16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 4953

Registration Code: S-L1461695065

RETROFITTING OF A HOSPITAL USING A TUNED MASS CONTROL SYSTEM

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Abstract

The contribution deals with the description of the seismic retrofit strategy for a hospital in Slobozia, Romania. After a brief introduction in the basic principles using a Tuned Mass Control System (TMCS) for the seismic control of structures, details of the executed project are presented. Results of numerical and experimental investigations are described to verify the effectiveness of the mitigation measures. A TMCS consists of an additional mass, usually arranged at the highest location of a structure. Helical steel springs can be used to connect the mass elastically with the structure. The stiffness properties of the spring elements are chosen to tune the corresponding frequencies of the TMCS in regard to the authoritative frequency range of the main structure. Viscous dampers are installed in parallel to the spring devices to widen the operating frequency band of the TMCS and to reduce the relative motion between the two structures. The protection system is able to reduce the induced acceleration and displacement levels as well as the internal stresses, support reactions and interstorey drift due to seismic loadings. Another important advantage is the possibility to operate inside the building as there is no disturbance by the upgrade activities.

Keywords: seismic retrofit; tuned mass control system; passive control

1. Introduction

Previous experience has shown that there is a significant threat of existing structures caused by earthquakes. There are many examples of existing buildings and cultural heritage that are not sufficiently protected against seismic demands. If the seismic safety of these structures is inadequate, a retrofitting strategy has to be developed. In contrast to the well-known conventional strengthening methods nowadays several projects utilize different or additional protection measures, like the arrangement of a Tuned Mass Control System (TMCS). A TMCS provides a passively working seismic protection. The system absorbs horizontal forces and is practically maintenance-free. Electrical power supply or any other form of drive or control mechanism is not required. TMCS are immediately effective when an earthquake strikes. They are applicable for the protection of existing or new structures against seismic demands.

A typical example of such a protection system can be seen in Fig.1, showing the building complex Palatul Victoria in Bucharest, Romania. The building, consisting of reinforced concrete members, as well as brickwork, has a length of about 100 m with a width of about 50 m and a height of about 24 m. This structure was built around 1937 and is used by the government of Romania. As the seismic demands were not considered during the design phase of the building a seismic retrofit was required to keep the limits of current standards, especially in related to interstorey drift values.

Fig. 1 – Front view of Palatul Victoria (left side) and TMCS at its roof (right side)

The seismic consolidation strategy consisted of the combination of conventional strengthening measures and the implementation of a TMCS. Fig. 1 shows one of five concrete blocks of the TMCS during its installation in 2011. The concrete block, weighting roughly 96 metric tons, is supported vertically by sliding bearings and elastically connected to the building with steel springs in horizontal direction. Viscous dampers are arranged additionally to reduce the relative displacements between mass block and building and to widen the effective frequency band of the TMCS. According to [1] the seismic responses in terms of interstorey drift and internal forces could be reduced by about 50 %. The important limits of the interstorey drift could be kept as well. The decisive advantage of the mitigation measures was the possibility to install the TMCS at the roof – without interrupting the use of the building. An important advantage of the TMCS is that this system can be used for the seismic retrofit of existing buildings as the inside of the structure is usually not objective to modification. Hence, the usual operation, like meetings of the government in the banquet rooms of Palatul Victoria, may go on during the upgrade activities.

The current paper starts with the presentation of some application principles of a TMCS as seismic protection measure and introduces the effectiveness and the parameters of such systems. Results of analytical and experimental research will be discussed. As a corresponding executed example the arrangement of the TMCS for the seismic protection of a hospital in Slobozia, Romania will be described in detail. The small city Slobozia is the capital of Ialomita County and is located approximately 120 km east of Bucharest. Due to the importance of the mentioned Hospital for the region a seismic upgrade of the building was strongly required. Therefore, a retrofitting strategy was developed. The most important results of the analysis, the design and the implementation of the TMCS as part of the retrofitting measures will be presented. Several selected pictures of the installation procedure and pictures of the final situation demonstrate the general applicability of the TMCS for the seismic retrofit of new or existing structures.

2. Basics of Tuned Mass Control Systems

The increase of structural damping of buildings or other structures is a common and well-examined strategy to reduce the dynamic responses of a structure due to seismic excitations. The application of a Tuned Mass Control System is one approach to achieve the increased damping. The principle of these systems is shown in Fig. 2.

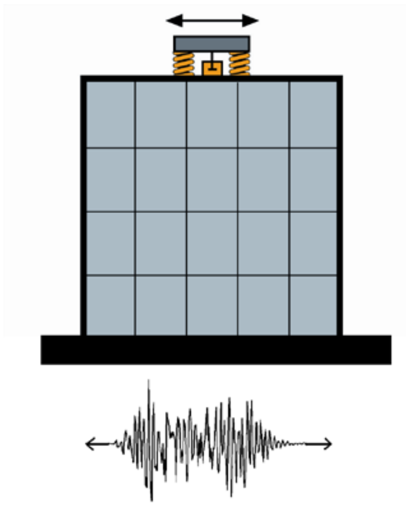

Fig. 2 – TMCS at highest elevation of a building

The additional mass, typically made out of concrete or steel, is usually arranged at the highest level of the structure. The mass block is connected with the substructure by springs such that the corresponding frequencies are related according to specific rules. Dampers are arranged additionally to reduce the relative displacements between tuned mass and structure and to widen the operating frequency band of the TMCS. The system yields a significant reduction of induced acceleration and displacement levels as well as of internal stresses and support reactions due to seismic excitation. Fig. 3 shows a typical result of calculated seismic responses of a structure.

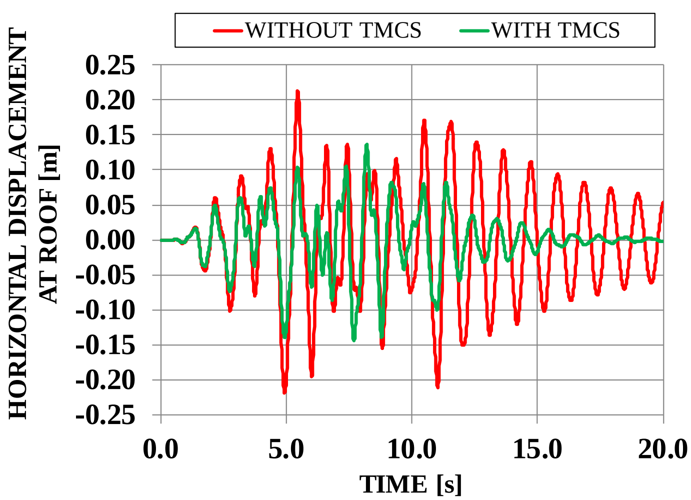

Fig. 3 – Analytical results of a structure with/without TMCS

The induced peaks due to seismic excitation are reduced by about 40 % in this example. Beneath the significant reduction efficiency it becomes obvious that the TMCS yields an increase of damping. After the strong motion phase at about 10 s the residual motion is significantly damped out during 2 to 5 s in the system with TMCS. During the mentioned time domain the result curve of the unprotected system still shows high amplitudes. The development of these systems is based on the wide experience from tuned mass damper systems that work against wind and men-induced vibration. For a seismic event it is important that the protection system works passively without additional electrical power supply. The helical steel springs and the viscous dampers are immediately effective when an earthquake strikes. The system is very efficient, even when the design is considering nonlinear structural effects as verified in [2].

A number of analytical studies were conducted to investigate the efficiency of such systems. For example, a reduction of seismic displacements in a range of 30 to 50 % is feasible, as presented in [3]. It is important to mention that the commonly known optimization criteria formulated in [4] are only applicable for harmonic excitations. For seismic applications it can be seen that a larger reduction of occurring reactions can be achieved if higher internal damping values are applied. Due to the subcritical tuning of the TMCS and the high damping the system works efficiently in a wide frequency range. Furthermore, the large damping values does not impair the efficiency of the TMCS considerably, as stated in [5] and it also helps to keep the relative displacements of the mass block in a certain range.

Experimental research on the mitigation effects of tuned mass systems for seismic applications was also performed. Within this scope, several shaking table tests have been carried out at IZIIS (Institute of Earthquake Engineering and Engineering Seismology) in Skopje, Macedonia. The main results of the tests of a steel frame model with and without TMCS are presented in [3]. Different seismic input data with different intensities were simulated by the shaking table and time history responses of displacements, accelerations and bending strain values are measured and compared to investigate the reduction efficiency of the seismic protection system. Summarizing the results of the extensive test program reveals that the TMCS reduces the structural responses in a range of about 25 to 40 %.

A TMCS is not only applicable for the protection of existing structures, like the government building at Bucharest, presented in Chapter 1 or the hospital that will be described in the following part of the paper. It is also a suitable approach for a new structure. A corresponding example is the Puente Oriente, also known as Puente El Alamo. This bridge is an elevated steel structure with a reinforced concrete deck, located near Guadalajara, Mexico. The total length of the bridge amounts to about 500 m with an average span of each bay of about 40 m. During the design of the structure it was discovered that the seismic behavior yields too large forces inside the concrete deck and the columns.

A Tuned Mass Control System was developed to improve the dynamic behavior of the structure during seismic events. For this purpose several calculations were performed. As described in [6] the time history analyses of the structure with and without protection system verified that the TMCS lead to significant reductions of seismic displacements, accelerations and base reactions in a range of 20 to 50 %. Finally, the structure was improved with 8 TMCS units underneath the deck in range of the central column structures to reduce the rocking vibrations of the bridge under seismic loads. Each mass block has a weight of approximately 10 metric tons and is equipped with a high internal damping ratio due to the installed viscous dampers between mass and bridge. Helical steel springs are arranged horizontally to tune the frequency of the system. Fig. 4 shows a view of the bridge and the installed mass block of the TMCS.

Fig. 4 – TMCS below bridge deck

3. Seismic Retrofit of a Hospital in Romania

This chapter exemplifies the seismic upgrade of an existing hospital in Slobozia, Romania. The small city Slobozia is the capital of Ialomita County and is located approximately 120 km east of Bucharest. The construction of the concerned hospital started around 1965 and since 1970 it is an important county hospital with more than 700 beds. The structure consists of reinforced concrete members, such as columns, beams and slabs. Total length amounts to about 110 m, 13 m width and the height of the main parts reach around 31 m. The total mass of the building could be assessed with approximately 18.000 metric tons. A picture of the hospital before the seismic retrofit is shown in Fig. 5.

Fig. 5 – Front view of the hospital in 2007

The building consisted of several different parts that were separated by joints. The seismic gap is very small and not persistent as shown in Fig. 6. In case of an earthquake high interstorey drift ratios as well as hammering effects were expected. The corresponding damage would have affected columns, walls and slabs and the repair work would have been tremendous. As the hospital is very important for the health care in this region of Romania the temporarily closure was not acceptable.

Fig. 6 – Seismic gap between two building parts

Thus, a strategy for the seismic upgrade of the hospital was developed. The chosen strategy paid special attention to the requirement that important rooms of the hospital (e.g. emergency rooms) must be used during the retrofitting works. Details of the strategy and important design details are presented in the following clauses.

3.1 Retrofitting strategy

The mitigation measure consists of the combination of conventional strengthening and the arrangement of a Tuned Mass Control System. The purpose of the strengthening was the increase of the resistance of the building to seismic loads. During the first step the slabs at the roof are coupled in such a way that the relative motion between the separated parts becomes very small in case of a seismic event. The expected hammering effects between adjacent buildings parts are avoided now. In the second step the possibility to arrange new additional shear walls inside the structure to reduce the interstorey drift ratio was investigated. The space for these strengthening measures was very limited. Due to the importance of the hospital the areas where new steel frames or new shear walls could be place are very restricted. As results of these provisions it was decided to arrange three new steel frame structures outside the building. These frames are connected rigidly to the building as shown in Fig. 7.

Fig. 7 – Connection between steel frame and building

The size and number of the new steel frames are not sufficient to achieve the required improvement of the seismic behavior of the structure. Therefore, this strategy had to be completed by additional measures. A suitable TMCS was developed. The following chapter provides the details of this seismic protection system.

3.2 Details of the TMCS

Three mass blocks made of reinforced concrete forms the main part of the Tuned Mass Control System for the hospital in Slobozia. Each horizontal bay of the three steel frame structures is equipped with one of these concrete blocks, weighting about 53 tons. The total mass of the building structure including the new steel frames amounts to approximately 18.000 tons. The corresponding mass ratio between the total mass of the TMCS and the mentioned building mass amounts to about 0.9 % only. The mass blocks are hanging on ropes and are elastically connected to the steel structure in both horizontal directions by spring elements. Two viscous dampers, arranged beneath the mass block, are used for each unit.

3.3 Seismic calculations

The seismic input at the site can be described by the peak ground acceleration of 0.28 g. The frequency range with the highest acceleration starts at 1.0 Hz. Up to 10.0 Hz an average spectral amplification factor of 2.75 must be considered. A three dimensional finite element model of the structures was prepared using the commercial software SAP2000 to perform response spectrum and time history analyses. In summary three different computer models are created to consider the single steps of the consolidation strategy. These models can be described as follows:

- Model A: Structure without any mitigation measure
- Model B: Structure with steel frames and coupled slabs at the roof
- Model C: Structure with steel frames, coupled slabs and TMCS

Results of field measurements in terms of eigenfrequencies and corresponding mode shapes are used to adjust the finite element models. After analyzing the models without TMCS the optimum parameters of the TMCS are defined based on the results of several seismic calculations. The TMCS was tuned in combination with a high damping ratio. Due to the subcritical tuning for both directions and the corresponding high viscous damping it is ensured that the operating range of the systems is within approximately 60 to 98 % of the measured main frequencies of the structure. All performed analyses verify that this range covers all dynamic events that realistically could occur. The corresponding efficiency of the proposed measures is explained by comparing some important structural responses in Fig. 8.

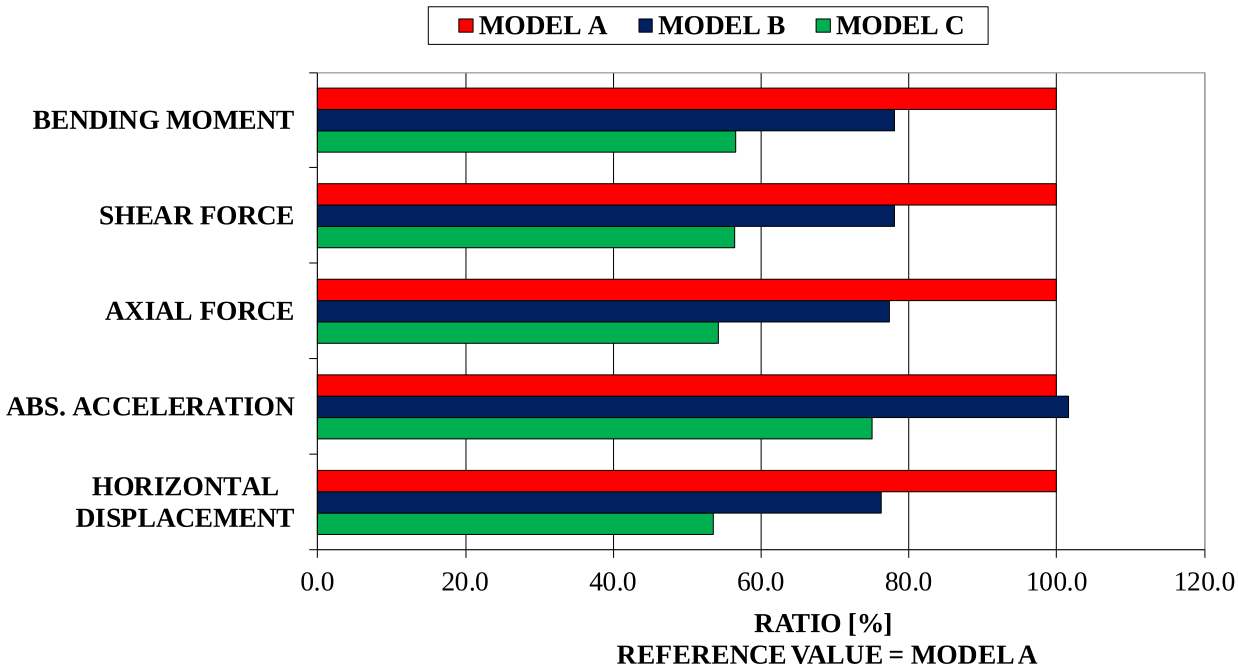

Fig. 8 – Efficiency of mitigation measures

The results of the seismic calculations show that the TMCS significantly reduced the top storey displacements, absolute accelerations, induced internal forces and as a consequence also interstorey drift values.

3.4 Structural and hospital performance

Internal forces and horizontal displacements as part of the structural performance during seismic excitation are already reduced after implementation of the conventional strengthening measures. Due to the stiffening of the structure the main horizontal frequencies are increased slightly leading to smaller relative displacements. Furthermore, the additional steel frame bears a part of the seismic forces. As a typical example for the results, the bending moment of an existing corner column can be reduced by more than 20 %, compared to the existing structure. The same value could be further reduced to a value of more than 40 % if the combined strategy of strengthening and adding the Tuned Mass Control System is used. This level of efficiency applies also to other important structural responses of the building. Thus, the seismic upgrade will lead to less damage and a remarkable increase in safety during a seismic event.

The authoritative advantage of the retrofitting strategy is the fact that all necessary measures could be prepared without the requirement of a temporary closing of the hospital or parts of it. The application of the conventional strengthening was not sufficient to keep all structural requirements. A further increase of these measures would have affected the use of the important hospital rooms. Thus, the mentioned steps are combined with the arrangement of the TMCS to improve the seismic behavior of the building, so that the complete seismic retrofit does not limit the usage of the hospital during the necessary construction works.

3.5 Construction works

The coupling of the slabs and the arrangement of the three new steel frame structures marked the beginning of the seismic retrofit. Fig. 9 shows a corresponding view of the building. Here, the renovation of the façade was also already completed.

Fig. 9 – Hospital after renovation and arrangement of steel frames

The ambient vibration measurements of the structure were performed after finalization of the strengthening measures. In comparison to the measured results of the unprotected building the new results show a slight increase in the first natural frequency in longitudinal and in transversal direction of the building. The chosen horizontal spring devices of the TMCS provide the possibility to change the helical steel spring, used inside the element. As each mass block was equipped with 4 spring devices per direction it was possible to implement the springs inside the elements in way to reach the desired frequency of the system. The tuning frequency of the TMCS was determined to about 2.0 Hz in the longitudinal and about 1.6 Hz in the transversal direction. Finally also the modal parameter of the TMCS are measured and verified. Fig. 10 shows one of the three concrete blocks implemented inside the steel frame and connected to it by ropes, steel springs and viscous dampers.

Fig. 10 – Tuned mass inside steel frame

4. Conclusion

This contribution explains and exemplifies the use of a Tuned Mass Control System as seismic protection measure. Technical background with details of analytical and experimental investigations is given. Beneath several other examples of executed projects the details of the seismic upgrade of a hospital in Romania is presented. The arrangement of a TMCS is able to significantly reduce the seismic results of the structure in terms of relative displacements, interstorey drift, absolute accelerations and internal forces. This type of system could be used for existing structure, sometimes in combination with conventional strengthening measures, as well as for new structures.

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