TLD0-M2-R2/3-BX and TLD1-M2-R2/3-BX

At this experimental test, both the aspect ratio of the building and the weight of the TLD are increased. The weight of TLD to the weight of the building was 15%. As shown in Figs. 10 and 11, it was found that the percentage improvement in the behavior of the building against lateral loads between the test models TLD0-M2-R2/3-BX and TLD1-M2-R2/3-BX was 48% which is more than the previous model 1.

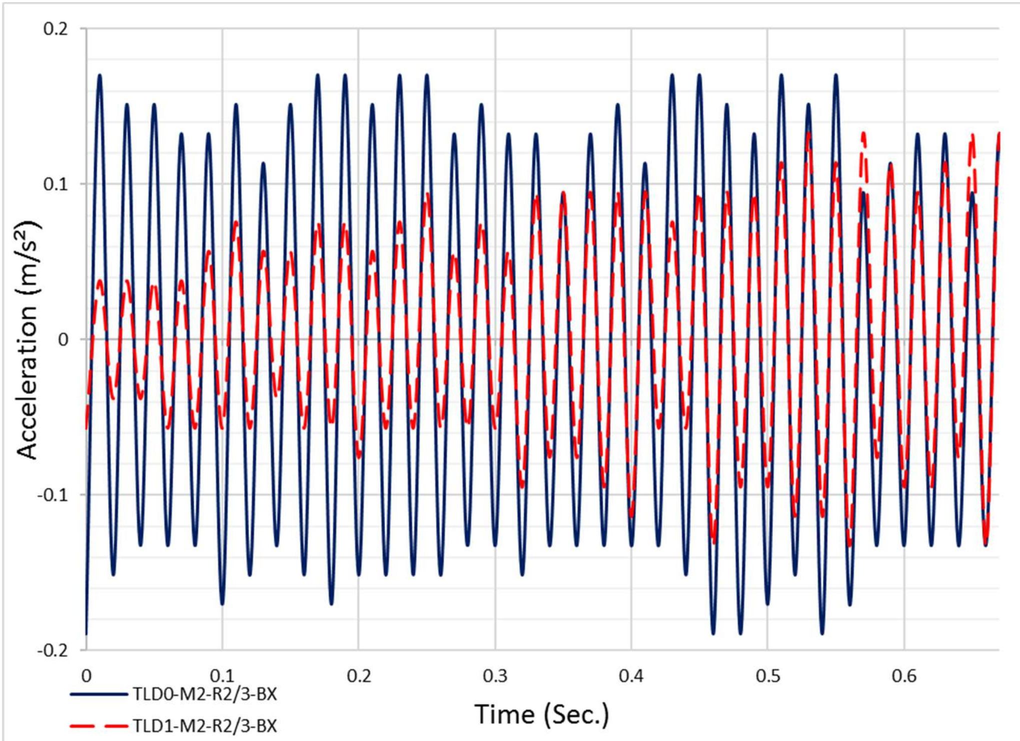


Figure 10. Comparison of acceleration at top for model 2

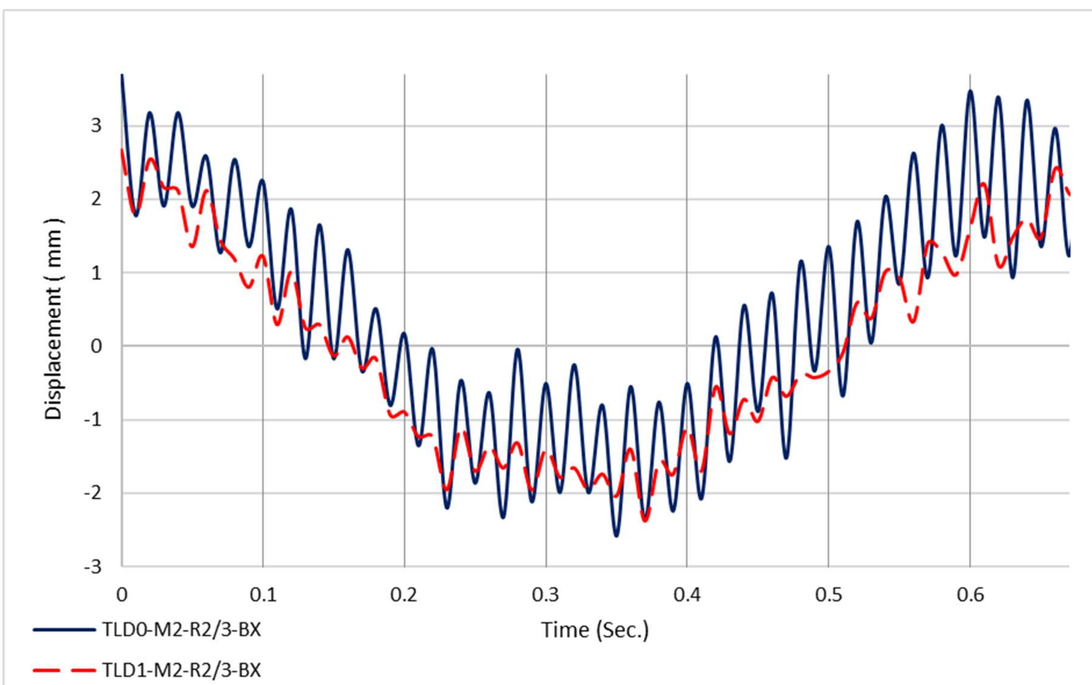


Figure 11. Comparison of top displacement for model 2

3.3 Model 3: Comparison between the cases TLD0-M3-R1-BX and TLD1-M3-R1-BX

At this experiment, structure models have an aspect ratio of one and 11.5% weight TLD to the weight of the structure are tested. As shown in Figs. 12 and 13, it was found that the percentage improvement in the behavior of the building against lateral loads between the tested models TLD0-M3-R1-BX and TLD1-M3-R1-BX was 18.2%. Figure 12 shown that the difference is stable, which increases then decreases then increases again with steady difference acceleration.

It was found that the effectiveness of the steel building against the lateral loads was effective with 18.2%. Figure 13 display the comparison between the acceleration at the top of the building for the two tests (TLD0-M3-R1-BX and TLD1-M3-R1-BX), which were measured by using the accelerometer. It was founded that using TLD with a percentage weight of 11.5 % at an aspect ratio of building 1 gives us the best behavior of the building against the lateral loads with a percentage of 18.2%.

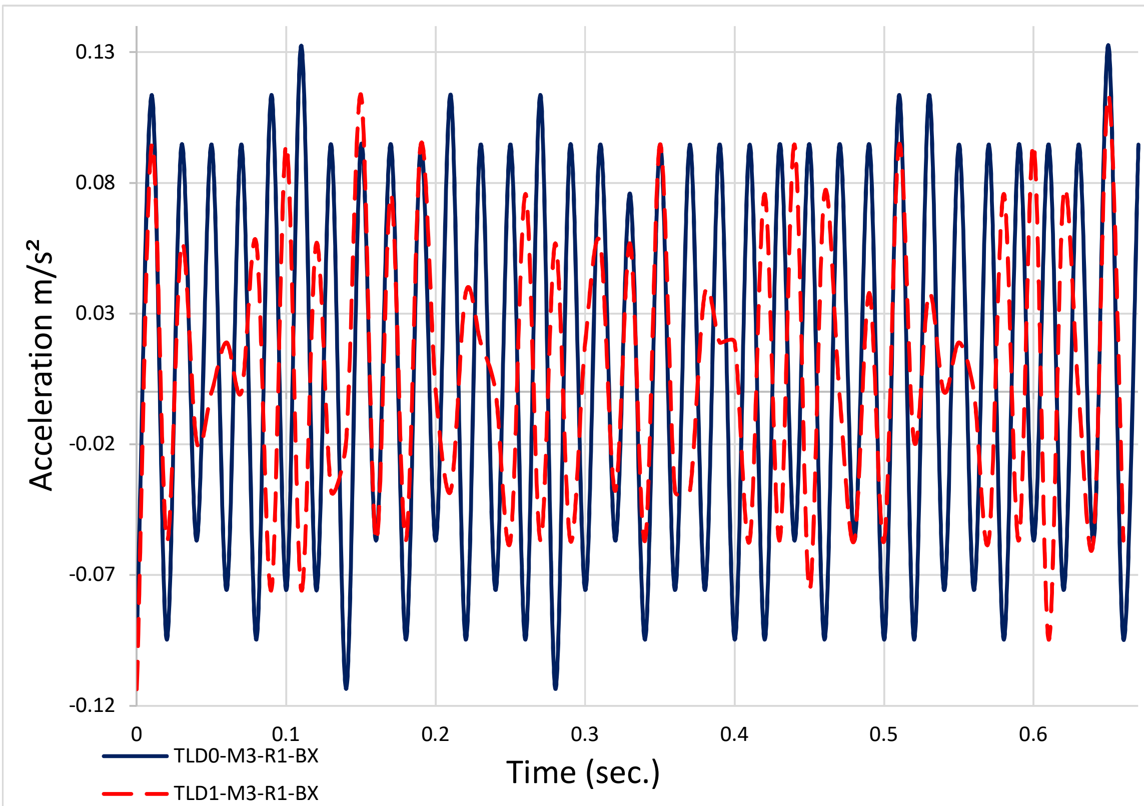


Figure 12. Comparison of acceleration at top for model 3

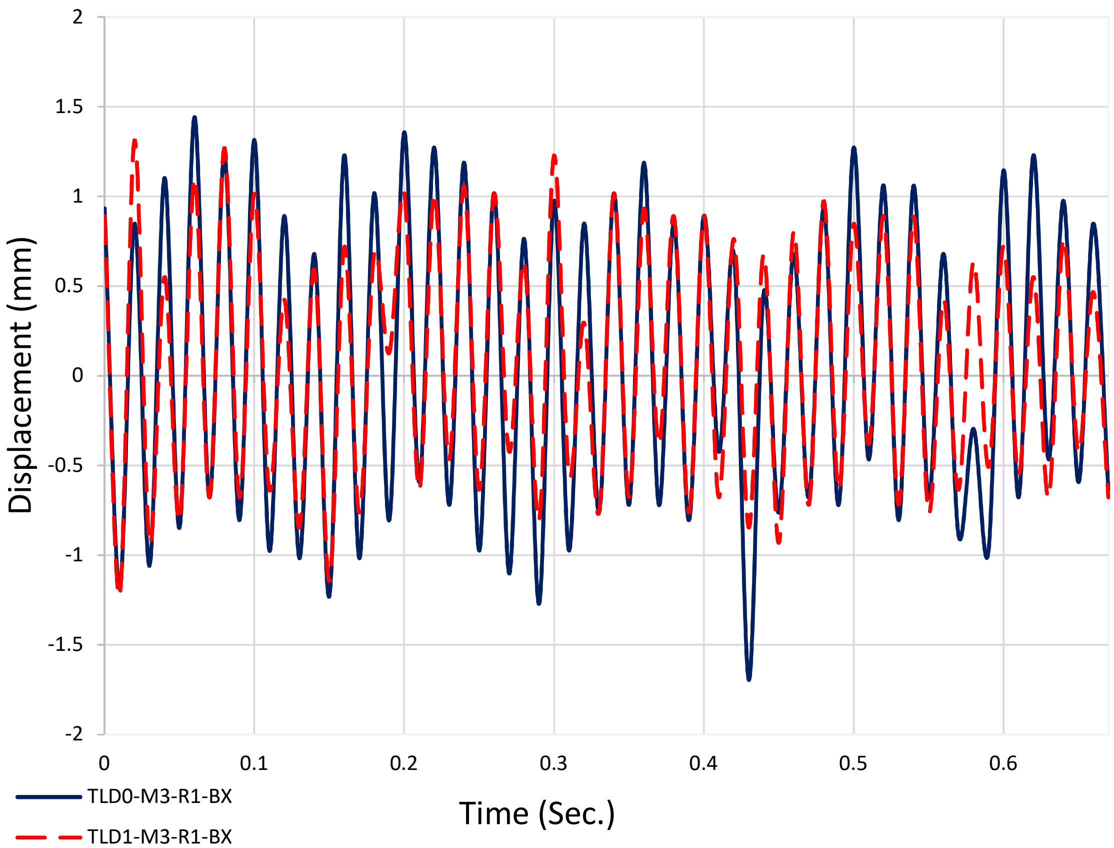


Figure 13. Comparison of top displacement for model 3

3.4 Damping ratio for model 2

A comparison at the end of the tests named TLD0-M2-R2/3-BX and TLD1-M2-R2/3-BX is made when the dynamic loads input machine was stopped to calculate the damping ratio as follows:

$$\zeta = \frac{\delta}{2\pi} \tag{1}$$

$$\delta = lin\frac{u_1}{u_2} \tag{2}$$

where ζ is damping ratio, u_1 is the peak displacement without TLD, and u_2 is the peak displacement with TLD.

As shown in Fig. 14, the numbers of cycles equal six, u_1 = 0.575 mm and u_2 = 0.283 mm. Therefore, the calculated damping ratio is approximately 1.9 %.

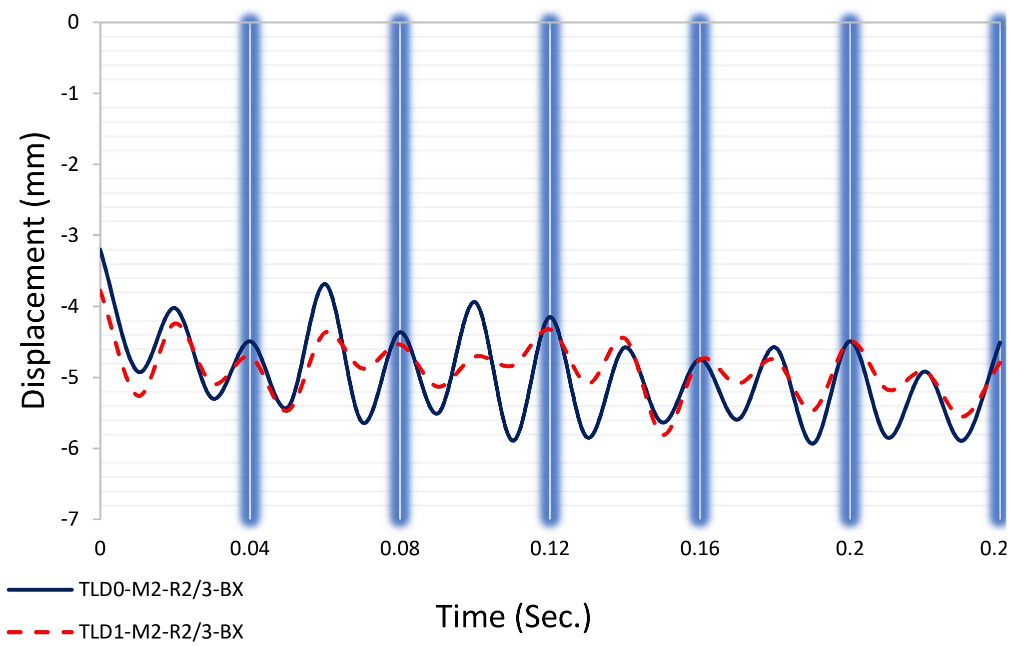


Figure 14. Comparison of displacements between TLD0-M2-R2/3-BX and TLD1-M2-R2/3-BX after applied dynamic force is stopped

3.5 Calculation the effectiveness of TLD

The main equation to calculate the efficiency percentage is:

$$\psi = \frac{x_o - x_{TLD}}{x_{TLD}} \quad (3)$$

where ψ is the efficiency percentage for the steel structures models, x_o is the displacement without TLD and x_{TLD} is the displacement with TLD.

Referring to Figs. 9,11 and 13 shown above, the calculated efficiency percentages are 23%, 48% and 18% for models 1,2 and 3, respectively.

4. CONCLUSIONS

The main aim of this paper is to determine the effectiveness of a Tuned Liquid Damper (TLD) to control the structure's vibration. Analytical and experimental works for three models have been conducted to investigate the effectiveness of the TLD in reducing the displacement of the top story level of the structure. The following conclusions are drawn from the present study:

1. It is observed that TLD increases the structure's effective damping when the structure is subjected to lateral forces.
2. It is observed that water sloshing of TLD has a significant factor in increasing the effectiveness of the TLD.
3. TLD decreases the acceleration and the displacement of the structure. This is allowing the structural engineers to enhance the performance of high-rise buildings under later loads.
4. For Model 1, it is observed that when using TLD with weight 8.0 % of the structure weight, there is a decrease in the top-level displacement by 23%.
5. For Model 2, it is observed that when using TLD with weight 15.0 % of the structure weight, there is a decrease in the top-level displacement by 48%.
6. For Model 3, it is observed that when using TLD with weight 11.50 % of the structure weight, there is a decrease in the top-level displacement by 18.20%.
7. Based on the obtained results, the calculated damping ratio for model 2 is about 1.9 %

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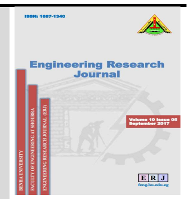

QoS Aware Resource Allocation for D2D Communication in mmWave 5G Underlay Network

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Abstract: Device-to-device (D2D) communication is considered the most promising technology for 5G networks which enables high speed communication in low latency time. D2D communications allows direct links without using central base stations (BSs). Millimeter wave (mmWave) technology is characterized by short distance directive propagation, and more available spectrum for communication. Integrating D2D communication with mmWave technology significantly enhances the system performance and reaches the demand for high capacity. In mmWave D2D communications 5G underlay networks, multiple cellular users (CUs) and D2D users co-exist. Since D2D pairs can utilize the spectrum assigned to CUs, efficient resource allocation algorithms are required. In this paper, a resource allocation problem in mmWave D2D communications 5G underlay network is investigated. A new resource allocation scheme that allows D2D pairs to share resource blocks (RBs) with cellular users is proposed. The proposed scheme prevents congestion on over a few resource blocks while the rest of resource blocks remain vacant through identifying a set of recommended resource blocks for each D2D pairs. The proposed scheme reduces interference by excluding interferer D2D pairs from resource blocks sharing process for each D2D pairs. The proposed scheme maximizes the spectral efficiency while satisfying minimum QoS requirements. The simulation results show the superiority of the proposed scheme in terms of spectral efficiency and outage capacity.

Keywords: D2D communications, mmWave communications, resource allocation, 5G.

1. Introduction

With the increase in the number of devices connected to multimedia networks, the flow of mobile data traffic and the capacity required for mobile communications increase and becomes a major challenge to meet the large bandwidth requirements. Many studies have been conducted to exploit new spectrum bands, including millimeter wave (mmWave), to compensate the scarcity of operational radio frequency resources.

The mmWave is considered as the promising candidate for implementing 5G technology networks to improve the energy efficiency and usage of spectrum. The mmWave network exhibits higher bandwidth in range of 1 GHz and large gigabit data rate due to its small wavelength signals [1-3].

The deploying of D2D communications enables direct communication between proximity user devices without resorting to the central controller Base Stations (BSs),