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THE USE OF TMD'S WITH HEAVY MASS TO MITIGATE THE SEISMIC RESPONSE OF STRUCTURES

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Abstract. *This document demonstrates the usefulness, operation and design of Tuned Mass Dampers (TMDs) in the structural control of seismic response. This vibration control system, which main asset is the introduction of additional damping on structural system, can improve the structural behavior particularly in terms of forces and displacements, in case of seismic loads. This paper describes some practical situations using TMDs and the theoretical approach of their operation. Then, design graphics are presented as a result of the research work developed at FEUP and the effectiveness of this type of solution is demonstrated by an illustrative example.*

1 INTRODUCTION

Tuned Mass Dampers have been widely used to control the dynamic response of structures in Civil Engineering. This devices consisting in an additional mass connected to the structure by a spring and a damper, and demonstrate effectiveness in the mitigation of harmonic vibrations. In this kind of vibrations, a well-tuned device behaves in a correct phase opposition to the response of the controlled system, reducing its vibrations [1]. Usually in these cases, the TMD mass represents 1 or 2% of the modal mass associated at the vibration mode in analysis, which results in a small control system, easily integrated architecturally or even hidden.

However, if the structure contains a non-harmonic response, as usually happens in Earthquake Engineering, the mechanism used by TMDs to reduce movement of the main system is no longer based on phase compensation to the movement. Thus, the main advantage is based on the effect of adding supplementary damping to the structure (Paredes, Barros and Cunha [2]). In these cases, the mobilization of considerable damping values which increase significantly the structural damping ratios and hence reduce the dynamic response of the system, is only possible through the use of additional heavy masses.

In this context, this paper aims to expose the research work that has been developed at FEUP about the possibility of using TMDs with heavy mass in structures, using as an additional mass a part of the own structure to control the remaining. This idea was inspired by some real applications in buildings such as the case “Applause Tower” located in Osaka, Japan. In this building, the mass associated with a helipad on the roof was used to act as control system of the remaining structure, using hydraulic actuators, which cause inertial forces between platform and building (Figure 1).

In the case of the control system proposed in this paper, the idea is use a passive system mobilizing a heavier mass. To realize a practical system of this kind will be necessary to use a portion of the structure less commonly used, such as roof and technical floor. Thus, it is possible to materialize the high amount of mass required for the passive system to become efficient. Figure 2 presents some possible solutions (Barros [3]).

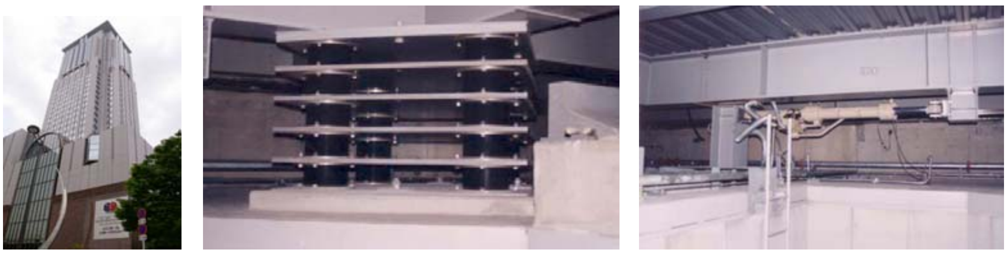

Figure 1 – a) Overview of the “Applause Tower”; b) Support equipment of the platform; c) Hydraulic actuators

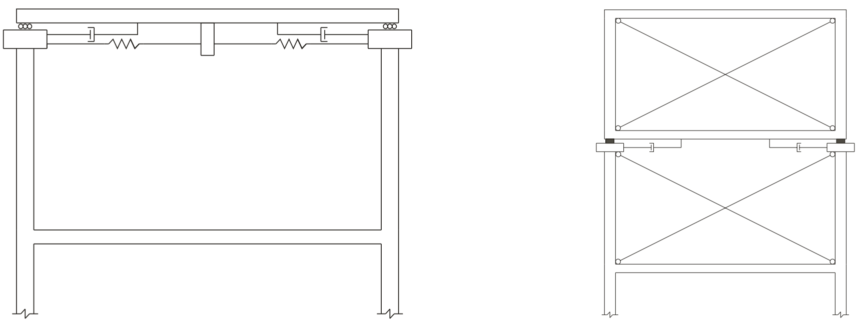

Figure 2 – Examples of use of part of the structure to function as the control system (Barros [3])

2 ANALYSIS OF THE TMD'S OPERATION

2.1 Application to structures with low damping under harmonic solicitations

The structural model usually used to the analyses of the TMD's operation in structures under harmonic solicitations is indicated in Figure 3, where m_1, k_1 and c_1 are the variables that define respectively the characteristics of mass, stiffness and damping of the initial structure, and m_2, k_2 and c_2 define the same characteristics in TMD. When this device is optimally designed, the Frequency Response Function (FRF) presents two peaks corresponding to the natural frequencies of the system of two degrees of system. The FRF curve should be determined so that the two peaks are flat and have de lowest possible value of the amplification of the initial system (Figure 4). In these circumstances it is said that the TMD is tuned optimally.

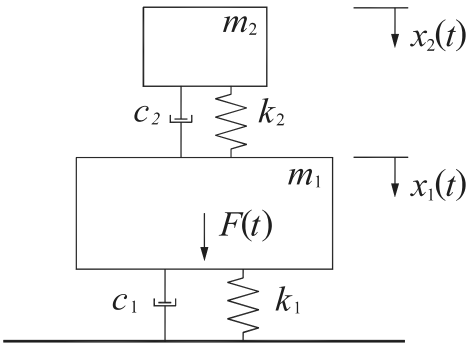

Figure 3 – One degree of freedom model with a TMD

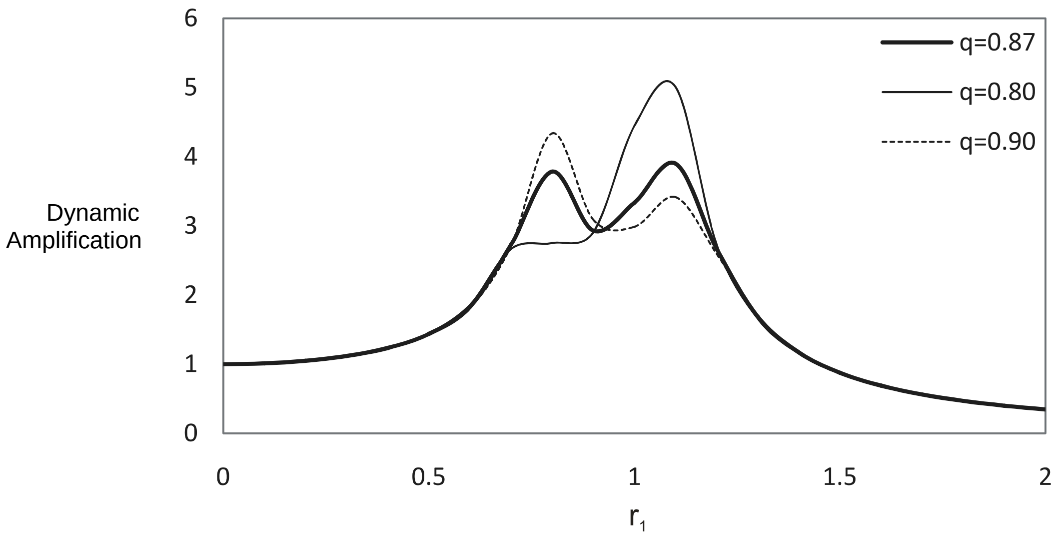

Figure 4 – FRF curves for three different TMDs in the same system $(q_{opt} = 0{,}87)$

In the particular case where the structural damping is null $(c_1 = 0)$, the TMD's design may be done by the following expressions proposed by Den Hartog [1]:

$$q_{opt} = \frac{1}{1+\mu} \tag{1}$$

$$\xi_{2opt} = \sqrt{\frac{3\mu}{8(1+\mu)^3}} \tag{2}$$

where

$$\mu = \frac{m_2}{m_1} \quad ; \quad q = \frac{\omega_2}{\omega_1} \quad ; \quad \omega_1 = \sqrt{\frac{k_1}{m_1}} \quad ; \quad \omega_2 = \sqrt{\frac{k_2}{m_2}} \quad ; \quad \xi_2 = \frac{c_2}{2m_2\omega_2}$$

In this situation, the design process begins through the quantification of μ which corresponds to the maximum dynamic amplification (D) imposed to the main system, and this parameter can be obtained by the following expression.

$$D = \sqrt{\frac{2+\mu}{\mu}} \tag{3}$$

After calculating the TMD's mass, using the parameter μ, the optimal frequency and damping of the device are given by the expressions (1) and (2).

The previous expressions can still be used on TMD's design in structures with low structural damping, typically less than 1% (Bachmann and Weber [4]). However, in structures with a higher level of damping, the assumptions used in obtaining such expressions are no longer valid, requiring a different methodology for the determination of the ideal characteristics of these devices. In this case, one should resort to numerical methods to obtain design graphics where to find the values of q_{opt} and ξ_{2opt} (or ξ_{TMD}) corresponding to a particular value of μ, which can minimize the dynamic amplification of the main structure.

2.2 Methodology used in the case of seismic actions

The implementation of a properly tuned TMD to a structure has as a result the introduction of a certain level of additional damping to the system. According to Villaverde [5], for one degree of freedom system with a damping ratio ξ_1 which is installed a small TMD optimally designed with damping ratio ξ_2, the final damping ratio of the system with TMD is approximately

$$\xi_{Final} \cong \frac{\xi_1 + \xi_2}{2} \tag{4}$$

This expression clearly indicates that the inclusion of a TMD in a structure may increase the final damping to a defined level required for the system, which TMD damping is given by the previous equation. This approach is clearly appropriate to the context of seismic design of structures, since effect of structural damping in the response is quantified in the regulations. So, if you need the structural behavior remains within certain limits, which is associated with a given damping required to achieve it, this level of damping can be achieved with the installation of a Tuned Mass Damper.

However, the design procedure of these devices is different in these cases. Indeed, the classical definition based on the mass of the TMD that corresponds to a certain level of reduction of structural response and subsequent determination of the stiffness and damping is no longer valid. In seismic design, to obtain a certain final damping in the structure, first it's need to fix the value of TMD's damping and then his mass and stiffness.

An important aspect in determining the optimal parameters of a TMD is that you can only mobilize high levels of damping in the use of additional high mass values. Due to this fact arises the need for TMDs with heavy mass. Notice for example the FRF curves shown in Figure 5 (Paredes [6] , Barros [3]) which correspond to a structure with an initial damping ratio of 5% associated with a TMD which mass represents 5% of the mass of the initial system. The continuous curve corresponds to the situation where the device is optimally tuned (lower maximum possible dynamic amplification) resulting in a device with a damping of 14%. The attempt to increase the TMD's damping without changing its mass results in the loss of efficiency of the device. Nevertheless, until a certain amount of increased damping it is possible to keep the peaks with the same ordinate. For increasing damping ratio values, the TMD begins to behave like it is "clinging" to the structure and the set begins to converge to a system without TMD.

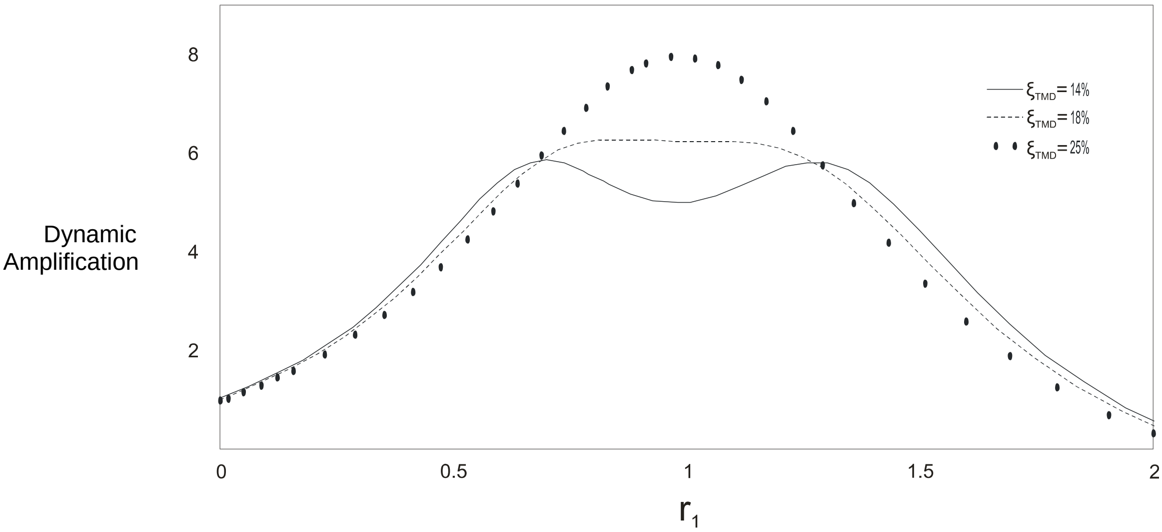

Figure 5 – FRF curves for three different TMDs in the same system $(\xi_{2opt} = 14\%)$

3 DESIGN GRAPHICS

3.1 Process for obtaining the TMD design graphs

In order to obtain the parameters of a TMD which can introduce a certain level of damping to the system, can be used a structural model similar to that shown in Figure 3. In this case, the values of m_1, k_1 and c_1 as well as m_2, k_2 and c_2 have the same physical meaning presented above. The m_2 parameter has to take several values fixed in corresponding to several values of μ , and the system was studied so that the initial damping ratio takes value of 1%, 3% and 5%, thus resulting in three curves in each graph. Then, for various values of μ up to 0,50 was determinate the value of q_{opt} that flat the two peaks of the FRF curves for various damping values installed on TMD. The damping installed on the control system that corresponds to a lower dynamic amplification, is the optimum damping of the TMD (ξ_{2opt}).

After the addition of Tuned Mass Damper, the two resulting vibration modes have almost the same modal damping, so their average is presented in a third graphic, depending on the value of μ . This reasoning is repeated for each one of the three initial structural damping considered (Barros [3]).

3.2 Design graphics for determination of the TMD's parameters

Following the procedure presented above, it is possible to compile all the values of optimal parameters for the design of TMDs, for the three initial structural damping of 1%, 3% and 5%. Thus, the values of q_{opt} and ξ_{2opt} for a given value of the μ , can be obtained from the graphs presented in the following Figures 6 and 7.

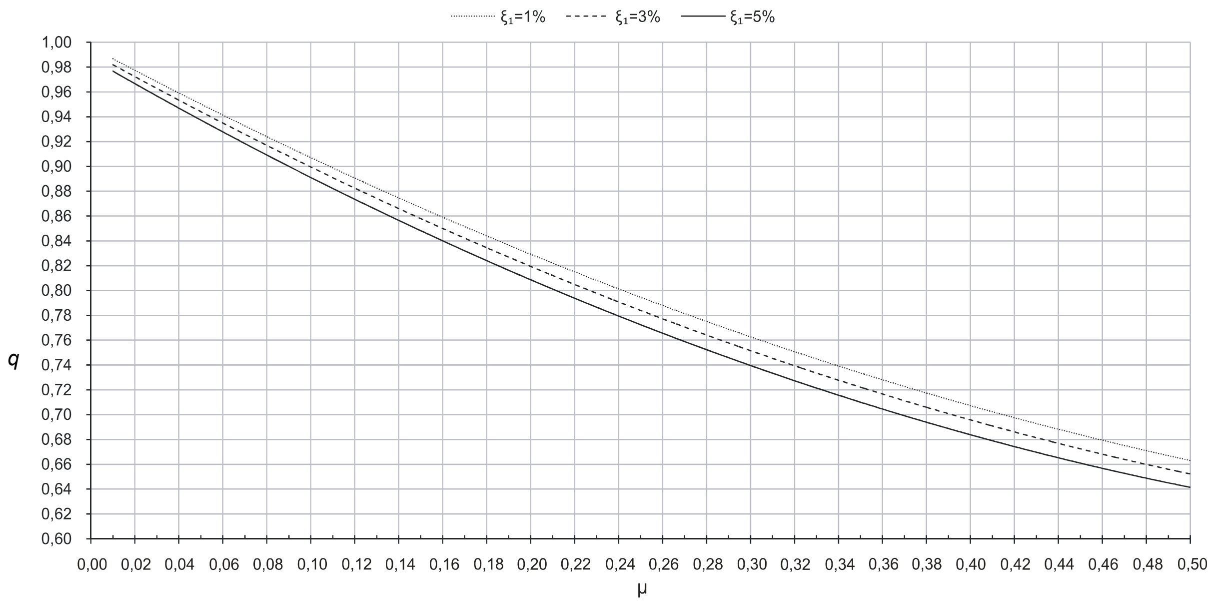

Figure 6 – q_{opt} for values of μ up to 0,50 , (Barros [3])

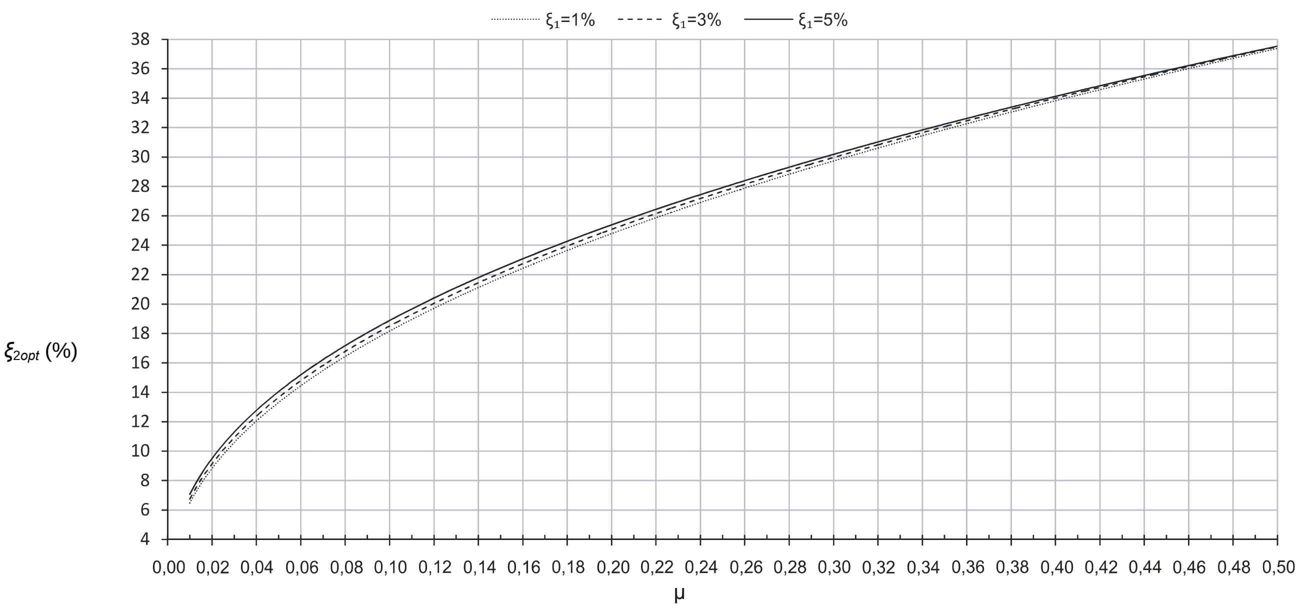

Figure 7 – ξ_{2opt} for values of μ up to 0,50 , (Barros [3])

As already mentioned, have been made a third graphic that reflects the average value of the two final modal damping achieved, and this has an additional utility as the input of the query graph can be given by any one of its axes. In other words, you can set up the final damping achieved for a given μ , or otherwise, can determine the value of μ and thus the mass of the TMD necessary to achieve a given final damping desired, from an initial damping significantly lower. This second way of using this graphic is particularly interesting for the cases of structural control under seismic actions. This third graph is represented in Figure 8.

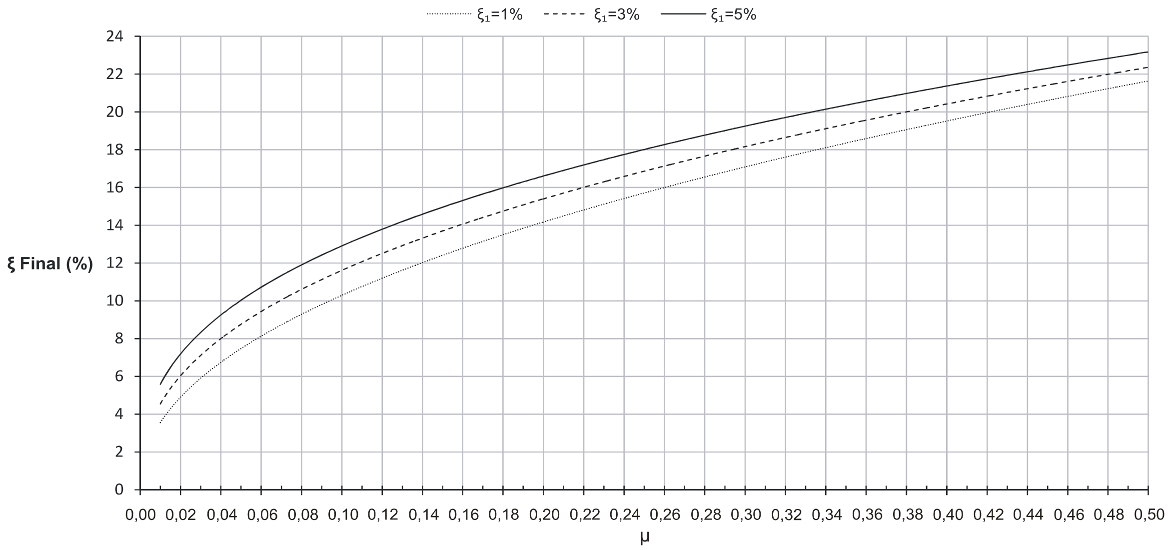

Figure 8 – Final structural damping for values of μ up to 0,50 , (Barros [3])

Comparing the final damping achieved with the inclusion of a Tuned Mass Damper in a system with an initial damping of, for example, 5% with the final damping proposed by Villaverde [5] (that would be approximately the average of both dampings in question), it appears that this formula is a good approximation for values of μ up to about 0,04. For higher values of μ , this match begins to lose its accuracy, thus corroborating the idea in the Villaverde's method that this approximation is valid for low values of μ and damping of TMD. The following Figure 9 represents the two curves referring to both final damping concerned and identifies the similarity to a range of μ up to 0,04 as well as the evolution of loss of accuracy of the approach suggested by Villaverde [5] for higher values of μ .

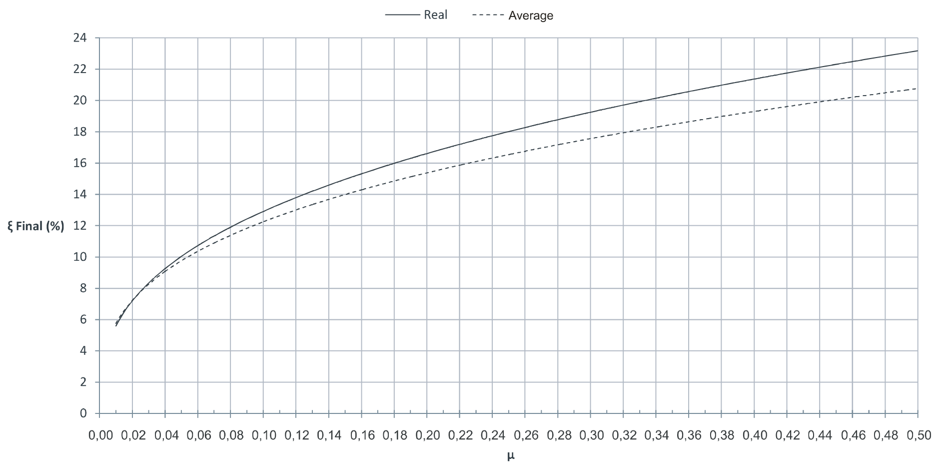

Figure 9 – Comparison between the real final damping achieved and the average of Villaverde's method [5]

4 EXAMPLE OF APPLICATION

4.1 Description of the problem

The application example presented consists in a fifteen storey reinforced concrete frame located in Portimão, Algarve. This case's study aims to compare the behavior of the structure in terms of displacements and applied forces resulting from seismic activity present in the regulatory response spectra of Eurocode 8 (EC8) [6], when the structure has or has not control system through a TMD. Also, when there is no TMD, the structure was studied as having two distinct behavior factors of 1,5 and 2,5, enabling the comparison of the effectiveness of the application of TMD into structures more or less ductile (Barros [3]).

This study was performed through a modal analysis by response spectrum which consists in a linear elastic analysis. This procedure is a simplified analysis by which, according to regulation FEMA 356 [7], when the structure is under control must behave elastically to the seismic action considered, although the EC8 does not refer such approach.

To realizing the TMD, was considered the two top floors of the frame structure as a mass to be used by the control system. The choice of the number of floors to behave as a mass of TMD was based on the final damping achieved in each scenario.

So, consider the structural scheme shown in Figure 10, which represents the frame structure treated, regular in height and plant and set on a ground classified as type C.

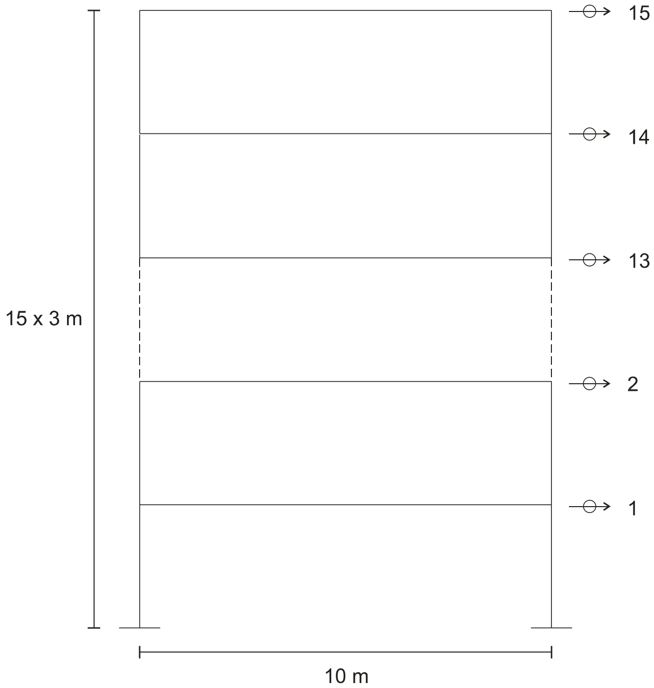

Figure 10 – Schematic structure of the frame in study (Barros [3])

Neglecting the contribution of the pillar's mass when compared with the floor's mass, it is assumed that in the almost permanent combination of actions the mass of each degree of freedom is worth 10 tones. With regard to the stiffness of the structure, the slabs are considered infinitely rigid in bending when compared with the pillars. It is also assumed that the section of the columns is constant in all the framed structures, with approximate dimensions of 0,30 x 0,40 square meters (C25/30 concrete), resulting in a fundamental frequency of vibration in the order of 1 Hertz.

4.2 Main results

In order to control the first vibration mode of the main structure (thirteen storeys), a TMD was installed consisting of two floors which should behave as a single mass, which is why the structure now has fourteen degrees of freedom. The TMD's characteristics were obtained from the design graphics presented and are shown in Table 1. The structural damping ratio of the frame structure increases from 5% to about 19%, consisting in a significant amplification of this parameter.

μ	q_{opt}	ξ_{TMD} (%)	ξ_{Final} (%)
0,295	0,741	30	19

Table 1 – TMD's characteristics and final damping achieved

As noted above, the structure without TMD is studied with two distinct behavior factors. The natural frequencies of vibration given bellow correspond to the frame structure without TMD (regardless of the behavior factor) and with TMD.

Vibration Mode	Natural frequency without TMD (rad/s)	Natural frequency with TMD (rad/s)
1	6,73	5,19
2	20,11	8,43
3	33,29	23,20
4	46,12	38,16
5	58,48	52,64
6	70,25	66,42
7	81,29	79,31
8	91,49	91,13
9	100,76	101,73
10	109,00	110,95
11	116,11	118,67
12	122,04	124,79
13	126,71	129,22
14	130,08	131,90
15	132,12	-

Table 2 – Natural frequencies of the structure with and without TMD

Regarding the effect of seismic accelerations in the structure are only shown the parameters for the type 1 earthquake, since the type 2 is not so onerous, being of course the type 1 that affects the design of the structure. Thus, Table 3 outlines the structure's displacements for the three cases of study, for each degree of freedom.

As can be seen by consulting Table 3, all degrees of freedom have strong reductions in their displacements after the installation of the control system. The exception is the two top floors, because they are associated with TMD have their movements increased, as expected. Another aspect that can be seen from the analysis of this table is that the final displacements of the structure without TMD are practically the same for both cases of different behavior factors.

Degree of freedom	Displacements for behavior factor of 2,5 (m)	Displacements for behavior factor of 1,5 (m)	Displacements for the structure with TMD (m)
1º	0,01506	0,01505	0,00566
2º	0,02993	0,02991	0,01114
3º	0,04444	0,04440	0,01633
4º	0,05842	0,05836	0,02113
5º	0,07172	0,07165	0,02553
6º	0,08424	0,08416	0,02953
7º	0,09586	0,09577	0,03315
8º	0,10651	0,10641	0,03639
9º	0,11610	0,11599	0,03924
10º	0,12455	0,12443	0,04171
11º	0,13177	0,13164	0,04374
12º	0,13768	0,13755	0,04530
13º	0,14220	0,14207	0,04635
14º	0,14526	0,14512	0,16487
15º	0,14681	0,14667	

Table 3 – Structure's displacements for the three studied cases

Likewise the seismic forces associated with each degree of freedom, for the two structural behavioral factors of 1.5 and 2.5, are tabulated in Table 4.

Degree of freedom	Applied forces for behavior factor of 2,5 (kN)	Applied forces for behavior factor of 1,5 (kN)	Applied forces for the structure with TMD (kN)
1º	4,90	8,17	14,59
2º	9,47	15,79	26,24
3º	13,43	22,38	33,15
4º	16,57	27,61	35,31
5º	18,79	31,31	34,57
6º	20,14	33,56	33,35
7º	20,84	34,71	32,59
8º	21,21	35,33	31,51
9º	21,68	36,11	29,99
10º	22,58	37,60	30,27
11º	24,00	39,97	34,41
12º	25,77	42,92	40,41
13º	27,56	45,89	39,02
14º	28,98	48,28	94,63
15º	29,77	49,59	

Table 4 – Applied forces to the structure for the three studied cases

In examining Table 4 it appears that when compared with the initial structure provided with a behavior factor of 2,5, the installation of a TMD does increase the seismic forces in the structure markedly. Moreover, when compared the seismic forces after docking the TMD with the forces arising from the same phenomenon in the structure with the behavior factor of 1,5, it appears that the addiction of forces is much less significant, as there are a few degrees of freedom whose forces diminish its value.

5 CONCLUSIONS

The numerical study conducted on this issue has enabled the development of design graphs for TMDs with a heavy mass, which allow an easy practical and quick way to obtain the optimal parameters of such passive system of vibration control, which can be of important use for both buildings and bridges (Paredes and Barros [9]).

As can be understood through the analysis of Table 3, the displacements checked in the structure due to seismic accelerations are practically equal in both cases of different ductility characteristics. Thus it appears that the displacements do not depend on the behavior factors of the structure. Because of this, the effectiveness of the use of TMDs in displacements values is similar in both cases so that these parameters are a little more than a third of what they were initially. This proves that this control system is quite effective in terms of displacements under seismic actions.

With regard to seismic forces that arise in the structure (Table 4), and not forgetting the obligatory of the structure remains in elastic regime when it has control system (imposed by FEMA 356), the influence of the installation of TMD has strongly depends on the characteristics of ductility concerned. Indeed, when the structure is characterized by a behavior factor of 2,5, there is a significant increase of forces, there are even a few degrees of freedom increased to more than double its initial value, resulting in an increase of almost 60% in foundation's bending moments. When the structure is less ductile, having a behavior factor of 1,5, the seismic forces installed in most of the degrees of freedom reduce its value. In the remaining degrees of freedom, the increase is much less significant when compared with the situation of more ductile structure, leading to a reduction in the bending moments at the foundations of around 4%. Due to this scenario, the use of TMDs to control the seismic response of structures is more interesting in more rigid structures, and in the more ductile the extra efforts may undermine the feasibility of using this damping system.

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REFERENCES

[1] Den Hartog, J. (1940), *Mechanical Vibrations*. McGraw-Hill, New York.

[2] Paredes, M.M., Barros, R.C. and Cunha, A.F. (2009). *A Parametric Study of TMD's for Regular Buildings under Earthquakes*. Computational Methods in Structural Dynamics and Earthquake Engineering (COMPDYN 2009), M. Papadrakakis, N.D. Lagaros, M. Fragiadakis (eds.), Rhodes, Greece, 22–24 June 2009.

[3] Barros, J.E. (2010). *Utilização de TMDs de Grandes Dimensões no Controlo da Resposta Dinâmica de Estruturas de Edifícios*. Dissertação de Mestrado, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal.

[4] Bachmann, H. and Weber, B. (1995). *Tuned Vibration Absorbers for Lively Structures*. Journal of IABSE, Structural Engineering International, vol. **5**, nº1.

[5] Villaverde, R. (1985). *Reduction in Seismic Response with Heavily-Damped Vibration Absorbers*. Earthquake Engineering and Structural Dynamics. Vol. **13**, pp 33-42, John Wiley & Sons, Ltd.

[6] Paredes, M.M. (2008). *Utilização de Amortecedores de Massas Sintonizadas no Controlo de Vibrações em Estruturas*, Dissertação de Mestrado, Faculdade de Engenharia da Universidade do Porto, Porto, Portugal.

[7] Instituto Português da Qualidade (2009). *Eurocódigo 8: projecto de estruturas para resistência aos sismos*. NP EN 1998-1: 2009. Caparica: IPQ, Portugal.

[8] American Society of Civil Engineers. (2000). *Federal Emergency Management Agency, FEMA 356*, Pre-standard and Commentary for the Seismic Rehabilitation of Buildings. Washington D.C., USA.

[9] Paredes, M.M. and Barros, R.C. (2009). *The Use of TMDs for Structural Vibration Control: Numerical Studies of Shear Buildings under Earthquakes and of a Pedestrian Bridge*. Proceedings of the Twelfth International Conference on Civil Structural and Environmental Engineering Computing, Edited by: B.H.V. Topping, L.F. Costa Neves and R.C. Barros. Civil-Comp Press, Paperback: 316 pages, CD-ROM: 293 papers, ISBN 978-1-905088-32-4, 2009.