Seismic Retrofitting of Structures with Tuned-Mass Systems

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SUMMARY:
The usual retrofitting of existing structures by strengthening measures is sometimes not possible, insufficient and/or uneconomical. Instead of conventional strategies or as an additional measure Tuned-Mass Control Systems (TMCS) can be used for the seismic upgrade of structures. The TMCS causes a significant reduction of induced acceleration and displacement levels as well as of internal stresses and support reactions. The present paper introduces the effectiveness and the parameters of such systems. As an executed example the application of the TMCS for the building Palatul Victoria in Bucharest, Romania will be described. The most important results of the numerical calculations of the structure will be shown. Selected pictures of the installation procedure and pictures of the final situation demonstrate the general applicability of the applied system.

Keywords: Passive Control, Tuned-Mass Control System

1. INTRODUCTION

In technical literature Tuned-Mass Systems are discussed controversially in regard to their efficiency against seismic action. Although Tuned-Mass Systems are widely used to reduce effects of wind and traffic excitation in standard applications nowadays, their efficiency has not yet been accepted in seismic design. While some investigations (Chung, Mohraz, Sadek and Taylor, 1997) have shown a noticeable reduction of the structural response to earthquake loads, the effectiveness has been denied by others. Most of the opposition is related to the operation frequency of the TMCS which is understood as a single value only. Modern Tuned-Mass Systems are working in a broad frequency band and thus, the efficiency is also given for altering structural characteristics.

Passive seismic control strategies are based on the reduction of energy, which affects a structure in case of an earthquake excitation. A well accepted strategy is the increase of structural damping.

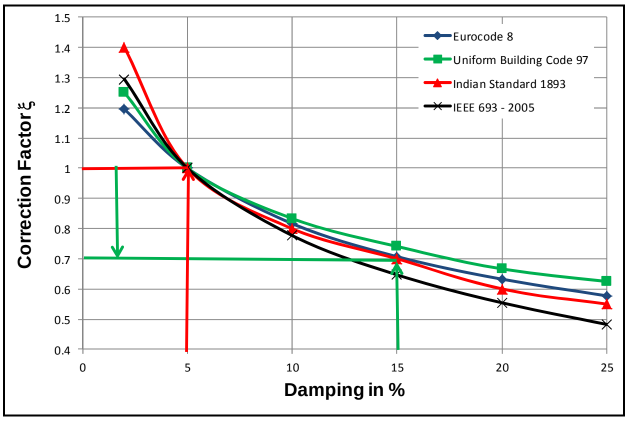

Figure 1.1. Seismic mitigation effects due to increase of structural damping

Fig. 1.1. shows the possible reduction of induced structural responses by the increase of viscous damping. Details can be taken from different national and international regulations. As an example, the increase from 5 % to 15 % of critical damping would cause a reduction of the induced seismic responses by about 30 % according to the Indian provisions (IS 1893).

The installation of a Tuned-Mass Control System will lead to a significant increase of damping. Thus, the demand curve will be lowered. The capacity curve will remain nearly unchanged in comparison to the capacity curve of the original structure. Theoretical investigations (Brendike, Petryna, 2011), taking into account nonlinear behaviour of the structure, describe the efficiency of Tuned-Mass Systems in case of earthquakes.

The commonly known optimization criteria formulated by Den Hartog (1956) is usually only suitable for a harmonic excitation. The application of Tuned-Mass Control Systems (TMCS) to reduce the response of earthquake loading requires some different criteria. This is one main reason for the controversial acceptance of the effectiveness of such systems for seismic cases.

The effectiveness of these systems is strongly dependent on the specification of the guiding TMCS parameters such as effective mass, tuning frequency and internal damping ratio. Several analytical and experimental investigations (Rakicevic, Zlatevska, Jurukovski and Nawrotzki, 2006) have been performed to verify the effectiveness of a TMCS. Furthermore, theoretical approaches have been used to find the optimum specification for the parameters of a TMCS.

2. TUNED-MASS CONTROL SYSTEMS FOR SEISMIC PROTECTION

Tuned-Mass Controls Systems (TMCS) consist of an additional mass, which is usually arranged at the highest level of a building (see Fig. 2.1.). It is elastically connected with the building by springs such that the corresponding frequencies are related according to specific rules. Additionally dampers are arranged to reduce the relative motion between additional mass and building and to widen the operating frequency band of the TMCS accordingly. The TMCS causes a significant reduction of induced acceleration and displacement levels as well as of internal stresses and support reactions due to seismic excitation.

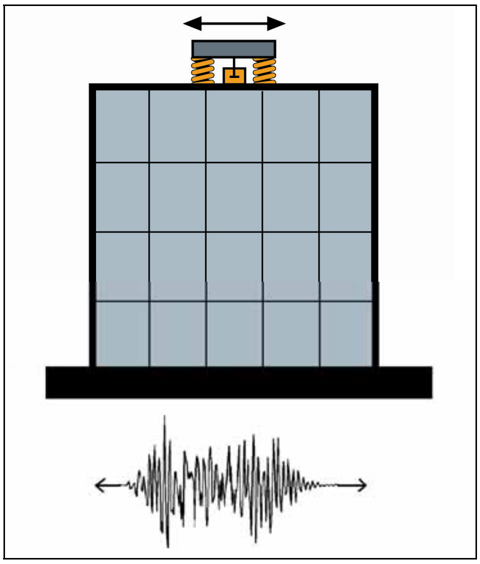

Figure 2.1. Principle of a Tuned-Mass Control System

As the use of passive tuned-mass systems for the seismic protections is in a controversial stage, it was required to perform several experimental and numerical investigations to determine the efficiency of these systems.

2.1. Experimental Investigations

Several practical tests have been performed at IZIIS (Institute of Earthquake Engineering and Engineering Seismology) in Skopje, Macedonia. The biaxial shaking table of this facility is able to generate a horizontal acceleration input up to 3.0 g, as well as a vertical acceleration input up to 1.5 g. The previous listed values apply for a zero pay load. The maximum pay load of the 5.0 x 5.0 m table amounts to about 40 tons.

A five-story steel frame model (see Fig. 2.2.), equipped with a Tuned-Mass Control System is tested. The total mass of the steel structure amounts to 19.0 tons and the mass of the TMCS is 0.26 tons. The mass of the TMCS is chosen as 1.3 % of the entire mass. The height of the steel frame system is 3.75 m, the height of each floor amounts to 0.75 m. The dimensions of the three spans in longitudinal direction are 1.5 m. The one span in transversal direction has got a length of 1.5 m. The red bracing structure in Fig. 2.2. is used to adjust the required stiffness and damping for the tests.

Figure 2.2. Tested model on the shaking table

Steady-state vibration tests, random vibration tests and hammer tests are performed to test and verify the natural frequencies and corresponding modal damping values of the structure. Several measured and artificial seismic time-histories with different intensities are simulated by the shaking table to excite the structure. For the evaluation of the tests time history responses of absolute displacements, relative displacements, absolute accelerations and bending strains are measured at several locations at the frame. The results of the frame with activated and with blocked Tuned-Mass Control System are compared to investigate the efficiency of the system.

As a typical example the recorded relative displacements at top of the structure and the bending strain at the bottom of the middle column are presented. Fig. 2.3. shows that the activated tuned-mass system causes an improvement of performance by nearly 40 %.

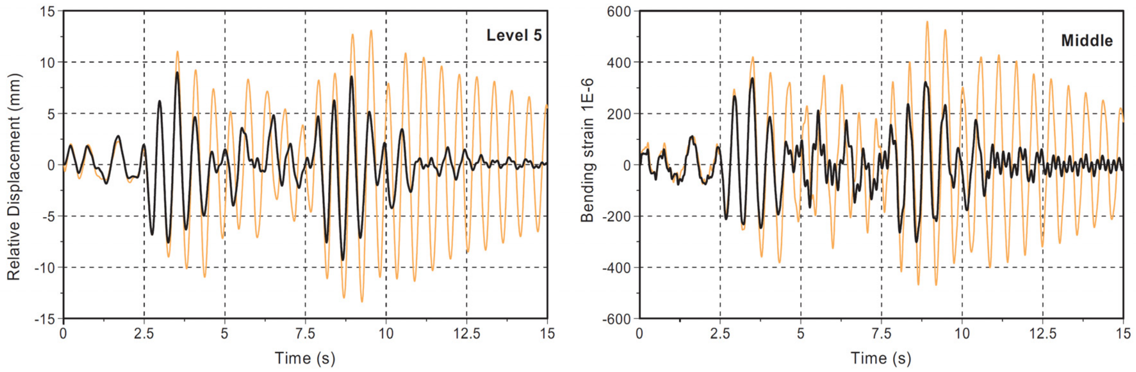

Figure 2.3. Recorded responses with activated (black curve) and locked TMCS (orange curve)

Evaluating the large number of recorded time history responses it can be concluded that the TMCS reduces the structural responses by about 25 % - 40 %. More detailed information can be found in Rakicevic, Zlatevska, Jurukovski and Nawrotzki (2006).

2.2. Numerical Investigations

In parallel to experimental investigations it is important to perform also numerical investigations. In Fig. 2.4. an example for the numerical modeling of a building without and with a Tuned-Mass Control System is given. On the left hand side the structure without TMCS is shown. The same building, equipped with 4 reinforced concrete mass blocks is shown on the right hand side.

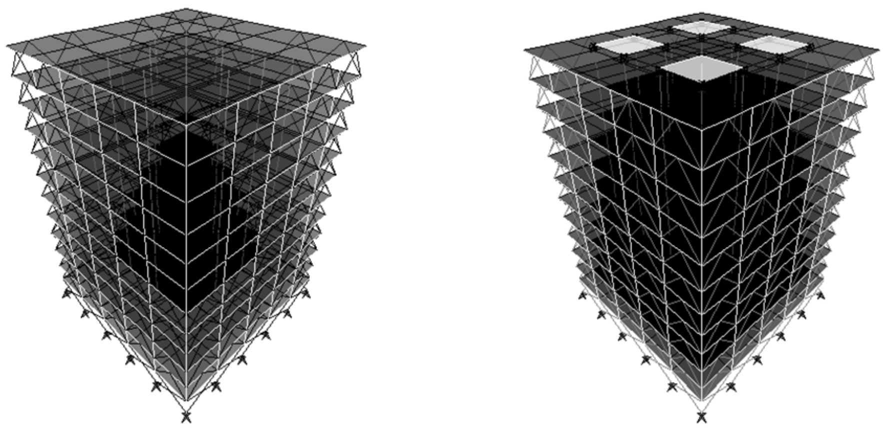

Figure 2.4. Computer model without (left) and with TMCS (right)

In case of an existing structure/building a first step for the calculation procedure could be the performance of vibration measurements of the structure. Afterwards it is possible to adjust the numerical model according to the results (e.g. natural frequencies) of the measurements. The choice of the parameters of the TMCS as effective mass, tuning frequency and internal damping ratio is guiding the effectiveness of the protection system. Depending on the structural system of the existing building the additional mass could be defined. The commonly known optimization criteria formulated by Den Hartog (1956) is not fully applicable as they are developed in regard to harmonic excitations. To widen the working frequency band of the TMCS it is recommended to use a higher internal damping ratio – up to 20 % – 30 %, depending also on the target motion values.

The TMCS significantly reduces the structural responses of the building. Relative displacements, absolute accelerations and internal forces are decreased. As an example the comparison of the horizontal displacement at the top and the axial force at a corner column is shown in Fig. 2.5. The response of the original, unprotected structure is plotted as a red curve and the blue curve shows the behaviour of the protected building. The induced peak responses are reduced by about 40 %.

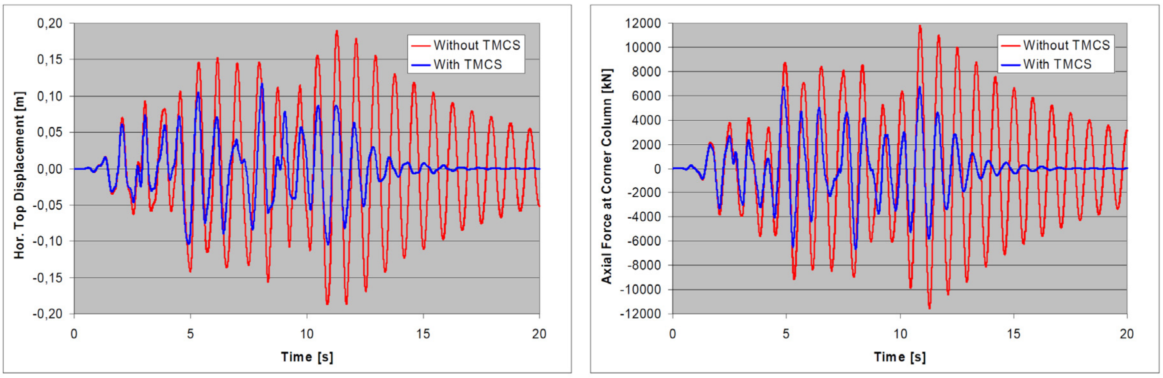

Figure 2.5. Typical time history responses with/without TMCS

It becomes obvious that the TMCS causes an increase of damping for the building. After the strong motion phase at about 10 s the residual motion is significantly damped out during 2 - 5 seconds in the system with TMCS. The unprotected system shows still high amplitudes in this time domain.

3. EXECTUED PROJECT: PALATUL VICTORIA

The seismic upgrade of Palatul Victoria was finished in summer 2011. The following paragraph describes the details of this interesting project.

3.1. General

The building Palatul Victoria (see Fig. 3.1.) was built in 1937 and is located in downtown Bucharest at the north eastern side of Victoria Square. The palace is a monumental building that covers a front of about 100 m, enclosing two courtyards connected with the ground floor. The length of the shorter side amounts to about 46 m. The maximum height of construction is about 46 m. The building occupies an useable area of about 20.000 m². The structure consists of reinforced concrete members, especially columns, beams and floors as well as of brickwork.

Figure 3.1. Front view of Palatul Victoria, Bucharest, Romania

The structure of the existing building consists of 6 different parts which are separated by joints. The clearance is very small and in case of an earthquake high interstorey drift ratios as well as hammering effects can be expected. Corresponding damage may affect columns, walls and panelling and the necessary repair work would be tremendous. As a consequence, the building could not be used in the meantime, which is not acceptable because of its importance for the Government of Romania.

3.2. Consolidation Strategy

For the improvement of the seismic behaviour of the building a suitable measure was developed. This measure consists of a combination of two methods. In the first step some floors were coupled in a way that the relative motion between the separated parts became very small in case of an earthquake. To reduce the interstorey drift ratio traditional strengthening methods were chosen. Due to the importance of the building the areas where shear walls can be placed are very restricted and hence, the number and size of these walls were not sufficient to achieve the required seismic safety.

Therefore this strategy has to be complemented by additional measures. The chosen TMCS consists of an additional mass, arranged at the highest level of the building. It is elastically connected with the building by springs. Additionally, Viscodampers® are arranged to reduce the relative motion between additional mass and building and to widen the operating frequency band of the TMCS accordingly. In case of seismic events a large portion of the energy is transferred to the Tuned-Mass System. The TMCS causes a significant reduction of induced acceleration and displacement levels as well as the reduction of internal stresses, support reactions and interstorey drift. Brendike and Petryna (2011) mention one further advantage: Usually a Tuned-Mass Control System can be applied to an existing building without limitations in the use of the building.

3.3. Seismic Excitation

At the site of Palatul Victoria seismic events have to be taken into account. The elastic response spectrum (see Fig. 3.2.) can be described as follows:

Peak ground acceleration	0.36 g
Spectral amplification factor:	2.75
Resonance plateau with	0.99 g at 0.63 – 6.30 Hz

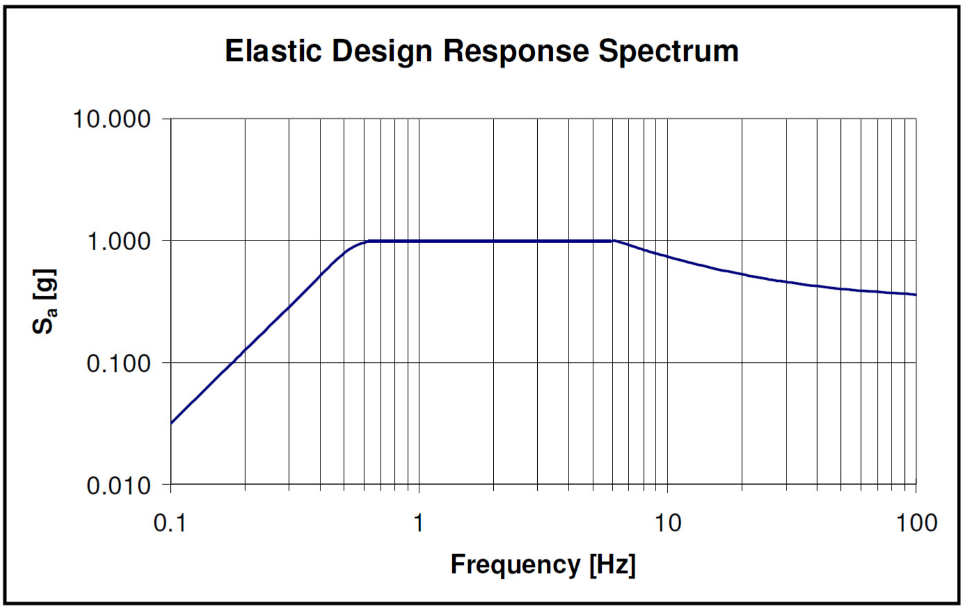

Figure 3.2. Design spectrum (D=5.0 %)

3.4. Details of Tuned-Mass Control System

At the beginning of the project several calculations (response spectrum analyses and time history analyses) are performed to define the optimum parameters for the TMCS. Fig. 3.3. shows the three dimensional model prepared by using the commercial software SAP2000.

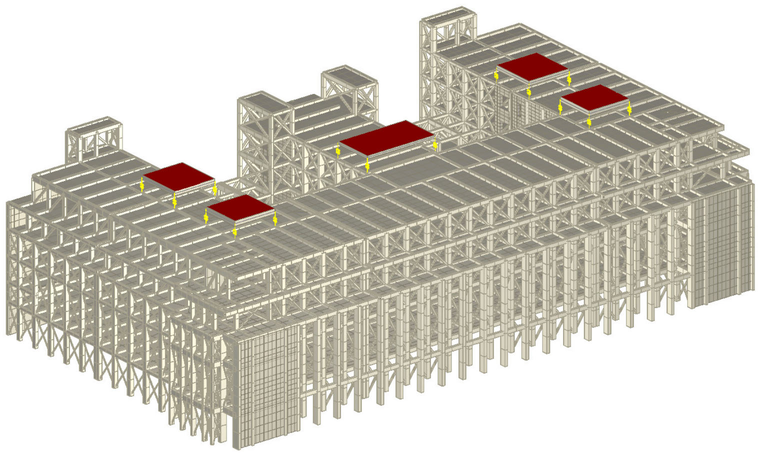

Figure 3.3. Computer model of Palatul Victoria with mitigation measures

The computer model was adjusted to the results of the field measurements. Altogether three different computer models are created to consider the single steps of the consolidation strategy as follows:

Model A: Original system with joints, without shear walls and without TMCS.
Model B: System with additional shear walls and with some connected floors.
Model C: System with additional shear walls, with some connected floors and with TMCS.

The results of the calculations show that the TMCS significantly reduces the top storey displacements, interstorey drift ratios, response accelerations and as a consequence induced internal stress responses due to earthquakes. In Fig. 3.4. the corresponding efficiency of the proposed measures are shown by comparing some important values.

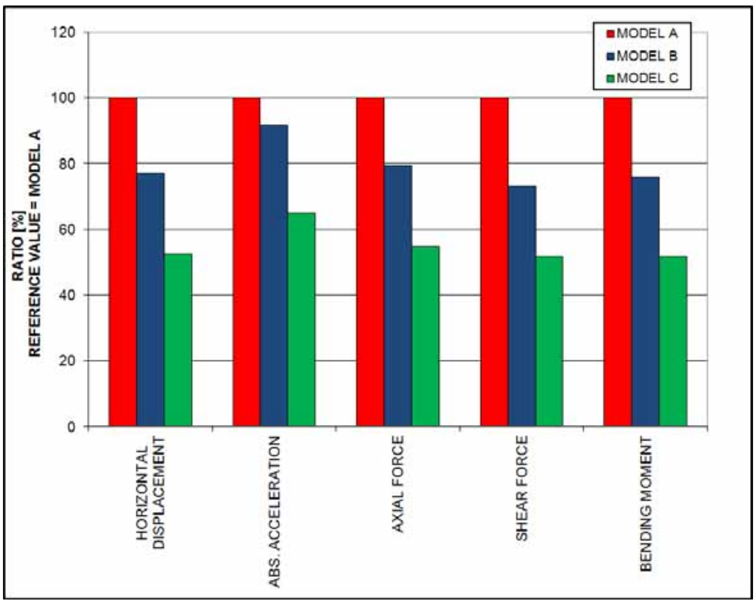

Figure 3.4. Efficiency of conventional retrofit and efficiency of conventional retrofit and TMCS

Finally, a Tuned-Mass Control System consisting of the following elements was chosen:

- 5 concrete structures (each one has a mass of about 96 tons) / supported by sliding bearings. The mass ratio between TMCS and total weight of the building amounts to about 1.2 % only.
- Each block is connected with spring elements to the roof in both horizontal directions.
- Damper elements are arranged.

Theoretical approaches according to Meinhardt and Siepe (2010) have been used to determine the parameters of the TMCS. A high internal damping ratio led to a more robust specification in terms of varying structural stiffness and inherent damping.

After the implementation of the new shear walls and the coupling of the slabs the concrete blocks are poured and the required embedded parts for the connection between spring element / damper element and the roof are fabricated and installed. Fig. 3.5. shows one of the blocks, already equipped with some of the devices.

Figure 3.5. TMCS at roof of building

Prior to the final installation of all elements, vibration measurements are performed. First ambient vibration measurements of the building are carried out. Additionally, also the modal parameters of the TMCS are measured. The tuning of the system was done, by choosing/changing the springs, which are mounted inside the elements. Finally, all concrete blocks are equipped with the required devices (see Fig. 3.6).

Figure 3.6. Installed elements

As the TMCS is located at the roof of the building, it was decided to arrange an enclosure around each block. The final situation can be seen in Fig. 3.7.

Figure 3.7. Final situation – TMCS with enclosure

Thus, the TMCS is protected against dust, dirt and other environmental influences. Summarizing the costs for the Tuned-Mass Control System itself, the concrete mass and the corresponding construction works the total costs amount to about 38 – 40 EURO/m² (useable area). The costs for the conventional measures are not included in this sum.

4. CONCLUSION

The presented retrofitting strategy possesses a large variety and represents an example of cost effective solution in order to improve the seismic performance of structures. In addition to the description of the experimental and numerical investigations the details of an executed project were presented. To achieve the highest effectiveness possible for the seismic upgrade of the existing government building Palatul Victoria a consolidation strategy has been introduced.

The strategy included the application of a Tuned-Mass Control System. Results of numerical calculations of the TMCS in combination with additional strengthening measures have been presented. It was shown that the application of a TMCS leads to a significant reduction of the structural response in terms of displacements, accelerations and internal stresses. Additionally, pictures of the executed works have been presented.

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