Assessment of the performance of rectangular shaped tuned liquid dampers for vibration mitigation in a building without seismic design

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SUMMARY:
The use of energy dissipation devices is seen as an efficient way to protect structures against seismic actions. Recently, devices of the type tuned liquid dampers (TLDs) have attracted the attention of the scientific community as a simple but effective way to reduce the response of structures against dynamic actions. In this work is made an evaluation of the performance of TLDs in real structures, based on routines developed. An existing structure in the Portuguese territory was considered, with fundamental frequencies compatible with the range of frequencies tested within an experimental study. Initially the description of the building is made, as well as aspects related to the simulation of the adopted protection system. Subsequently, were compared and discussed the results obtained for the situation without TLDs and with the corresponding results obtained for the structure with those seismic protection devices included.

Seismic Protection; Mathematical Models; Mitigation of Vibrations; Tuned Liquid Dampers

1. INTRODUCTION

The design and implementation of secondary systems for the control of structural vibration corresponds to a relatively recent scientific area. In particular, the development of seismic protection systems, such as tuned mass dampers (TMD) and tuned liquid dampers (TLD) has increased quickly since their first implementation in structures, such as the Citicorp building in the 70s of the twentieth-century and Hotel SYP in the 90s [Kareem et. al., 1999], respectively.

This type of device was first used to control vibration associated with wind in tall and slender structures, in view of improving the comfort of the occupants in skyscrapers, and has been extended to other applications, particularly in the field of the protection of structures against the occurrence of moderate to high magnitude seismic actions.

In the study presented in this paper it was intended to simulate the hypothetical application of TLD real structures, without specific seismic design, existing in the Portuguese territory. The selection of structures and secondary TLD systems proposed, intends to express a realistic application of the design for both the main system and the secondary system. The choice was mainly based on the geometric characteristics of the building and in previously studies performed [Rodrigues, 2006] [Novo, 2008] from which it was possible to extract relevant information, especially concerning their fundamental vibration frequencies, in order to establish a parallel between them and the range of frequencies tested during an extensive experimental program developed at LNEC [Falcão Silva, 2010]. The TLD proposed for each simulation were similar to those considered during the said experimental program, only varying the height of fluid at rest inside them in order to achieve the frequencies predicted, desired and adjusted to each case.

The incorporation of damping systems, such as TLD, on existing structures is beneficial as they allow, in most cases, a considerably more simple and inexpensive installation when compared with other devices for mitigation / reduction of dynamic vibrations imposed. The inclusion of devices such as TLD in new constructions has the same benefits as those observed for existing structures, but adding the possibility for designers to eventually use water storage systems, which in many instances, are thought to more slender structures, as secondary systems. Because of their inherent characteristics, TLD devices allow, in most situations, a large variety of distributions and arrangements in terms of installation.

2. CASE STUDY: AV. INFANTE SANTO BUILDING

2.1. Structures description

For this study a building representative of a particular building era and belonging to the Portuguese housing park was considered. The situation chosen corresponds to a building located in Av.Infante Santo and stands as representative of modern architecture. It was designed and built during the 50s of the XXth century, when seismic design was not included in existing national rules. The choice of this case study is justified, because of the highly dangerous characteristics of the site where it is located, the large number of buildings built in the Portuguese territory during that period, and in particular the densely populated area of the city of Lisbon where the building is inserted. It is certainly an excellent case to demonstrate the applicability and efficiency of TLD devices in vibration mitigation in structures without specific seismic design.

The building on which the study was carried out corresponds to building number 3 of a compound of 5 housing buildings (Fig. 2.1.) perpendicular to Av. Infante Santo, with the same geometry (in plan and front) and constructed with the same structural materials. All buildings of the compound consist of eight housing floors, "suspended" to pillars at the ground floor, as seen in Fig. 2.2.

Figure 2.1. Location of the building compound: air view [Google Earth, 2007]

Figure 2.2. Facade of the building under study [Novo, 2008]

The building under study is 46.1m long (longitudinal direction or x direction) by 11.1m wide (transverse direction or y-direction) and a height of 30.0m. The schematic representation in plan is presented in Fig. 2.3.

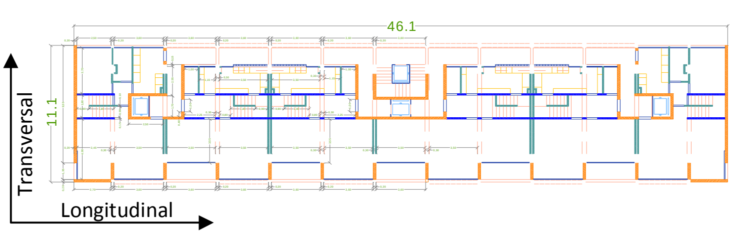


Figure 2.3. Type floor plan of the building in Av. Infante Santo, adapted from [Novo, 2008]

At the ground floor there is one floor without masonry walls, as can be seen in Fig. 2.2, and with a clear height of 5.5 m. The remaining eight floors have masonry exterior walls and partitions. The first and eighth floors have a height of 3.2 m and the remaining floors 3.0 m. The height of the columns on the first floor favours the emergence of soft-storey type behavior mechanisms, which makes this structure very vulnerable to horizontal actions, such as those induced by earthquakes.

The building's structural system is defined by twelve reinforced concrete plane frames and nine floors, oriented with the transverse direction of the building. Each plane frame comprises two columns and a three opening beam at each floor, being two of the openings in console. On each floor, there is a concrete slab, which is the only element connecting the frames. All frames have the same geometric characteristics in terms of overall design and cross sections of its elements. The transverse direction emerges as the direction in which the frames forming the main structural system of the building develop themselves, and it mobilizes the greater stiffness of the columns and beams. In the longitudinal direction, columns are oriented according to its lower stiffness, and as mentioned above, they are not connected by beams on the floors, being displacements only made compatible by means of the slab. For this reason, the longitudinal direction appears as the lower stiffness direction, although it is the highest development direction of the building [Rodrigues, 2006].

2.2. Analytical modelling

The dynamic behavior of structures can be determined analytically or numerically, for example, by the finite element method. Several possible numerical approaches for seismic analysis of structures are known, using different methods of analysis, combining the consideration of material and geometric nonlinearity, depending on the desired results, the level of information available, among others. In the present work, and for the type of analyses desired, we used the MDF_LNEC and MDF + TLD_LNEC routines, developed to implement the mathematical models for numerical simulation of dynamic behaviour of TLDs, based on the hyperbolic equations of the non-linear wave theories [Falcão Silva, 2010] as well as the commercial automatic calculation software SAP2000TM [SAP2000, 2003], as an auxiliary tool, for definition of configuration and modal characteristics of the structure.

For use in numerical MDF_LNEC and MDF + TLD_LNEC simulations, the main structural features of the system, i.e. the building of the Av. Infante Santo, were defined from an analysis based on the modal response of a number of preset modes. Features used were the vibration modes, their frequencies, damping, modal participation factors for each main translation direction and the configurations for each main translation direction associated with the modes under analysis. The validation of the numerical model was performed by comparing the frequencies measured in situ [Rodrigues, 2006] with the frequencies estimated based on the numerical model developed, having been obtained values very close to these, which make it possible to validate the elastic model developed for the structure, and used in the analyses that will be presented. Linear analyses carried out are based on the modal overlap, having been considered an equivalent viscous damping of 5%.

2.2.1. Properties of the materials

Whenever possible, it was tried to adequately reproduce the behaviour of existing materials on site. For the modal analyses performed, was considered a class B25 concrete, according to the directions of the project, the constructive practice of the time and the results of tests conducted using the sclerometer [Cruz, 1955]. An elasticity module E_C = 29GPa was considered. In what concerns steel, as there is no reference in the project, an A400 steel was adopted, with elastic module E = 210GPa, typically used at that time [Rodrigues, 2006]. In relation to masonry, properties adopted were determined from empirical expressions and experimentally validated, when measuring the frequency of the structure.

2.2.2. Static loads, mass and damping

To carry out the numerical simulations, a vertical load distributed in the beams was considered, in order to simulate permanent loads, taking into account the weight of the reinforced concrete elements, the masonry infill panels, coatings and the value of the overload ($\psi 2 = 0.2$). As a result of the assessment and observation in situ of permanent and variable loads on the building, the average value of 8.0kN/m2 was considered as distributed load on the floors [Rodrigues, 2006]. In the dynamic analyses, the mass of the structure was considered as being concentrated on the floors. On each floor, was considered the mass of the reinforced concrete structural elements, masonry infill panels, coatings and the value of the overload, an average value of about 4000tons/floor has been estimated.

2.2.3. Soil

Soils in the area under study are included, according to previous studies [Teves Costa et. al, 2004], in the so called rock formations of the Jurassic, Cretaceous, Volcanic Complex of Lisbon and Eruptive Massif of Sintra. As such, the soil adopted in the numerical model is characterized, according to the National Annex of the European regulation as belonging to type A. In fact, as for the soil type, and based on previous studies, there is, in Lisbon, in particular in the area of Av. Infante Santo, a type A soil, with a predominance of rock.

2.2.4. Seismic action

The seismic action applied to the structure was represented by the spectrum proposed by EC8 (Fig. 2.4.). With regard to territory zoning, one can conclude that the city of Lisbon is included in zone 1.3, for far earthquakes (Type 1) and in zone 2.3 for near earthquakes (Type 2).

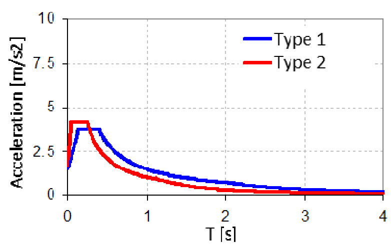


Figure 2.4. Spectra of elastic response in period for Lisbon, type A soil, for both seismic actions

In the analyses carried out, the seismic action applied to the structure was represented by an artificially generated temporal model based on a finite fault model [Carvalho, 2008]. Earthquakes thus obtained were calibrated to the Portuguese territory and was tried to simulate the likely occurrence of earthquakes in the area where the building under study is implanted. For this study, were used 10 earthquakes artificially generated for each reference return period considered, i.e, 43, 72, 475, 975, and also, 2475 years.

To use the set of routines developed for the implementation of mathematical models based on wave theories (MDF + LNEC and MDF + TLD_LNEC), the seismic action was introduced in the form of time series of displacements, velocities and accelerations to solve the equation of movement obtained for each structural system [Falcão Silva, 2010].

2.3. Dynamic Characterization

On the basis of graphics displayed, taking into account the main frequencies which influence the system, obtained in the modal analysis (Table 2.1), it is also possible to identify, for the fundamental vibration modes of the structure, which is the seismic conditioning action and thus perform the corresponding dynamic analyses.

Table 2.1. Frequencies and accumulated participation factors of mass

Mode	Freq [Hz]	Part Masses x [%]	Part Masses y [%]	Characteristics of the mode
1	1.09	99.91	0	1ºLongitudinal
2	1.75	99.91	0	1ºRotation
3	1.79	99.91	93.66	1ºTransversal
4	4.92	99.91	99.35	2ºTransversal

Considering the frequencies of the structure obtained for the analyzed modes, as well as the accumulated mass participation factor, it appears that in this particular situation, the conditioning seismic action to about 3.5Hz corresponds to the action of far earthquakes, while above this value the conditioning action corresponds to near earthquakes. Once over 90% of the mass contribution is reached with the first 3 modes, corresponding to frequencies below 1.79 Hz, there is a predominance of far earthquakes over near earthquakes. The numerical simulations presented were carried based on artificial earthquakes characteristic of far earthquakes, with higher content of lower frequencies, thus potentially affecting more significantly the building under study, since its frequencies in the main longitudinal and transverse translation directions are about 1.08Hz and 1.79Hz, respectively.

3. DESIGN OF TLDS FOR VIBRATION MITIGATION

In the mentioned routines, TLD have been considered, by introducing in the data file of their geometric characteristics the specific weight of the fluid present inside and, furthermore, the number of devices necessary to verify the desired mass ratio between the TLD set and the structural system to which they are coupled. It was assumed that the rectangular TLD selected for this purpose are placed in uniform distribution, so that loads are transmitted better and in a more balanced way throughout the building structure. This distribution appears to be the most appropriate, since it allows that the performance of the set of devices for dynamic vibration mitigation is undoubtedly the most efficient and safe. Each rectangular TLD was defined in accordance with the prototypes tested during the experimental program developed in the scope of a PhD [Falcão Silva, 2010]. Prototypes have in the longitudinal direction 0.446m length, by a total width of 0.235m in the transverse direction, corresponding to a free value of 0.422m by 0.211m, respectively, due to the fact that the thickness of each wall of the device is 0.012m.

The TLD designed and introduced in the mathematical model were considered as grouped in sets with varying number of tank modules, compatible with the plan dimensions of the structure and dependent on the mass ratios to be checked. Thus, each module was defined by a mesh of 7 containers in the transverse direction of the building and 9 containers in the longitudinal direction. Each level of a module has 63 TLD with overall dimensions of 4m by 1.65m. For each TLD module, reservoir platforms are overlapped vertically, depending on the desired mass ratio, μ.

Given the plan dimensions of the structure at the ground floor, this configuration of tank modules allows proper accessibility to every single tank through a circulation lane around them for the purpose of maintenance and eventual repair of the various units when necessary. Fig. 3.1. shows the schematic representation of a possible location in plan of the sets of TLD modules in the real structure, taking into account the existence of a circulation lane around the tank modules to allow proper accessibility to all individual tanks for maintenance and repair purposes when necessary. The schematic representation of the location of TLD modules in the building façades is presented in Fig. 3.2.

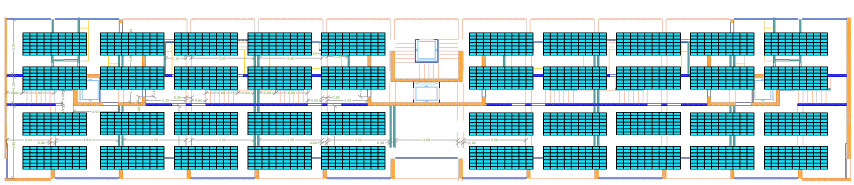
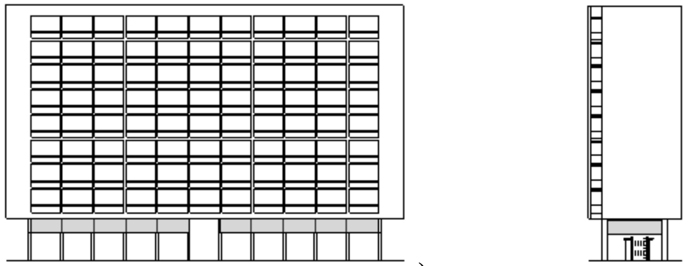


Figure 3.1. Schematic representation of a possible location in plan of TLD modules.



a) b)

Figure 3.2. Schematic representation of TLD location on the ground floor: a) SO façade and b) SE façade.

This hypothesis appears to be very attractive, since the ground floor has an available height of 5.5m, which is compatible with the placing of the desired levels of TLD, being only required to create a bearing structure, for example, metallic, rigidly connected to the building structure, to bear the impact caused by the fluid motion inside TLD devices. It should be noted that the aforementioned bearing structure should be sufficiently stiff, so that it will not act as an additional pendulum.

It should also be noted that, at this stage, no safety check has been made on slabs, beams or pillars, having in view the load increase associated with the installation of the devices. However, it is assumed that there should be no significant problems in terms of structural safety, since the installation of the vibration mitigation devices is being proposed for the ground floor, area in which sections of the structural elements have undoubtedly more generous dimensions to meet the loads considered in the design.

4. ANALYSIS AND INTERPRETATION OF THE OBTAINED RESULTS

Several analyses were performed using the routines developed with the purpose of evaluating the performance of TLD devices for dynamic vibration mitigation, when implemented in real structures. The devices considered were perfectly adjusted to the longitudinal direction, i.e. for a frequency of 1.08Hz, while, for the transverse direction, adjustment is only approximated to a frequency of 1.79Hz.
The analysis of the results obtained allowed to obtain the profiles of lateral displacement, the profiles of interstorey drift, the temporal variation of the dissipative force associated with the fluid motion inside TLD devices, dissipative force-displacement ratios and the dissipated energy for the several series simulated, for the different directions and return periods considered.

In addition to the aforementioned variables, average efficiency rates were also determined, based on all time series simulated, for each mass ratio situation of the devices in question and the structure and return period, determined in accordance with the proposed in previous work [Falcão Silva, 2010]. As examples, are presented below the profiles of the lateral displacements (Fig. 4.1.) and drifts (Fig. 4.2.) obtained for the series whose spectrum is closer to the average spectrum of the set of all simulated series, for a return period of 475 years and variable mass ratio (of the TLD set and the structure).

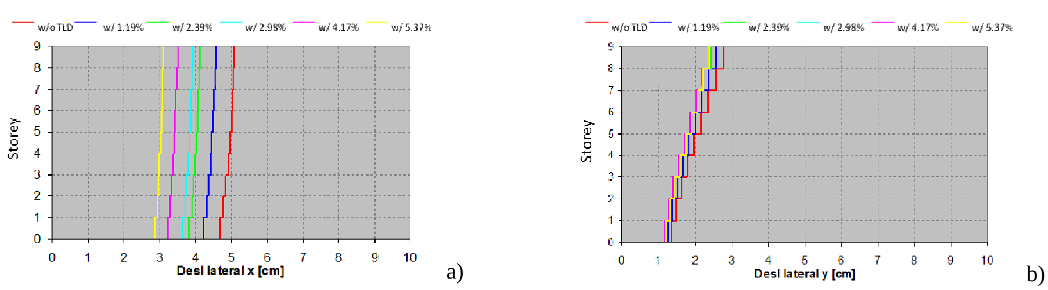


Figure 4.1. Lateral displacement profiles (PR 475): a) longitudinal direction and b) transverse direction

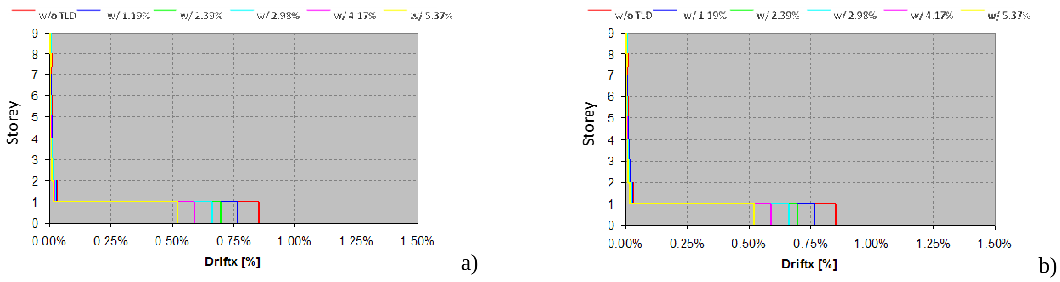


Figure 4.2. Drift profiles (PR 475): a longitudinal direction and b) transverse direction

Analysis of the results presented, for lateral displacement and drift profiles shows that, as expected, the building presents a behavior characterized by the concentration of deformations at the ground floor, which can favor the emergence of a soft-storey mechanism. This behavior is more evident in the longitudinal direction. The upper floors hardly deform, concentrating almost all deformation demands at the ground floor, what reinforces the idea of implementing the TLDs at this level. This behavior is still observed for seismic loading higher than the regular seismic action, and a very considerable increase in the deformation levels installed in both directions is also observed. As regards the behavior of the main structural system with TLD devices with different mass ranging from 1.19% to 5.37%, there is very considerable deformation reductions for all levels of dynamic action imposed, as can be evidenced in previous works [Falcão Silva, 2010].

As frequency adjustment is, as already noted, better for the longitudinal direction, it is obvious that the deformation reduction introduced by devices with different mass ratios will be more evident for the longitudinal direction. The identified reductions reflect evident changes in the performance levels recommended by VISION2000 [SEAOC, 2005]. Fig. 4.3. shows the dissipative force-displacement ratios, varying with the percentage of mass considered, for each direction analyzed and corresponding return periods; in Fig. 4.4., are included graphical representations corresponding to the dissipated energy.

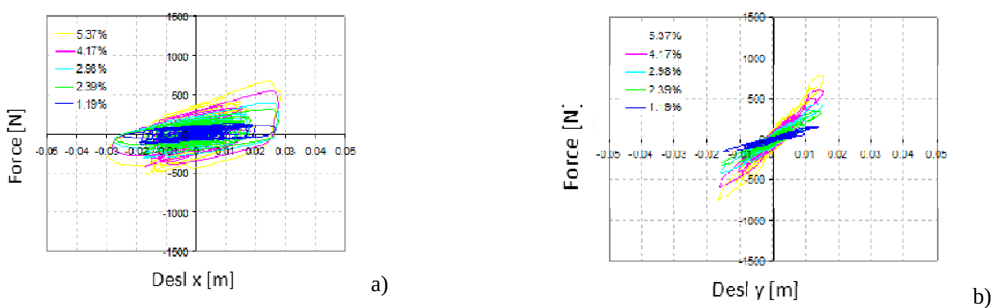


Figure 4.3. Dissipative force – displacement ratio (PR475): a) longitudinal direction and b) transverse direction

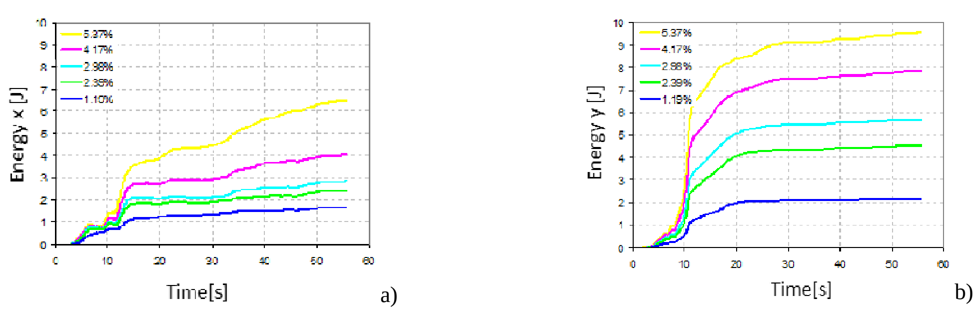


Figure 4.4. Dissipated energy (PR475): a) longitudinal direction and b) transverse direction

The analysis of Fig. 4.3 and Fig. 4.4. allows to confirm that the actual increase of the dissipative force in each direction is generally higher than the effective increase of the displacement registered in the same direction. One can thus conclude that in fact there is an effective increase in the dissipated energy for each direction, which may enhance the applicability of such devices in mitigating vibrations associated with seismic actions. In the direction in which the TLD frequency is optimally adjusted to the frequency of the structure, we observed that the dissipative force-displacement ratio shows a gradually increase from lower return periods to higher return periods, which affect the energy dissipated. For regulatory return periods (PR475) the energy dissipated in the transverse direction corresponds to approximately twice the energy dissipated in the longitudinal direction. One reason for this may be related to the fact that, for example, for these types of actions, a better frequency adjustment occasionally occurs in the transverse direction, which is specifically responsible for a better performance in this direction with consequent repercussions on vibration mitigation [Falcão Silva, 2010].The efficiency of the solutions studied throughout this work, in terms of displacement and acceleration reduction, can be evaluated based on efficiency rates [Falcão Silva, 2010]. These rates, calculated based on the results obtained in numerical simulations for the different time series and return periods are undoubtedly an excellent measure for defining criteria for the implementation of TLDs in real structures, existing or to be constructed. In Fig. 4.5 is presented, on average, the evolution of efficiency rates, in terms of RMS values of displacement, in each direction, for the particular situation of the structural system studied.

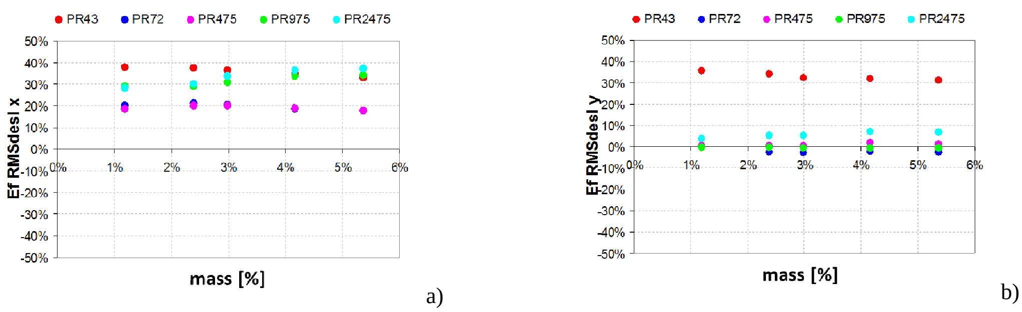


Figure 4.5. Average efficiency rates for RMS values of displacements on top of the structure: a) longitudinal direction and b) transverse direction

5. QUANTIFICATION OF PERFORMANCE LEVELS

The graphical representation of lateral displacements envelopes of the linear analysis carried out for different mass percentages and return periods considered in numerical simulations enables the evaluation of performance in terms of deformation of the structural system (Fig. 5.1).

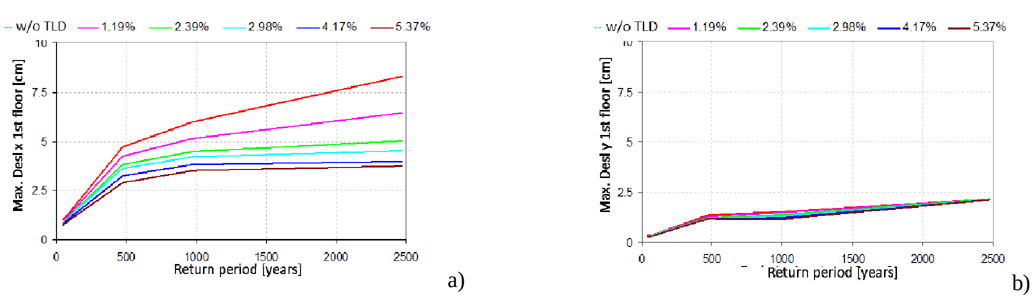


Figure 5.1. Maximum lateral displacement of the 1st floor for each return period and mass ratios: a) longitudinal direction and b) transverse direction

From the analysis of the displacement obtained in the linear regime, it appears that in fact deformation is concentrated at the first floor in the longitudinal direction, which will reflect the aforementioned soft-storey mechanism which is enhanced this level. Confirmation of this fact may be made by means of nonlinear dynamic analyses [Rodrigues, 2006]. In addition, there is, in the transverse direction an improvement in performance up to return periods of 975 years which becomes inverse for higher actions (PR = 2475 years). This inversion in trend seems to indicate the prevalence of TLD devices operation preferably in a direction which, in this case, corresponds to the fundamental direction of the structure, ie the longitudinal direction, in which, in no circumstance, devices lose their efficiency.

Since the building under study is a current structure, it is understood that it falls in the class of structures which must meet the eligibility criteria defined as basic objectives, according to the proposed in Vision 2000. In fact, taking into account the criteria for each performance objective, it is possible to define a relationship between the return period of the dynamic action, directly related to the peak ground acceleration, and the maximum displacement between floors or interstorey drift. In Fig. 5.2. is presented the representations that enable the quantification of performance levels by comparison with what was proposed in VISION2000 [SEAOC 2005].

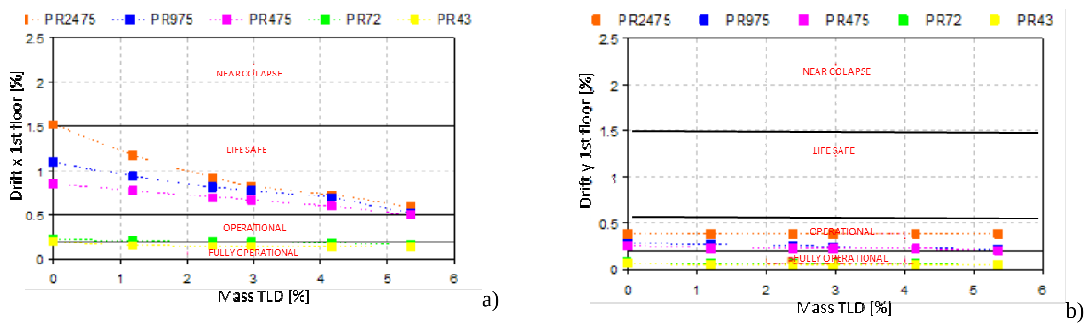


Figure 5.2. Maximum deformation (drift) demand for each structure and for each return period: a) longitudinal direction b) transverse direction

For both directions, the interstorey drift reduction can be globally observed with the introduction of TLD devices and increasing mass ratio considered. In fact, the efficiency of such devices can be clearly confirmed, but , in some situations, we verify the passage from a performance level to the level immediately above, as identified in the longitudinal direction for seismic actions with return period between 475 and 2475 years, in which we pass from a level of saving life to a level of operability. For actions with lower return period, behavior is almost constant, regardless of the amount of mass introduced in the form of water inside the TLD, although for the highest mass ratios tested, we can observe the passage from a performance level of operability to full operability. The observed facts seem to confirm the better efficiency of TLD devices for more violent seismic actions.
As regards the transverse direction, regardless of the return period seismic considered the behavior of the structure without TLD or with TLD remains constant. In this case, this can happen because the frequency adjustment is not as good in this direction as in the longitudinal direction.
In spite of what has been mentioned, very accurate conclusions cannot be drawn in what concerns the safety of the structure under analysis, since we are in the presence of results obtained in linear analyses. Thus, the estimation of response to verify the basic performance objectives, in accordance with international recommendations VISION2000 [SEAOC, 2005] and ATC-40 [ATC 40, 1996], should have been performed using more sophisticated (nonlinear) models, since the estimated actual response will certainly correspond to the installation of certain levels of damage to the structure.

6. CONCLUSIONS

The obtained results allow to drawn some conclusions about the adequacy of implementing such type of passive devices for dynamic loads mitigation on existing structures without specific seismic design.
The displacement reduction observed on top of the structure, after inclusion of TLD devices, varies significantly depending on the intensity of the dynamic action imposed and the percentage of mass

considered. After analysis of displacements, it was found that the structure does not meet, for all levels of seismic action, the seismic safety requirements recommended by VISION2000 [SEAOC, 2005], reason why it is necessary to introduce deformation reduction measures, so that the structure can meet those requirements. However, in most situations simulated, the introduction of TLD devices allows to mitigate the adverse effects of dynamic actions imposed, being responsible, for example, for the reduction of calculated damages, and immediately allowing lower performance levels to be observed. This observation is confirmed for any return period considered. Dissipative forces, dissipative forces - displacement ratios and dissipated energies were also determined and they enabled us to strengthen what was identified for displacements, ie, that the introduction of TLD allows a very significant vibration mitigation, for any action imposed, and mass ratio between the set of devices and the structure in which they are included.

It can also be seen that the efficiency of the devices is so much better as the frequency adjustment is better, as can be confirmed by the results obtained for the longitudinal direction ($\gamma = 1.0$) and the transverse direction ($\gamma \neq 1.0$). The efficiency of the TLD devices placed in the structure of Av. Infante Santo grows with the mass ratios simulated, what can be justified by the violence of the impact of the fluid inside the device. In fact, these impacts can increase the dynamic mass mobilized, with the consequent repercussions that such a situation will have on the structure, ie, in the impact force that arises and that is used to oppose the movement of the structure. Due to the proven agreement between previous experimental results and the results of numerical simulations, it is believed that, in fact, the proposed calculation tools are an excellent way of simulating the behavior of real existing or new structures, as they approach not only the behavior of the structure as well as its overall behavior with passive devices for vibration mitigation, such as TLD, included [Falcão Silva, 2010]

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