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Optimal Tuned Mass Damper Properties to Reduce the Response of Floors Subjected to Rhythmic Induced Loads

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Abstract. Building floors designed for gyms can present high level of vibration due to human induced dynamic load during rhythmic activities. This problem can be solved by increasing the structural stiffness and damping, or by using passive energy dissipation devices known as tuned mass damper (TMD). This paper analyses a steel-deck slab subjected to dynamic load due to rhythmic activities and relates the maximum acceleration of the model with the material damping ratio. Four material damping combinations are analyzed and a two-dimensional equivalent orthotropic plate is proposed to represent the slab tridimensional behavior. A parametric study is performed, where an optimization process is employed to find the best combination of stiffness and mass of a tuned mass damper that minimizes the mass required to achieve a given vibration reduction. The vibration attenuation ranges from 10% up to 80% reduction of maximum acceleration of the reference model without any damping absorbing device. The results showed that the structure with lowest structural damping ratio is the most sensitive to the presence of the tuned mass dampers. Moreover, increasing in the TMD damping ratio can significantly reduce the total mass required to achieve a certain main structure vibration reduction, proving that this solution can be a great cost-effective approach to mitigate structural unwanted vibrations.

Keywords: tuned mass damper, steel-deck slabs, passive damping device.

1 Introduction

Modern calculation techniques and development of new materials with higher strength resulted in more slender and flexible civil structures. The work environment also has experienced considerable changes, with reduced number of furniture, books were replaced by computer, and open spaces are preferred instead of partitioned layouts. At the same time, the number of indoor activities like group dancing, aerobics, live concerts and sport events has increased. The result of these modifications are structures prone to vibration problems that can cause discomfort and do not satisfy vibration serviceability requirements.

Solutions for vibration problems in building floors, pedestrian footbridge or stadiums are focused in increasing structural stiffness or damping. However, in some cases, the implementation of these measures may be cost prohibitive or they cannot provide the required performance to satisfy the comfort criteria. The other approach to reduce the vibration is through the installation of tuned mass dampers (TMD), a passive dissipation energy device that consists of a mass connected to the main structure by a spring and damper. The tuned mass dampers have been used in several civil structure types. An example is the Toda Bridge located in Japan where a tuned liquid damper (TLD) was used to reduce the lateral vibration amplitude from 8.3 mm to 2.9 mm [1]. Similar solution was used in the Solferino Bridge in Paris, Pedro e Inês Bridge located in Coimbra [2] and in the Millenium Bridge [1].

Application of TMD is also reported by Lima [3] in a gym floor subjected rhythmic activity. In this case the passive damper system could presented a better performance if its properties were better adjusted to match the critical flexural mode natural frequency. A further improvement in the TMD properties is presented by Santos [4], who studied influence of mass, frequency and damping ratio in the damper performance. The study demonstrated that a higher mass results in a better vibration isolation performance, however this parameter will be limited by static analysis criteria. Both Lima [3] and Santos [4] reports the lack of optimal design recommendations for tuned mass dampers applied to building floors. The optimal relations for the damper design were available only for simplified model as shown in Den Hartog [5] or Moutinho [6]. Since the structural model of a building and the dynamic load is more complex, the same relations cannot be applied.

This paper analyzes steel-deck slabs subjected to dynamic loads due to rhythmic activities. Despite its cost, steel-deck has been preferred by the market due its properties of light weight, strength, and reduced loss of material during construction, compared with reinforced concrete e.g. This progress resulted in slender and low damped structure, contributing to the increased number of vibration problems in floors and affecting the building serviceability. To solve this problem is proposed a solution using tuned mass dampers. The influence of the mass, natural frequency and damping ratio are analyzed as function of floor damping ratio and level of vibration attenuation.

2 Tuned Mass Damper

The model shown in Fig. 1 represents a single tuned mass damper, characterized by a mass, viscous damper and spring, coupled with the main structure represented by a mass and spring. In this simplified model the main structure and the TMD are constrained to move only along *x* axis. The mass is subjected to a harmonic dynamic load *p*, its displacement with respect to inertial reference is given by x_1, and x_2 indicates the displacement of *m* in the same reference frame.

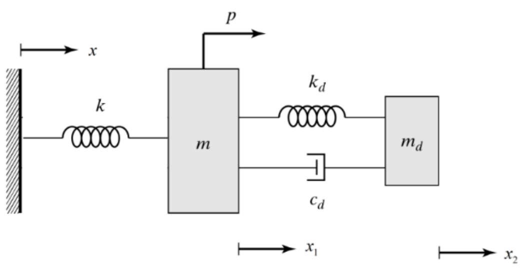

Figure 1. Single tuned mass damper simplified representation

The optimization performed by Den Hartog [5] resulted in frequency response function with the same amplification in both main structure displacement peaks if the TMD mass, stiffness and damping are set according with the following dimensionless equations:

$$f = \frac{1}{1+\mu} \qquad \frac{c}{c_c} = \sqrt{\frac{3\mu}{8\left(1+\mu\right)^3}}, \tag{1}$$

where *f* is the ratio of the natural frequency of the tuned mass damper over the main structure natural frequency; μ is the ratio of TMD mass over structure mass; and c_c is the critical damping of the tuned mass damper. The model shown in Fig. 2 is equivalent to the simplified system analyzed by Den Hartog [5]. The main structure is represented by the steel-deck slab, which has an inherited material damping ratio, and the tuned mass damper is composed by a set of circular plate supported by helicoidal steel springs. The only damping presented in the TMD is due to steel material damping, which corresponds to 2%. However, in the following analyzes a viscous damping device which increases the damping ratio to 10% is also considered.

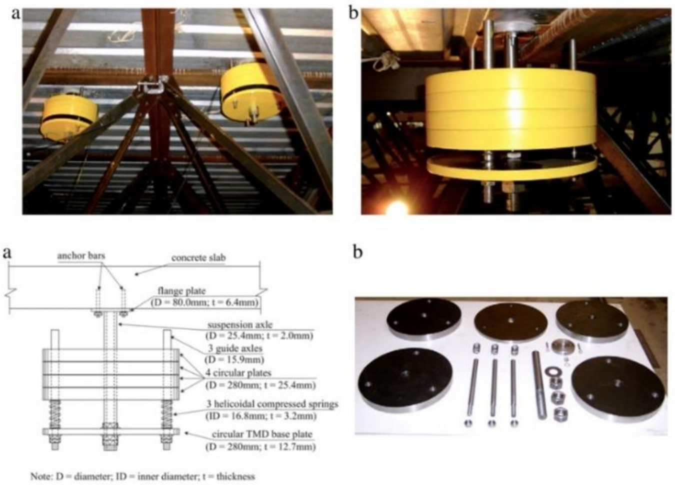

Figure 2. Tuned mass damper for Steel-Deck Floors developed by Varela [7]

3 Equivalent Orthotropic Steel-Deck Slab

An equivalent model is proposed to represent the steel-deck tridimensional model by a two-dimensional orthotropic plate as shown by El-Dardiry and Ji [8]. The simplified model is adjusted such that mode shapes, first natural frequency, and slab static deflections in both models has no significative difference. The steel-deck profile adopted in the simulations is shown in Fig. 3. The concrete has a f_{ck} of 50 MPa, Poisson ratio of 0.2 and density of 2500 kg/m^3. The steel deck sheet has a thickness of 0.9 mm, 200 GPa modulus of elasticity, Poisson ratio of 0.3 and density equals to 7850 kg/m^3.

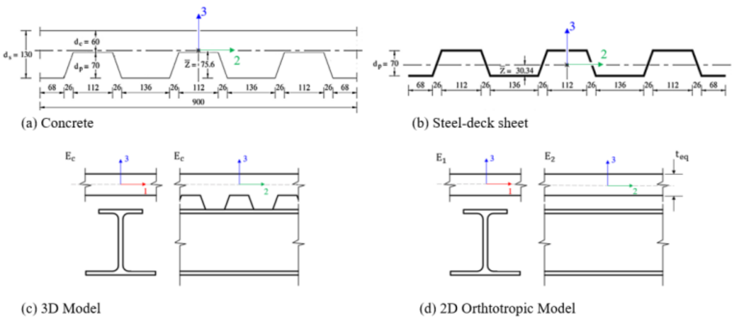

Figure 3. Steel-deck profile analyzed with dimensions in mm [8]

The orthotropic modulus of elasticity in direction 1 and 2, equivalent density and thickness are calculated following El-Dardiry and Ji [8] procedure and the results are shown in Tab. 1. Shear modulus and Poisson ratio are calculated as recommended by Szilard [9].

Table 1. Equivalent orthotropic plate properties

Parameter	Value
E_1 [MPa]	107456.54
E_2 [MPa]	33658.28
G_{21} [MPa]	22153.31
ν_{21}	0.20
ρ_{ortho} [kg/m^3]	3125.79
t_{eq} [cm]	8.11

To completely characterize the orthotropic plate for dynamic analysis is also required to define the equivalent damping ratio. Several frequency response analyses were performed, varying the concrete damping ratio from 2% up to 5% and steel-deck sheet from 1% to 2%. as recommended by Paz [10]. A critical case where the element damping is half of the minimum suggested is also investigated. The harmonic load used in each simulation corresponded to a unit load applied at the node of maximum modal displacement. The damping ratio is adjusted such the frequency response function of the simplified and 3D model has the same peak amplitudes. The results show that the equivalent material damping ratio is equal to 0.9 of the concrete damping ratio. Finally, it is possible to completely define the equivalent material used in the analyzes. The model adopted in the simulations has 9 meters length by 9 meters width, connected to the girder and joist with I section beams shown in Tab. 2, simply supported at the four edges.

Table 2. Beam properties

Beam	Total Height - d [mm]	Flange Width - bf [mm]	Web Thickness – tw [mm]	Flange Thickness - tf [mm]	Mass [kg/m]
IPE 300	300	150	7.10	10.70	42.20
IPE 450	450	190	9.40	14.60	77.60

A concentrated harmonic load due to rhythmic activities of 25 people, which results in an area per person of 3.25 m², as recommended by Murray [11] is considered. Since the exact position of each person is unknown a homogenous distribution is assumed as shown in Fig. 4. The tuned mass damper is represented by a spring-damper element that connects a concentrated mass to the structure.

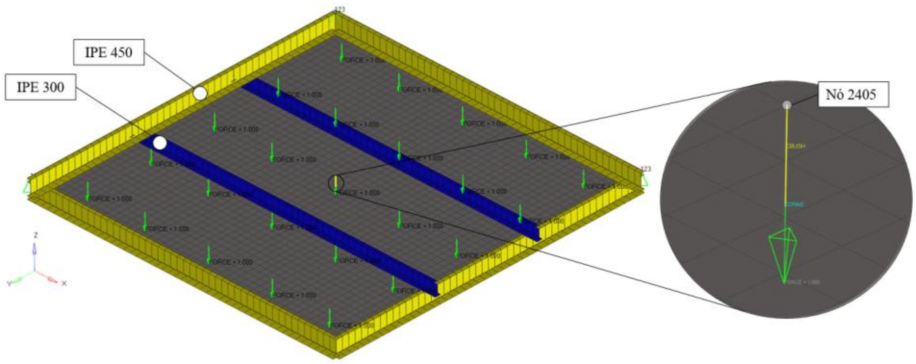

Figure 4. Finite element model of the steel-deck slab with tuned mass damper at the center

The harmonic load applied in each point is given by eq. (5) as suggested by Murray [11]:

$$F(t) = P\left[1 + \sum_{i=1}^{3} \alpha_i \cos(2\pi f_i t)\right], \tag{2}$$

where P represents the person weight of 800 N, α_i and f_i refers to the harmonic coefficient and excitation frequency, respectively. The critical case occurs when the first natural frequency is within the frequency range of one of the harmonics shown in Tab. 3.

Table 3. Rhythmic activity harmonic range and coefficient

Harmonic	Frequency Range [Hz]	α_i
1	2.0 - 2.75	1.5
2	4.0 - 5.50	0.6
3	6.0 - 8.25	0.1

4 Modal Analysis

The modal analysis allows the identification of the system natural frequency and preferred motion direction. First five mode shapes of the structure analyzed are shown in Fig. 5, where only the first mode can be excited in resonance by the dynamic loading eq. (2). Therefore, the center of the slab, which corresponds to the maximum nodal displacement of the first mode, is the point that the tuned mass damper must be placed to achieve its maximum performance. In larger structures, with wider beam spam, it is possible that both first and second vibration mode can be excited in resonance due to rhythmic activities, in such cases multiple tuned mass dampers has to be placed in the respective modal maximum displacement nodes, otherwise the structure still may present human comfort issue.

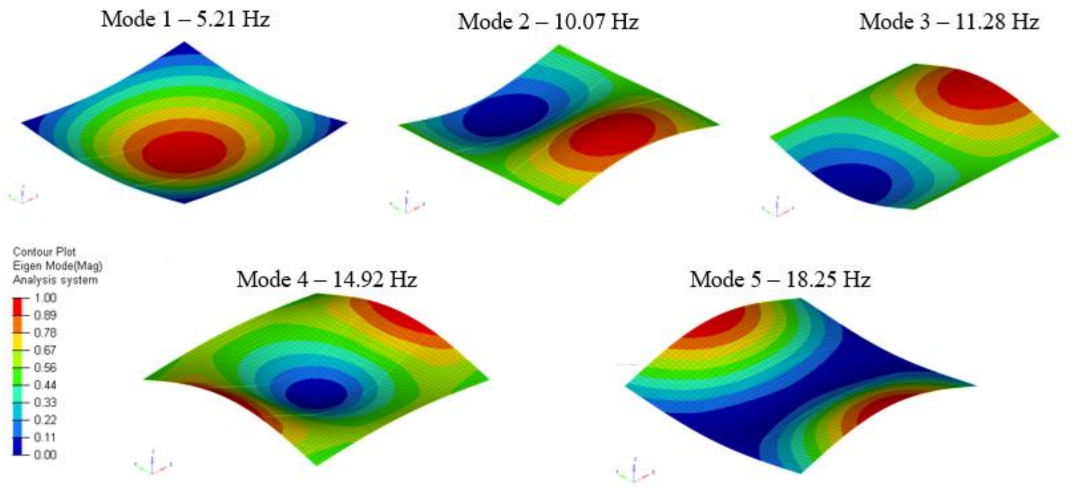

Figure 5. Mode shape and natural frequency of the slab

5 Optimization

The optimization problem can be summarized in determining the design variables vector x, that minimizes the objective function *f*, subjected to the maximum acceleration at the center of the steel-deck slab:

$$\mathrm{x} = [M_{TMD}, K_{TMD}] \qquad f(M_{TMD}) = M_{TMD} \qquad \max\left(a\left(M_{TMD}, K_{TMD}\right)\right) \leq a_{\max}. \tag{3}$$

The process consists in finding the best combination of stiffness and mass of the tuned mass damper that minimizes the mass required to achieve a given vibration reduction. The vibration attenuation ranges from 10% up to 80% reduction of maximum acceleration of the reference model without any damping absorbing device. To determine the maximum acceleration is implemented a code, using *HyperMath Software*, that calculates the steady state response of the model due to load given by eq. (2) for various points within the excitation frequency range.

To solve the optimization problem is employed the algorithm known as Global Response Surface Method (GRSM). This method belongs to the exploratory optimization category, which does not present the typical local minimum/maximum problems faced by the gradient based optimization algorithms [12]. Moreover, during the iterative optimization process the algorithm generates new samples spread along the design space ranges, providing a well balanced local and global search.

6 Results

The optimization results for the various configurations analyzed are presented in Figs. 6 and 7. Comparing the M_{TMD} plots it is clear that the TMD with 10% damping ratio reduces considerably the required mass to achieve a given vibration attenuation. The simulations also showed that slabs with lower structural damping are the most sensitive to the presence of the tuned mass damper, since in both cases a mass ratio lower than 2% could reduce up to 80% of the maximum floor acceleration. Furthermore, there is a sudden increase in the mass required to move the attenuation from 70% up to 80%, this may present a cost issue to the solution of floor vibration problem through passive dampers.

The frequency ratio, which refers to the ratio of TMD natural frequency over the slab first mode natural frequency, is also plotted. In the simplified model presented by Den Hartog [5] the frequency ratio is close to the unit for a small mass ratio and decreases accordingly with eq. (1). Similar behavior is obtained in the following optimization results, however, for small mass ratio, the frequency ratio is even higher than the unit.

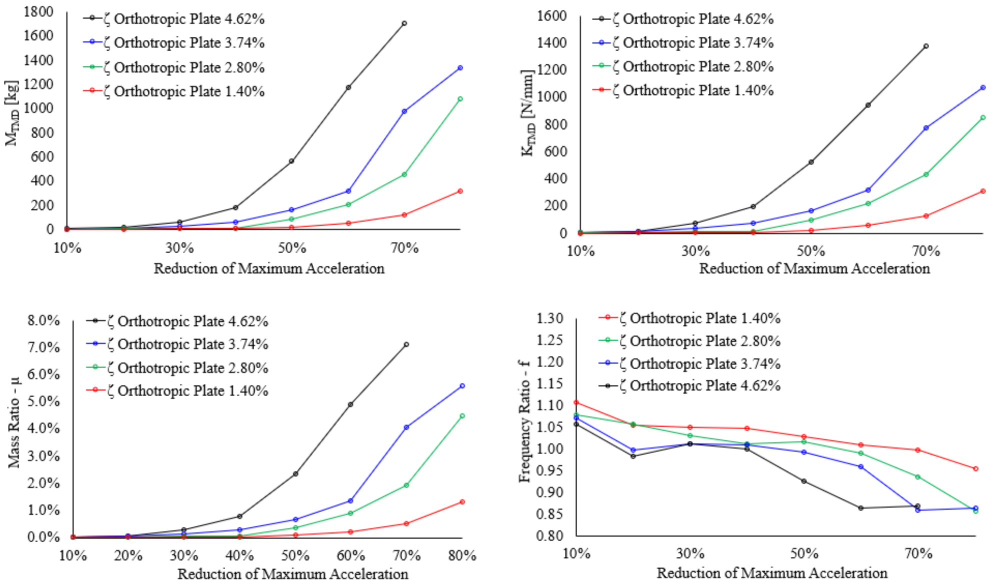

Figure 6. Optimization results for TMD with damping ratio equals to 2.00%

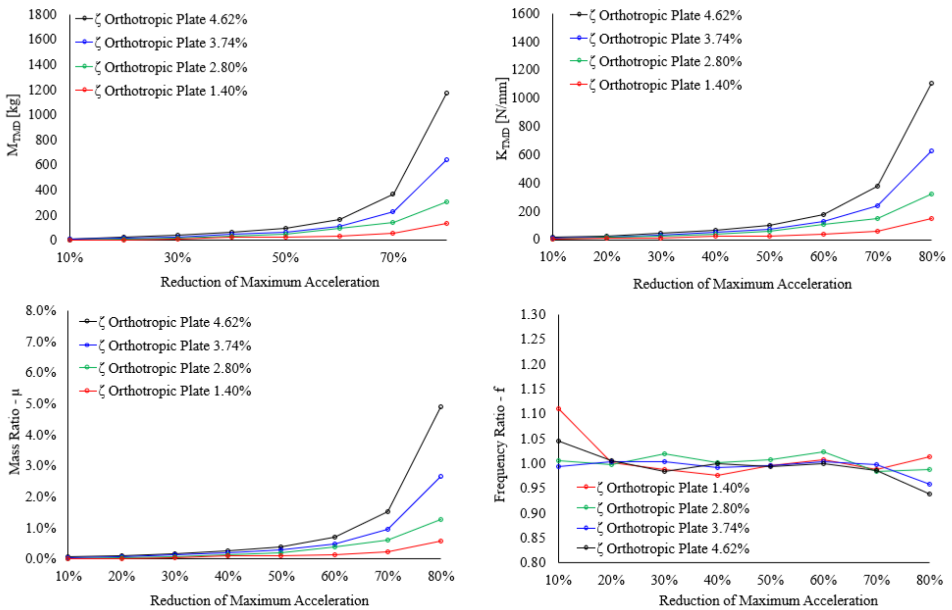

Figure 7. Optimization results for TMD with damping ratio equals to 10.00%

Conclusions

After the analysis developed in this paper it is possible to realize the influence of damping ratio factor in the structure behavior. Since this parameter it is difficult to be obtained through numerical simulations, field measurements using accelerometers should be employed to determine it precisely and use as input in the dynamic analysis. The hole of the damping ratio of the TMD itself it also analyzed, showing that a proper design of the device could reduce up to 50% of the mass required to result in a given vibration isolation.

Suggestions for future work include the consideration of larger structures and different loads, to considerer for example the human comfort in offices and commercial building. Another possibility is the evaluation of a larger batch of geometries, varying the slab width and length, and analyzing the variation of the optimal properties of the tuned mass damper. An interesting investigation could also be performed considering that the damping ratio could be increased to 20% to verify whether the total mass required could be minimized even more.

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