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ScienceDirect
Procedia Engineering 95 (2014) 204 – 212
Procedia Engineering
www.elsevier.com/locate/procedia

2nd International Conference on Sustainable Civil Engineering Structures and Construction Materials 2014 (SCESCM 2014)

Tuned Mass Damper On Reinforced Concrete Slab With Additional "X-*Shaped Metal*" Absorber

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Abstract

The problem of excessive structural floor vibrations due to human activities is critical because it results in excessive interference response at specified frequencies. Excessive vibrations can occur in slab systems with low stiffness or a low damping ratio. Increasing the stiffness of the slab is one method which can be used to reduce excessive floor vibration. In some cases this is, however, not possible because the additional mass of the stiffening structure will indirectly increase the overall mass of the structure; therefore, it will increase the stress of the structural elements. Other methods are using passive, active and semi-active dampers. This study used a passive damper system named *tuned mass damper* (TMD) with an additional *"X-shaped metal"* absorber as an additional damper which was applied to the concrete slab having a dimension of 4 m in length, 0.90 m in width and 0.08 m in thickness. This research showed that the mass ratio of the TMD to slab (μ) of 2.00 % with a spring stiffness (k) of 80.281 kN/m could increase the damping ratio of the slab from 1.82% to 2.06%. The TMD with the additional *"X-shaped metal"* absorber resulted in the damping ratio of 3.40%.

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*Keywords:*Floor vibration, Tuned mass damper, Vibration, *"X-Shaped metal"* absorber

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Peer-review under responsibility of organizing committee of the 2nd International Conference on Sustainable Civil Engineering Structures and Construction Materials 2014
doi:10.1016/j.proeng.2014.12.180

1. Introduction

Human activities on the building floor can sometimes be disruptive. Excitation can stimulate the floor resonance and cause vibration levels that potentially disturb occupants. The excessive vibration can occur on floor systems with a low stiffness and low damping ratio. These problems are often ignored in design, only to be identified after the completion of the structure. Increasing the stiffness of the floor is one way that can be used to reduce the excessive vibration; however, in some cases such a method is not possible because the mass of the stiffening structure will indirectly increase the stress of the structural elements. Additional supports to shorten the span in between the existing columns are sometime impossible for functional or aesthetic reasons [1]. Other methods include using active, semi-active and passive dampers. Compared to other systems, an active damper has better performance, but has a disadvantage in terms of maintaining power supply and cost of installation. A passive damper depends only on the result of the reaction of potential energy which is generated by the structural response, while a semi-active damper system is a combination between the active and passive dampers.

A tuned mass damper (TMD) is a vibration energy control tool with a passive system,consisting of a mass smaller than that of the structure. The spring(s) and mass are mounted on the structure to reduce unwanted vibrations [2-5]. The first application of tuned mass dampers to an engineering problem was presented by Frahm in 1909. He used undamped vibration absorbers for reducing the rolling motion of the ship, also for the reduction in vibration of the hull of the ship [6,7]. Fig. 1 shows some TMD types for buildings [8]. The TMD has many advantages over the other dampers in terms of reliability, efficiency and low maintenance costs. The TMD is generally positioned in two possible directions: vertical and horizontal, where the application depends on the disruptive mode behavior. The vertical TMD in its operations is usually supported by a steel spring [9,4], and the frequency may be tuned by varying the mass upon the spring while the horizontal TMD, which is based on the response of the horizontal spring stiffness, in some cases is set as a pendulum system.

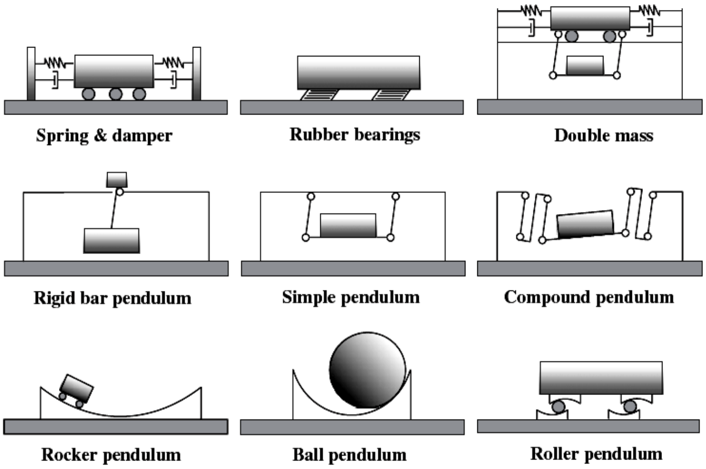


Fig 1. TMD types for buildings [8]

The TMD will be effective when it is tuned to the natural frequency of the main structure; otherwise, it will aggravate and even disrupt the structure itself. The TMD design relies on several considerations, such as: material of mass (concrete or steel), the available space for installation, the target frequency, and architectural restrictions [9].

2. Research Methodology

This study used a reinforced concrete slab with a dimension of 4 m in length, 0.90 m in width and 0.08 m in thickness as shown in Fig. 2 The response of the slab to the vibrations was obtained by a step by step forced vibration technique where a mechanical exciter with a capacity of 1 Hp was attached on a slab. The slab vibration response was captured by an accelerometer through a data acquisition system. The time domain as well as the frequency domain was analyzed using available software in the computer. A total of two accelerometers were used here and were positioned at 0.25L and 0.5L.

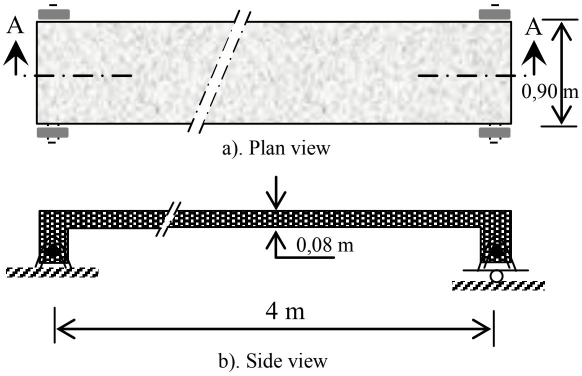


Fig 2. Reinforced concrete slab models

The steady state test applied in this experiment, as illustrated in Fig. 3, is a step by step excitation method with a varying frequency starting from low to high. The higher amplitude reveals the natural frequency of the slab of the first mode, while the damping ratio of the slab was determined by free vibration test. The setup of free vibration test was similar to the steady state test. A mass of 40 kg was hung under the mid span of the slab and suddenly released, which caused vibrations on the slab. A recording started a few seconds before releasing the mass. From the recorded signal the damping ratio of the slab was determined by the logarithmic decrement method as seen in the equation below.

$$\xi = \frac{\delta}{\sqrt{(2\pi)^2 + \delta^2}} \tag{1}$$

where

$\delta = \frac{1}{n}\ln\left(\frac{x_0}{x_n}\right)$, ξ is the damping ratio, δ is a constant known as the logarithmic decrement factor, x_0 defines the amplitude for the 0th cycle, x_n is the amplitude for the successive nth cycle which occur at the time t, in second, and n is the number of peaks of complete oscillations made in the time, t. (Fig. 4)

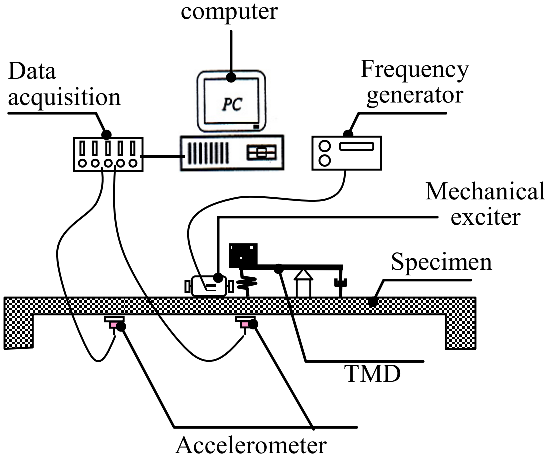


Fig 3. Steady state testing sketch

The logarithmic decrement represents the rate at which the amplitude of a free damped vibration decreases, and it is defined as the natural logarithm of the ratio of any two successive amplitudes. It is obtained from the time response of under damped vibration.

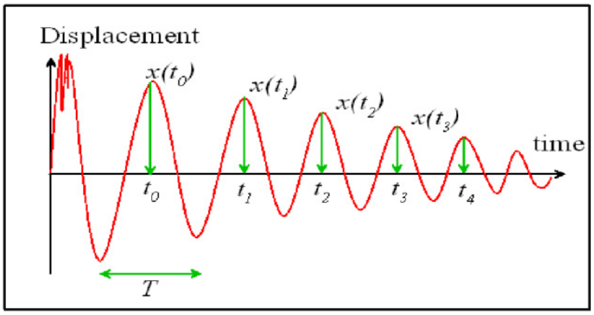
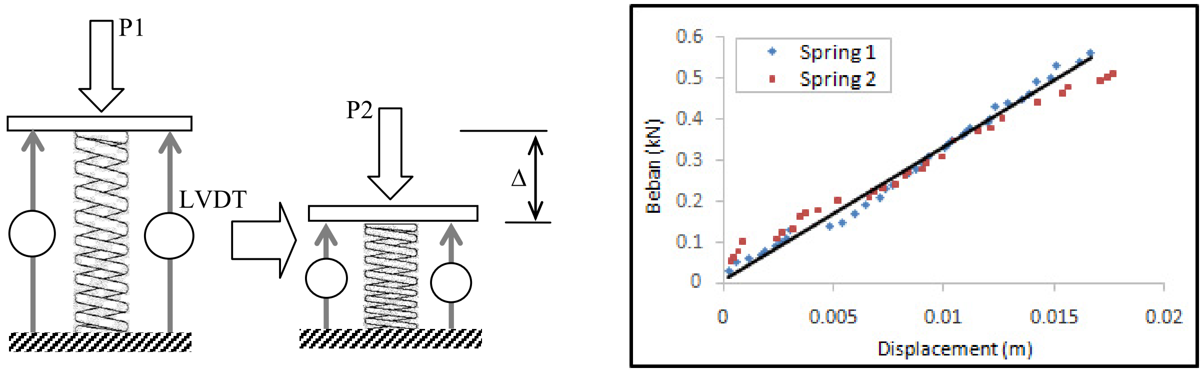


Fig 4. Damped harmonic oscillation

2.1. Analytical Model and Design of Tuned Mass Damper (TMD)

The TMD is a structural control device which is used to reduce the amplitude of vibration in buildings and mechanical systems. The use in structures is especially to spare building occupants from inconveniences. The TMD consists of a mass, a spring with or without dampers, and is attached on the main structure to provide a system with multiple degrees of freedom (MDOF systems).



(a). Spring test (b). Load-displacement relationship

Fig 5. Spring stiffness test

The TMD system in this study was made of a steel plate with a dimension of 35x 35x1.2cm^3, and a spring, 12 mm in diameter and consisting of 7 spindles. The spring stiffness (k) can be obtained from a test as shown in Fig. 5a. The magnitude of the load (P) will cause the deflection in the spring of (Δ) so that the spring stiffness can be calculated by the equation below:

$$k = \frac{P}{\Delta} \tag{2}$$

The relationship between P and Δ is illustrated in Fig. 5b The TMD mass was set as such that the acquired TMD frequency would be around the frequency resonance of the slab was, ω_1 = 6.96 Hz. Calculating the dynamic properties of the slab with a mass m_1 of 691 kg and the effective mass of TMD m_2 of 13 kg, resulted in a mass ratio μ of 2.0%.

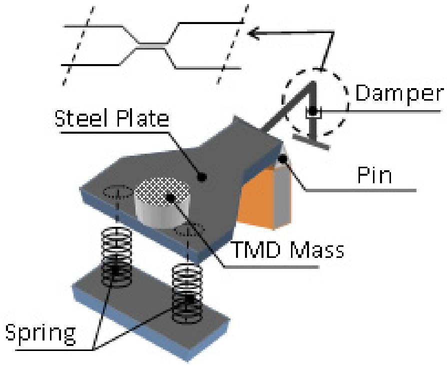


Fig 6. The TMD Systems

When we designed a TMD, it was found that the greater the mass of the TMD (m_2), the more effective the system. For practical purposes the mass ratio of TMD to the system (μ) may be freely determined between 2.0% and 6.7% [4]. The TMD response is out of the excitation phase, which results in the force that partially removes the vibrational excitation. Fig. 6 shows a TMD system with additional *"X - shaped metal"* absorbers attached on the back of the TMD. The additional *"X- shaped metal"* absorbers were made of steel plates of 2x1mm with a yield stress of 332.84 MPa. The idea of utilizing metallic dampers in a structure to absorb the vibration energy started with the conceptual and experimental work of Kelly et al.(1972) [10,11]. The TMD frequency was usually set on the first mode of the slab system. A model of two degrees of freedom can be used here to represent the dynamic behavior of the floor-TMD system as shown in Fig. 7 The equation of the motion of the TMD-slab model is:

$$\begin{aligned}&(m_1+m_2)\ddot{x}+m_2 l\ddot{\theta}+c_1\dot{x}+k_1 x=F_0\\&m_2 l\ddot{x}+m_2 l^2\ddot{\theta}+c_2 a^2\dot{\theta}+k_2 l^2\theta=0\end{aligned} \tag{3}$$

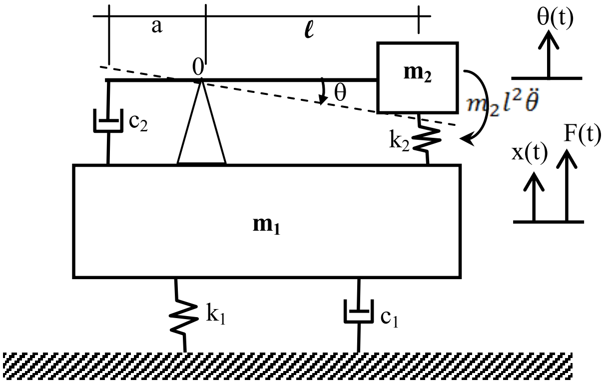


Fig 7. TMD model of the slab

where m_1, k_1 and c_1 are respectively the mass, stiffness and damping of the slab, whereas the TMD has a mass of m_2, stiffness of k_2, and a damping coefficient c_2, as shown in Fig. 7, $\ddot{x}$, $\dot{x}$ and x are respectively acceleration, velocity and displacement of the floor. The $\ddot{\theta}$, $\dot{\theta}$ and θ are rotational acceleration, velocity, and displacement of the TMD, respectively. The slab was subjected to a force function F(t) as a representation of human activities such as walking, running, and dancing.

The force, the response of the slab, and response of the TMD may be defined as shown below:

$$\begin{aligned}&F=F_0 e^{i\omega t}\\&x=Xe^{i\omega t}\\&\theta=\theta e^{i\omega t}\end{aligned} \tag{4}$$

Where ω = excitation frequency. The dynamic system parameters are defined as f_1 = slab natural frequency

(Hz) = $\omega_1/2\pi$ = $(1/2\pi)\sqrt{k_1}/m_1$; f_2= TMD natural frequency (Hz) = $(l/2\pi l)\sqrt{k_2}/m_2$; μ = mass ratio = m_2/m_1; f_r = frequency ratio of the TMD to the slab = f_2/f_1; ξ_1 = damping ratio of the slab = $c_1/2m_1\omega_1$; and ξ_2 = damping ratio of TMD = $c_2/2m_2\omega_2$. Substituting equation (4) into equation (3), the floor displacement response factors of the TMD is as follows:

$$X=\frac{\left(k_2l^2+c_2a^2\omega+m_2l^2\omega^2\right)F_0}{\Delta} \tag{5}$$

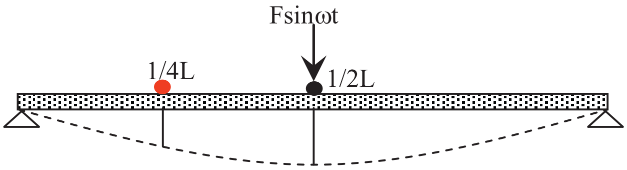
$$\theta=\frac{\left(-m_2l\omega^2\right)F_0}{\Delta} \tag{6}$$

where

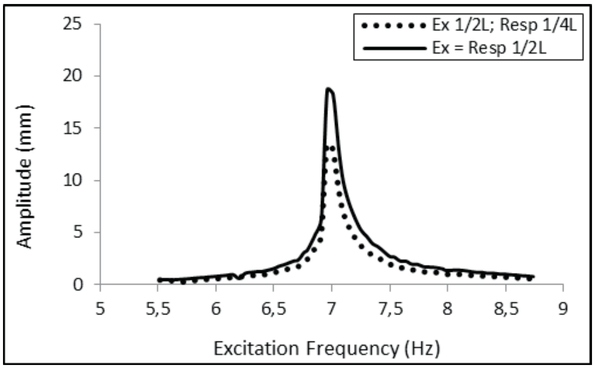
$$\Delta=(k_1+c_1\omega+(m_1+m_2)\omega^2(k_2l^2+c_2a^2\omega+m_2l^2\omega^2)-(m_2l\omega^2)^2$$

3. Results And Discussion

The response of the slab system to the vibration excitation in the frequency domain of the first mode is shown in Fig. 8b The vibration excitation was applied at midspan, at a distance of 1/2L from the supports and the acceleration responses were measure data distance of 1/4L and 1/2L from the supports.



(a). The first mode shape of slab



(b). Slab frequency on $X_{1/2L}$ and $X_{1/4L}$

Fig 8. Slab response due to vibration excitation

Two acceleration spectra in Fig. 8a were obtained from recording the signal at two different places (1/4L and 1/2L). The curve with the dashed line is the acceleration response at 1/4L and the solid line curve was recorded at a distance of 1/2L from the supports, both with the same vibration. Both peak acceleration responses at 1/4L and at 1/2L indicate the resonance frequency of the first mode (6.96Hz). The larger amplitude (18.68mm) indicates the middle span position of the slab, while the lower one (13.36mm) represents the quarter span position.

The TMD was be positioned at about the maximum response of first natural frequency of the slab as shown in Fig. 9 In this case the TMD frequency is set at 6.74Hz, which is very close to the resonant frequency of the slab without the TMD. The TMD eliminates the resonance of the slab at a frequency of 6.96Hz, but it creates two other peaks (6.25Hz and 7.79Hz) adjacent to the existing resonant frequency. The TMD mass and the spring control the frequency as well as the magnitude of the response function. The TMD clearly influences the amplitude response of the first resonant frequency down to 0.68 at 6.96Hz. The amplitude response of the original system is decreasing from 18.68mm to 0.68mm, but it creates additional amplitudes at its surrounding with amplitudes of 12.93 mm.

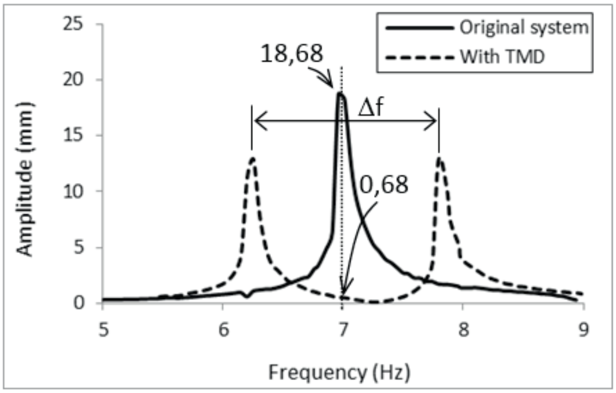
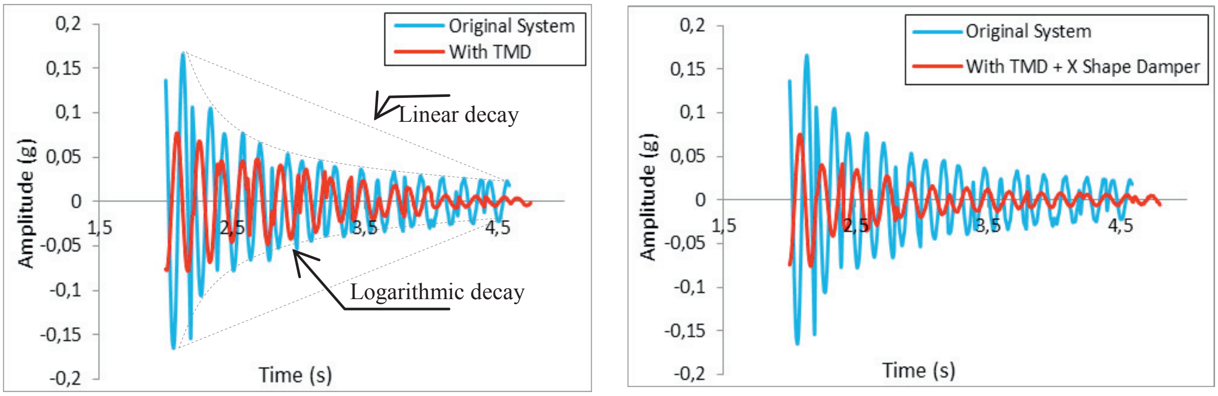


Fig 9. Slab response with and without TMD

3.1. Effects of the *X-Shaped metal absorber* on the TMD System.

It was shown from the free vibration experiment, amplitudes of the slab system decrease due to application of the damper in (Fig. 10a). It shows that the time domain response is slightly different due to the application of the *"X shaped metal"*absorber (Fig. 10b). The shape of this decrease indicates a viscous damping type. The larger the damping ratio the greater the decay,and vice versa. Fig. 10b shows the time domain response of acceleration of the slab with the additional "*X-shaped metal*" absorber. The amplitude reduces significantly in comparison to Fig. 10a.



(a). Acceleration response of the slab with TMD

(b). Acceleration response of slab with TMD and *"X- shaped metal"* absorber

Fig 10. Comparison of acceleration response of the slab without and with TMD and *"X shaped metal"* absorber

Fig. 11 shows graphically the effect of the additional TMD and *"X-shaped metal"* absorber on the damping ratio of the slab. The damping ratio of thes lab increased from 1.82% to 2.06% and 3.40% respectively for the slab without TMD, with TMD and with TMD plus an additional *“X-shaped metal”*absorber. The energy of the vibration of the slab is absorbed by the mass of the TMD and the additional *“X-shaped metal”* absorber. When the *"X-shaped metal"* absorber yields, then an energy dissipation process will occur. So, the increasing in damping here is due to the yielding of the additional *“X- shaped metal”*absorber.

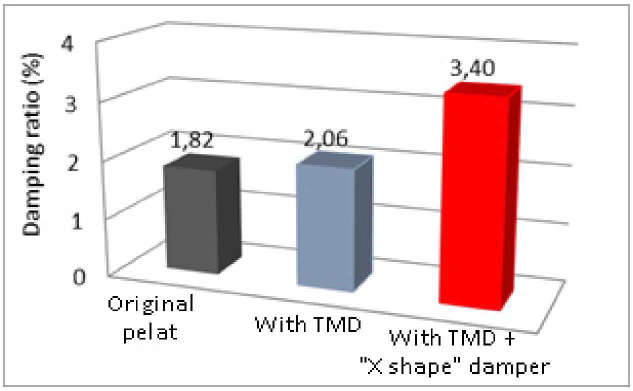


Fig 11. Damping ratio of slab

4. Conclusion

This study has presented the application of the TMD systems as a device to control the excessive vibration in the slabs due to human activities. An experimental model in the laboratory has been developed here to study the dynamic behavior of the slab when the TMD with an additional *"X-shaped metal"* absorber was applied. From this research, it can be concluded that:

1. A TMD system will be able to optimally reduce the excessive vibration when the TMD frequency is set to near that of the resonance frequency of the main structure.
2. With the TMD mass ratio of 2.0%, the TMD is able to reduce the amplitude of the main system (slab) from 18.68 mm to 0.68 mm at the original natural frequency, but it stimulates additional amplitudes of 12.93 mm at its surroundings.
3. The TMD is able to increase the damping ratio of the slabs. From this study it was proven that the increase of the damping ratio was 1.82%, 2.06% and 3.40% respectively for the slab without TMD, with TMD, and for the slab with the TMD and an additional *"X- shaped metal"* absorber.

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