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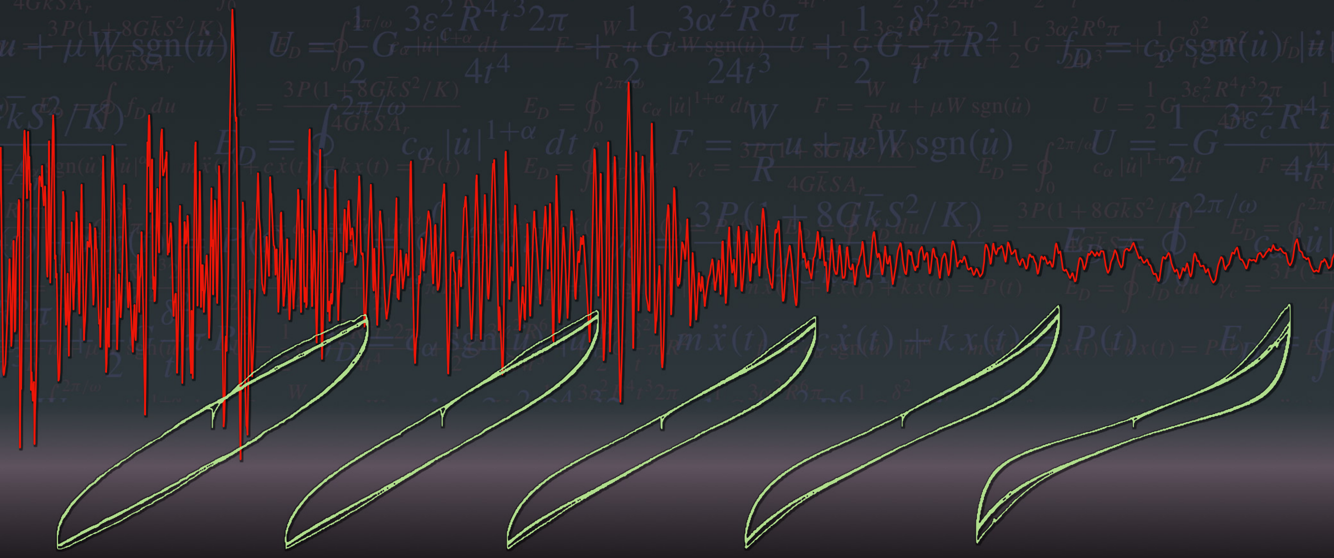

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PASSIVE DAMPING DEVICES FOR EARTHQUAKE PROTECTION OF BRIDGES AND BUILDINGS

CHRISTIAN MEINHARDT, DANIEL SIEPE AND PETER NAWROTZKI

This contribution describes the practical application of tuned mass control systems (TMCS) to bridges and buildings. Besides the experimental verification of significant reduction effects, results the results of a theoretical analysis that document the achievable improvements on the seismic response even in case of large structural damping ratios, is presented. Optimization approaches for these passive control systems will be discussed as well as practical considerations regarding the resulting specification of the TMCS. For the discussion, theoretical approaches will be introduced and results of additional numerical calculations will be presented. Design considerations for the selection of the parameters of the TMCS that take into account the nonlinearities due to the possible decrease of structural stiffness and the increase of structural damping due to cracks and local damages, will be discussed as well.

In the context of TMCS, two example projects will be introduced. One example explains the application of TMCS systems to a low damped elevated bridge structure and design solutions for these systems are presented as well as in-situ test methodologies to verify the increase of structural damping. The other example describes the application of TMCS systems as part of a consolidation strategy to successfully retrofit a large RC-structure / masonry wall building. Results of numerical calculations — verified by in-situ ambient vibration measurements — that examine the reduction effect of the TMCS in combination with additional measures will be shown together with cost effective design solutions.

1. Introduction

Increasing the structural damping of constructions to reduce the dynamic response to seismic loading is a common and well-examined strategy which is considered as a correction factor for response spectra in several codes and standards (see Figure 1).

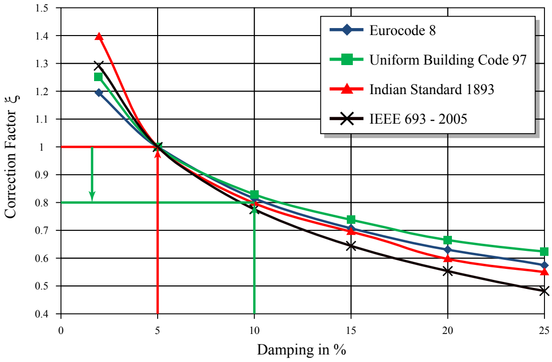


Figure 1. Effects of damping increase.

Keywords: passive damping devices, optimization approach, earthquake protection, tuned mass control systems.

One method to achieve an increase of structural damping is the application of passive energy absorbing devices such as tuned mass control systems (TMCS), though this method is still under debate. While some researchers have observed a noticeable reduction of the structural response to earthquake loads, the effectiveness has been denied by others.

Considering the evidence, which has been shown in experimental tests as described in Section 2 and [Rakicevic et al. 2006] that passive appendages cause a reduction of the structural seismic response, it has been noticed in theoretical investigations that 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. Since the commonly known optimization criteria formulated in [Den Hartog 1956] are only applicable for a harmonic excitation, these resulting conventional specifications do not lead to the desired reduction effects for earthquake loads.

To apply TMCS successfully, their specification has to be optimized by applying load characteristics that reflect those of seismic loading. In the following, several methods to estimate an optimum specification of TMCS for light dampened structures and also structures with bigger structural damping ratios will be discussed. The introduced methods are compared with numerical calculations. Additionally, the resulting specification shall be discussed under practical considerations.

The objective of this theoretical approach is the concrete practical application of TMCS equipment to an elevated bridge structure and to a RC structure/ masonry wall building by using the generalized results. In addition FE-models of both structures have been used to verify the effectiveness of the specified system and effects for practical considerations have been assessed. The results of the numerical analysis, the design, and the implementation of the TMCS units will be introduced in this contribution.

2. Experimental investigations

Several practical tests of a five-story steel frame model equipped with a TMCS, tested on a biaxial shaking table, have been performed at IZIIS (Institute of Earthquake Engineering and Engineering Seismology) in Skopje, Macedonia. Figure 2 shows a five-story steel frame model equipped with a TMCS, tested

Figure 2. Shaking table test of TMCS.

on a biaxial shaking table. The dimensions of the table are about 5.0 m in both horizontal directions. The shaking table is suitable for pay loads up to 30.0 tons and is able to generate horizontal acceleration of 1.0 g, as well as vertical acceleration of 0.5 g. Each floor of the steel structure has got a height of 0.75 m, while all three spans in the longitudinal direction amount to 1.5 m. The one span in transversal direction amounts to 1.5 m. The total mass of the steel structure is 19.0 tons, and the mass of the TMCS is 0.26 tons, which corresponds to about 1.3% of the entire mass. The structure in the middle span has a special bracing substructure (the red steel structure in Figure 2), which is used to adjust the required stiffness and damping for the tests.

At the beginning the modal parameters (natural frequencies, damping) of the structure have been tested and verified by different test methods (hammer test, steady-state vibration and random vibration test simulated by the shaking table). The main premises of the described tests were to investigate the reduction effects for different type of seismic load characteristics with different frequency contents so the structure underwent a couple of measured and artificial seismic waves with different intensities. Among them were several well-known seismic time-histories as Northridge, Kobe, Mexico City, Vrancea (Romania) and Izmit (Turkey).

The inherent structural damping of the steel frame has not been varied since the focus of the investigations was on the behavior of the system structure + TMCS under seismic loading.

The efficiency of the system was investigated by comparing the results of the frame with activated and with blocked TMCS.

At first, the model was tested with unlocked TMCS, and all selected earthquakes were simulated for minimum three different intensities. The same procedure has been repeated with the model with locked TMCS. During the tests time history responses of relative displacements, acceleration values and bending strains are recorded at different locations at the structure.

In Figure 3 a comparison of relative displacements for three different earthquake time records at top of the structure shows an improvement of seismic performance by nearly 40%.

The investigations have shown that the TMCS reduces the structural responses by about 25–40%. In parallel to the experimental investigations also several numerical investigations have been performed. Qualitatively the results of these calculations correspond well to the measured data. For more information please refer to [Rakicevic et al. 2006].

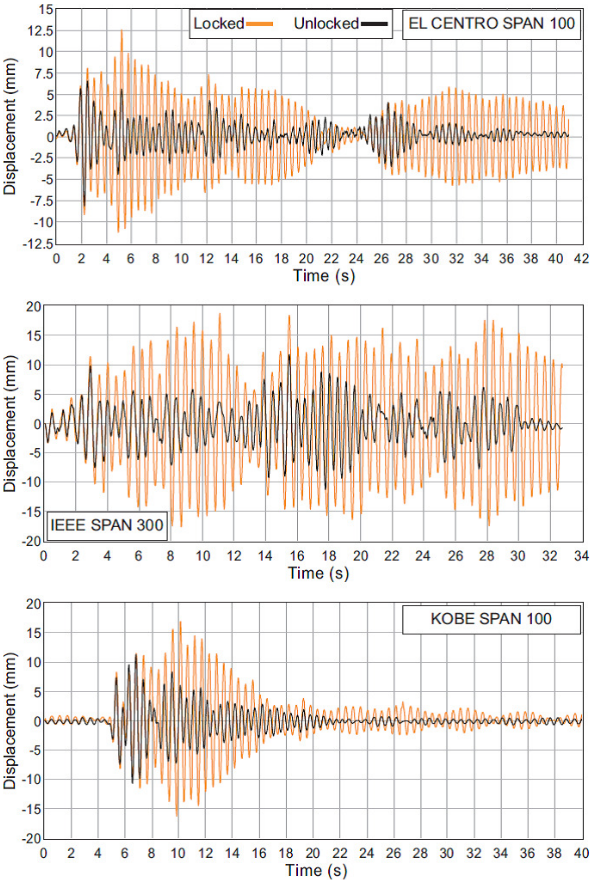


Figure 3. Recorded responses with activated (black curve) and locked TMCS (orange curve).

3. Theoretical investigations

Additionally to the experimental tests theoretical investigations have been performed for simplified analytical models, example structures and existing structures (e.g. bridges and buildings) with a focus on the optimization of the system specifications for the characteristics of seismic loading and for varying inherent structural damping ratios. Prior to detailed numerical calculations of the existing structures optimization approach was examined to determine the optimal parameters of the TMCS.

3.1. ***Optimization for a single-degree-of-freedom model.*** To derive an optimal specification for the TMCS, the characteristics of seismic loading has to be approximated. A legitimate approach is the assumption that ordinary earthquake excitation can be approximated with sufficient accuracy by a stationary white noise stochastic process (see Figure 4).

According to [Ayorinde and Warburton 1980] for an analogous model (see Figure 5) the optimization can be found by minimizing the variance σ_x^2 of the structural displacements $\boldsymbol{X}$.

The displacement $\boldsymbol{X}$ is related to the constant white noise spectral density S_0; we have

$$\sigma_x^2 = [E(x^2(t)] = S_0 \int_{-\infty}^{\infty} |H(\nu)|^2 \, d\nu, \tag{1}$$

in which $H(\nu)$ is the complex response function of the displayed analogous model with the tuning frequency of the TMCS f_T and the natural frequency of the structure f_S.

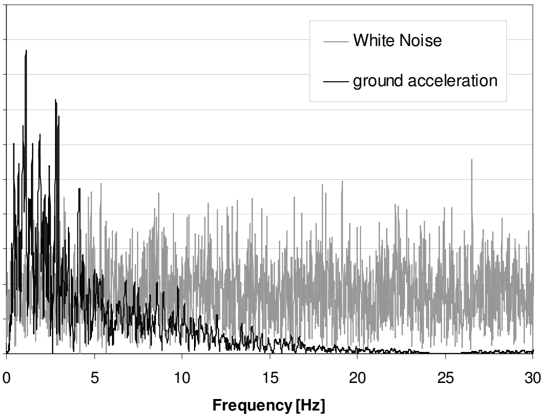


Figure 4. Frequency content of stationary random white noise and a measured ground acceleration time history.

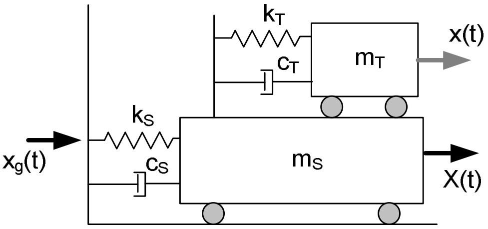


Figure 5. TMCS model as a two-degree-of-freedom appendage.

The complex response function amounts to

$$H(\nu)=\frac{\dfrac{m_T}{m_S}+\dfrac{\left(\dfrac{f_T}{f_S}\right)^2+2i\zeta_T\left(\dfrac{\nu}{f_S}\right)\dfrac{f_T}{f_S}}{\left(\dfrac{f_T}{f_S}\right)^2-\dfrac{\nu}{f_S}+2i\zeta_T\left(\dfrac{\nu}{f_S}\right)\dfrac{f_T}{f_S}}}{\dfrac{m_T}{m_S}\left(1-\left(\dfrac{f_T}{f_S}\right)^2+2i\zeta_T\left(\dfrac{\nu}{f_S}\right)\dfrac{f_T}{f_S}\right)}\cdot\left(\frac{\nu}{f_S}\right)^2\cdot\left(\frac{f_T}{f_S}\right)^2. \tag{2}$$

To optimize the TMCS parameters f_T and ζ_T a performance index J_0 has to be introduced that complies with the mentioned variance σ_x^2:

$$J_0=S_0\int_{-\infty}^{\infty}|H(\nu)|^2\,d\nu \tag{3}$$

The minimization process of J_0 can be expressed for slightly damped, or (better) undamped, structures in an analytical solution:

$$\left(\frac{f_T}{f_M}\right)_{\text{opt}}=\frac{\sqrt{1-\dfrac{m_T}{2\cdot m_S}}}{1+\dfrac{m_T}{m_S}}, \tag{4}$$

$$\zeta_{\text{opt}}=\sqrt{\frac{\dfrac{m_T}{m_S}\left(1-\dfrac{m_T}{4\cdot m_S}\right)}{4\cdot\left(1+\dfrac{m_T}{m_S}\right)\cdot\left(1-\dfrac{m_T}{2\cdot m_S}\right)}}. \tag{5}$$

Assuming a low damping for most structures that require seismic control devices is absolutely inappropriate. Inherent structural damping for RC-structures has to be considered as well as the nonlinear damping behavior for large deformations that might occur during an earthquake. So there are other approaches by solving the complex eigenvalue problem $|\boldsymbol{A}-\lambda\boldsymbol{I}|$ that derives from the free vibration equation for a system matrix $\boldsymbol{A}$ (see [Villaverde and Koyama 1993]); the problem can be written as

$$\left(\frac{\lambda}{\omega_0}\right)^4+\left[2\frac{f_T}{f_M}\zeta_T\left(1+\frac{m_T}{m_s}\right)+2\beta\right]\left(\frac{\lambda}{\omega_0}\right)^3+\left[1+\frac{m_T}{m_S}\left(\frac{f_T}{f_M}\right)^2+4\frac{f_T}{f_M}\zeta_T\beta\right]\left(\frac{\lambda}{\omega_0}\right)^2 \\ +2\frac{f_T}{f_M}\left(\zeta_T+\beta\left(\frac{f_T}{f_M}\right)\right)\frac{\lambda}{\omega_0}+\left(\frac{f_T}{f_M}\right)^2=0, \tag{6}$$

which contains the stiffness and damping information of the main system (ω_0 and β), the mass ratio between the main structure and the TMCS and the TMCS parameters for the tuning-frequency and internal damping ratio.

The solution of the eigenvalue problem is in complex conjugate pairs with complex eigenvalues:

$$\lambda_{r,r+1}=-\bar{\omega}_r\zeta_r\pm i\bar{\omega}_r\sqrt{1-\zeta_r^2} \tag{7}$$

The optimum TMCS specification is determined when the difference between the damping values ζ_{T1} and ζ_{T3} resulting from the eigenvalues is minimal.

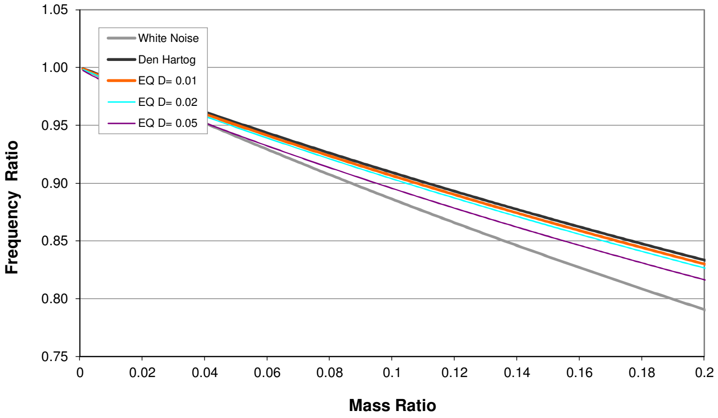


Figure 6. Optimum frequency ratio as a function of the mass ratio for different inherent damping ratios.

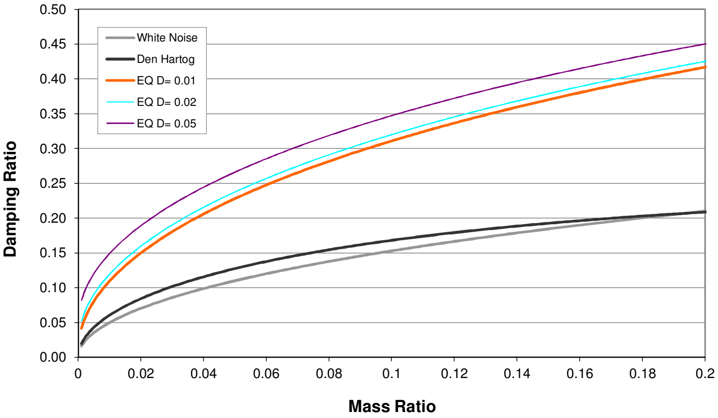


Figure 7. Optimum internal damping ratio as a function of the mass ratio.

The iterative analysis can be done numerically [Sadek et al. 1997] and leads to the optimum values, shown in Figures 6 and 7. As a comparison, the resulting values for an optimization according to Den Hartog and for an approach using white noise excitation are displayed as well.

3.2. ***Optimization for a multiple-degree-of-freedom model.*** To assess the reduction effect of TMCS on multiple-degree-of-freedom structures such as multistory buildings, numerical calculations of a six-story have been done for which a TMCS has been applied. The inherent damping ratios of the building, as well as the ratio between the modal mass of the relevant mode and the mass of the TMCS have been varied. The reduction has been assessed also for different internal damping ratios of the TMCS such as the optimal damping according to the Den Hartog optimization and the previously introduced criteria. The numerical analysis has been done for the time domain using ground acceleration time records from the Northridge Earthquake, the El Centro Earthquake and the USNRC standard time history. Figure 8, left, shows the time records that have been used for a one-directional base excitation. The numerical first horizontal bending mode is in range of the highest spectral density for each time record (Figure 8,

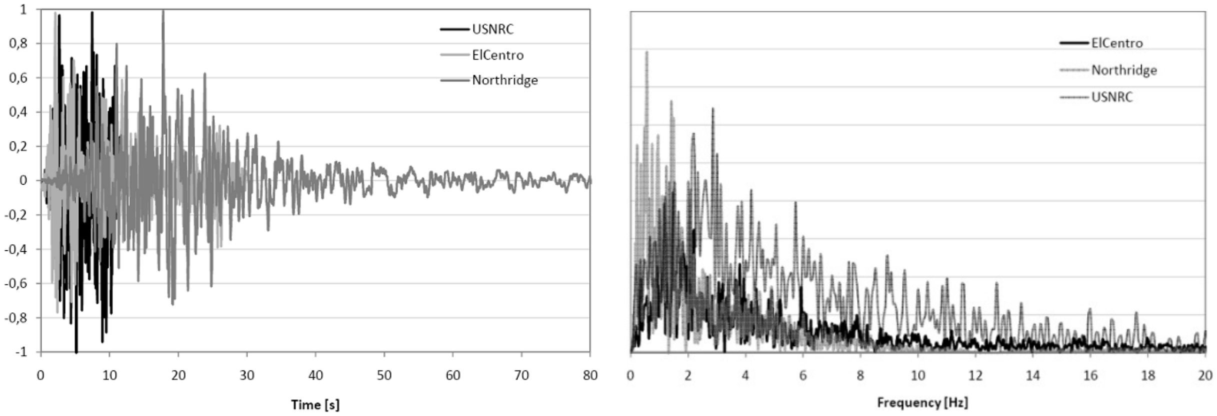


Figure 8. Left: time records of the applied earthquakes. Right: spectral density of the applied earthquakes.

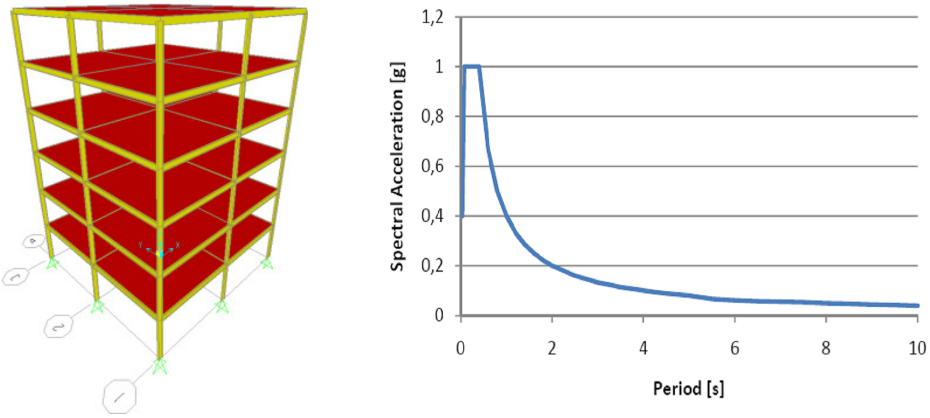


Figure 9. Left: model of the six-story building analyzed. Right: UBC 97 response spectrum used.

bottom), so it can be assumed that the structure has a sufficient dynamic response in that mode to which the TMCS is tuned for.

A response spectra analysis has also been performed with the same model and the same variation of the TMCS parameters to asses the reduction effect of a TMCS. For the analysis the UBC 97 response spectrum for 5% damping and a seismic coefficient of 0.4 has been used (Figure 9, right). The maximum displacements of the system with TMCS have been normalized to the displacements without TMCS to derive a reduction factor (u_T/u_0).

The calculated time responses of the building for the different ground acceleration time histories were transformed into the frequency domain to obtain an effective value u_e by deriving the square root of the sum-of-squares for each FFT-line (see Figure 10). Again a reduction factor (u_{Te}/u_{0e}) has been calculated to determine the TMCS effectiveness, were u_{Te} are the displacements of the structure TMCS and u_{0e} without.

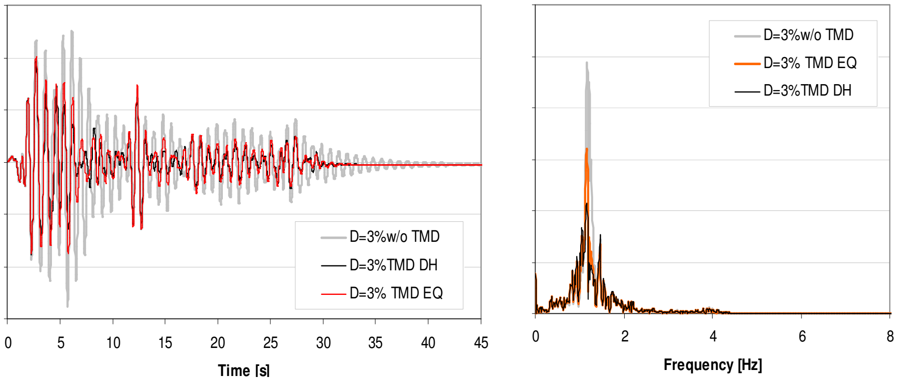
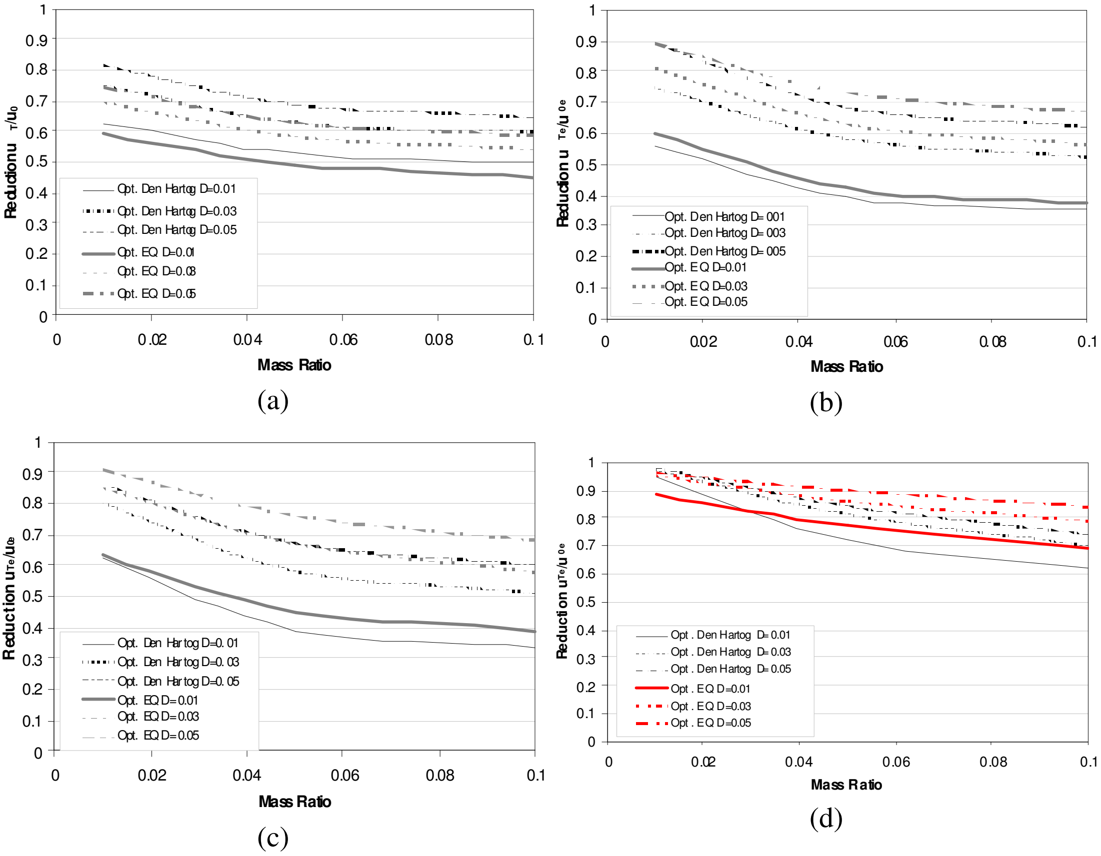


Figure 10. Left: calculated time responses of the model (3% inherent damping) without TMCs and with TMCS (DH = Den Hartog; EQ = specification and optimization according to [Ayorinde and Warburton 1980]). Right: corresponding frequency spectra to obtain the sum of squares.



(a)

(b)

(c)

(d)

Figure 11. Calculated reduction factors for different inherent damping ratios and for different optimization approaches: response spectrum analysis (a), time domain analysis with the USNRC earthquake (b), El Centro earthquake (c), Northridge earthquake (d).

Figure 11 shows the calculated reduction factors against the mass ratio between the modal mass of the structures relevant mode and the mass of the applied TMCS for different inherent damping ratios of the structure. For the response spectrum analysis the maximum reduction that can be achieved is 55% for a big mass ratio and structures with a low inherent damping ratio. A reduction in excess of 30% can be achieved also for higher inherent damping ratios. It can be seen that a bigger reduction can be achieved when the optimized damping values are applied according to the introduced approach are applied.

The results from the performed time domain analyses show an even bigger reduction for the calculations with the time records of the El Centro and the USNRC earthquake. Only the calculations for the Northridge earthquake show a rather small reduction of the structural seismic response by the application of a TMCS (10–30%). In addition it can be noticed that an optimization of the internal damping doesn't increase the effectiveness as it was observed for the results of the response spectrum analysis. The cause for this effect can be found in the theory for a two-degree-of-freedom model where the amplification function of a highly damped appendage to a main system shows a reduced amplification over a broader frequency range than for appendages with lower damping. Considering a broad frequency range instead of a time response due to a stochastic time record, leads to the observed effect.

The characteristics of the applied earthquake-time records are also the reason of the varying results for the three different analyzed earthquakes. The USNRC earthquake and the El Centro earthquake have their highest energy content in the frequency range in which the analyzed building tends to respond, so the buildings response has a larger free-vibration participation than for the Northridge earthquake which has its highest energy contents at lower frequencies. By having a higher free vibration participation due to the characteristics of the ground acceleration time record, the TMCS also tends to be more effective for an Den Hartog optimizations since the building response has more harmonic components. In this regard, the difference of the reduction factors for an optimization according to Den Hartog and the optimization for seismic loads is less distinctive for the Northridge earthquake than for the USNRC and El Centro earthquakes.

In light of the results presented, it can be summarized that the application of a TMCS leads to a significant reduction for sufficient mass ratios if the internal damping ratio is bigger then the optimum value according to the optimization for harmonic loads (Den Hartog). A higher internal damping ratio of the TMCS leads to a better effectiveness for an excitation that leads to a smaller free-vibration participation of the structure.

The average value of the reduction factors for the three examined earthquakes is in range of those calculated for the response spectrum analysis. The effectiveness is more distinctive for lighter damped structures.

3.3. ***Practical considerations.*** For a practical application of a TMCS, additional effects that occur in reality have to be considered. Nonlinearities due to the structural degradation of the structure during seismic loading, such as the decrease of structural stiffness and the increase of structural damping due to cracks and local damages should be considered for the determination of the optimum device specification.

To assess the robustness of a TMCS specification regarding these two effects, the reduction factors of the introduced model were calculated varying for an inherent structural damping of 8% for different frequency ratios — actual tuning frequency of the TMCS to the optimum tuning frequency (see Figures 12 and 13).

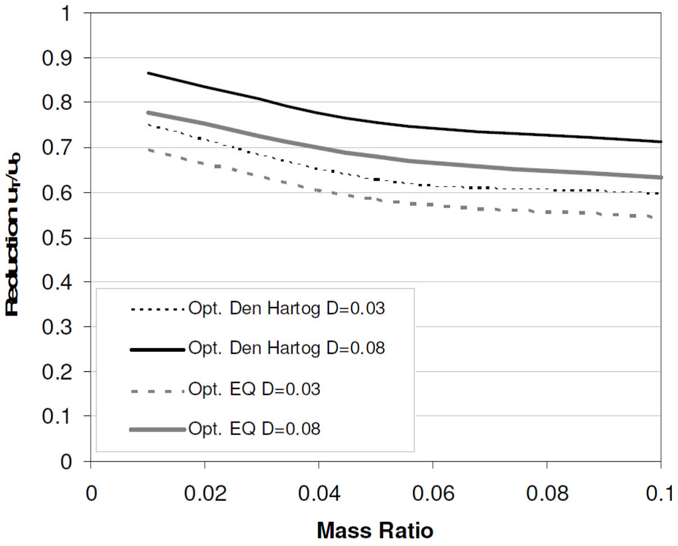


Figure 12. Calculated reduction factors for 8% inherent damping.

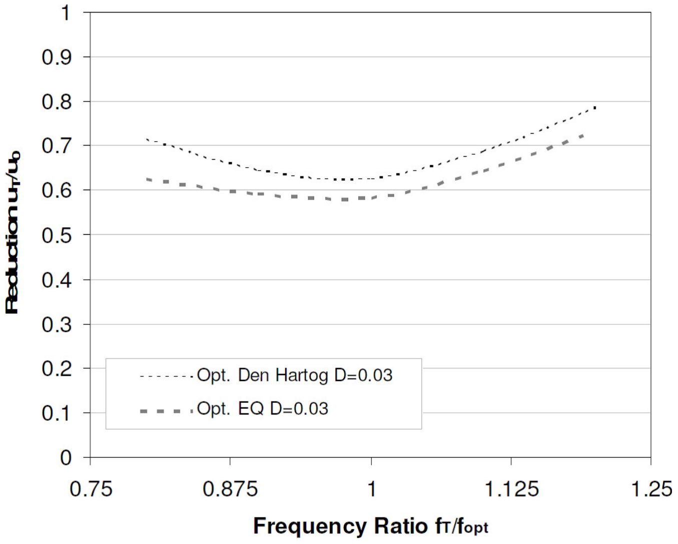


Figure 13. Calculated reduction factors for different frequency ratios.

The results show that the TMCS is more effective for a detuned system if a higher internal damping is applied. For this case the TMCS is effective in a broader frequency range, which matters when the stiffness of the structures decreases during an earthquake. It can also be seen that even with a big structural damping value a distinctive reduction can be achieved again if a higher internal damping is applied. Another point that has to be considered is the resulting displacements of the TMCS-mass. The higher internal damping ratio can again be used to reduce the resulting displacements.

4. Project example: TMCS for an elevated bridge structure

4.1. ***Introduction.*** The Puente Oriente, also known as Puente El Alamo, is an elevated bridge structure near Guadalajara, Mexico, and will be used as a fly-over distributor road for the local highway system.

The total length of the structure is approximately 500 m and the average span of each bay is 40 m. The substructure underneath the reinforced concrete deck consists of steel columns and two main steel beams with a trapezoidal cross section (see Figure 14). To reduce the rocking vibrations of the bridge deck under seismic loads, 8 TMCS units, each with an effective mass, have been applied underneath the deck in range of the central column structures (see Figures 15 and 20).

Figure 14. Bridge during construction.

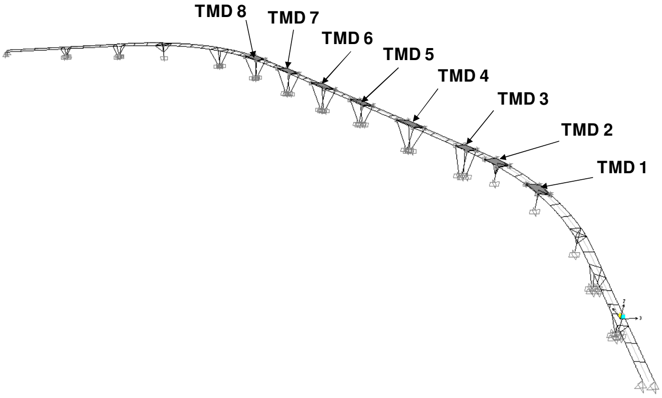


Figure 15. FE-Model of the bridge / positions of the TMD's.

Prior to the final design of the units several numerical calculation have been completed to determine an optimal mass ratio and to verify the corresponding specification according to the previously described procedures.

4.2. ***Specification of TMCS: calculation of the effectiveness of the designed devices.*** The bridge structure was modeled by using the commercial finite element program SAP2000 (CSI Berkeley, Inc.). A plot of the bridge and the 8 arranged masses is shown in Figure 15. The TMCS was modeled as single masses connected to the main structure by spring and damper elements. The parameters for these elements have been chosen according to the optimization criteria and verified variation calculations.

The structural response was calculated by performing a response spectrum analysis with and without TMCS units. The design spectrum (see Figure 16) was defined by the local authorities. The numerical modal analysis, which is necessary to accomplish the response spectrum analysis, showed that the relevant vibration mode is in range of 1.69 Hz (see Figure 17).

The resulting reduction factors of the occurring displacements and accelerations for load cases that consider the orientation of the bridge are shown in Figure 18.

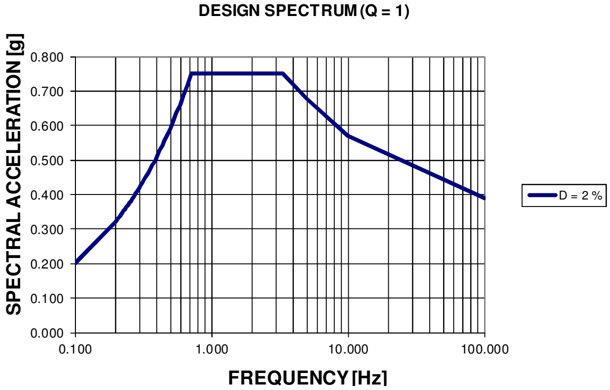


Figure 16. Design spectrum.

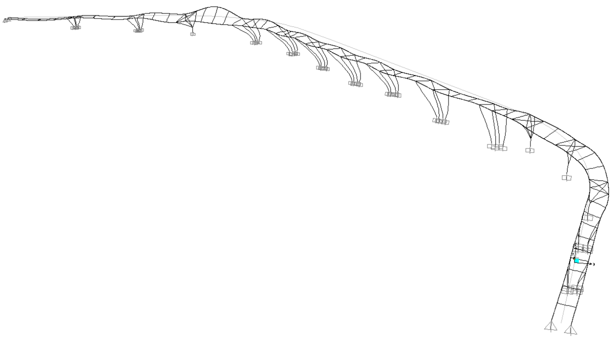


Figure 17. Relevant mode shape (1.69 Hz) of the bridge.

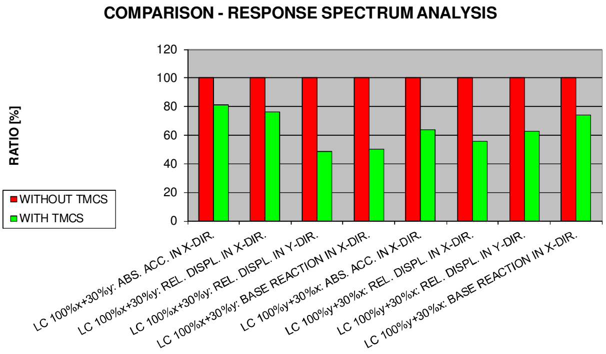


Figure 18. Reduction factors from the response spectrum analysis.

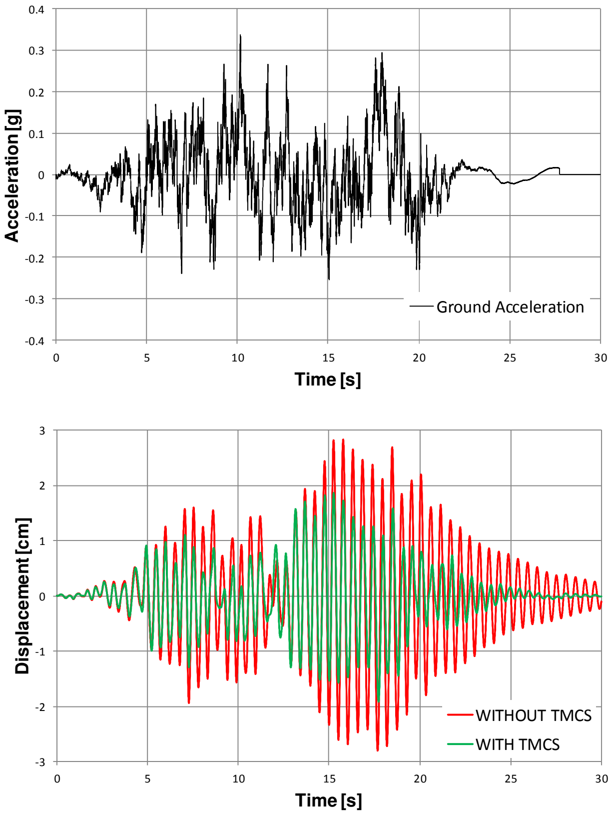


Figure 19. Top: Generated time history for ground acceleration. Bottom: structural responses without and with TMCS.

Additionally, an artificial time history of the ground acceleration has been generated using the given spectrum. Figure 19 shows the input data and the structural response to that seismic load without and with TMCS.

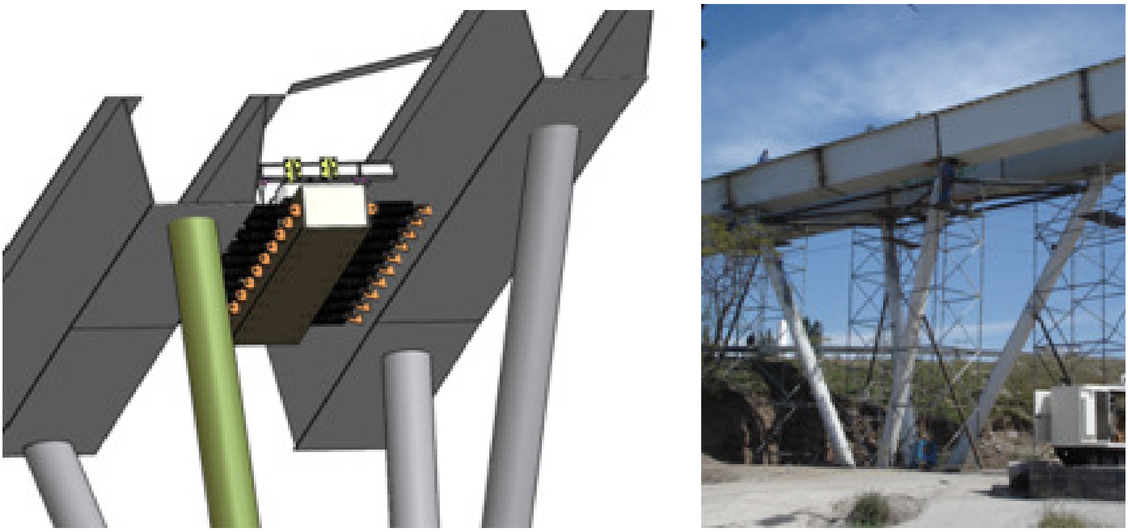


Figure 20. Left: TMCS at designated location. Right: bridge substructure prior to installation.

The results of the time history analyses show a significant reduction of the structural responses when a TMCS is applied. Qualitatively the results of the time history analysis correspond very well to the results of the response spectrum analysis. The numerical results of both types of analysis shows a high efficiency of the TMCS in regard to the earthquake protection.

4.3. ***TMCS design.*** The TMCS units were designed to be laterally effective once attached to the bridge deck. Each unit consists of an effective mass which has been designed as a concrete filled steel bin. The mass is supported on pendulum rods to allow frictionless oscillations.

The required internal damping is achieved by Viscodamper® (by GERB Vibration Control Systems) units that provide an ideal viscous damping behavior which is independent from the shear velocity. The damper can be adjusted by varying the shear area while the whole TMCS system can be tuned with horizontal tuning springs which connect the elastically supports mass and the main structure (see Figure 20).

Prior to installation, the damping units will be tested on a shaking table, where force/motion diagrams will be recorded to verify the units damping coefficient and to determine the additional stiffness of the damping unit that has to be considered for the tuning setup on site.

4.4. ***In situ tests.*** Once the TMCS units are installed, ambient vibration measurements at the bridge structure will be performed to assess the modal parameters (natural frequencies, corresponding mode shapes and damping ratios) of the bridge before the TMCS units will be adjusted on site.

Ambient vibration testing is more or less the only way to obtain the modal parameters of large structures as a forced excitation means a too big effort. The wind velocity spectrum and/or the traffic spectrum is showing content over a broad frequency range. It can again be assumed that the statistic average of the ambient excitation equates a white noise excitation, which excites all relevant structural modes. For this reason, ambient vibration records can be used to determine the natural frequencies and the structural damping of the bridge structure.

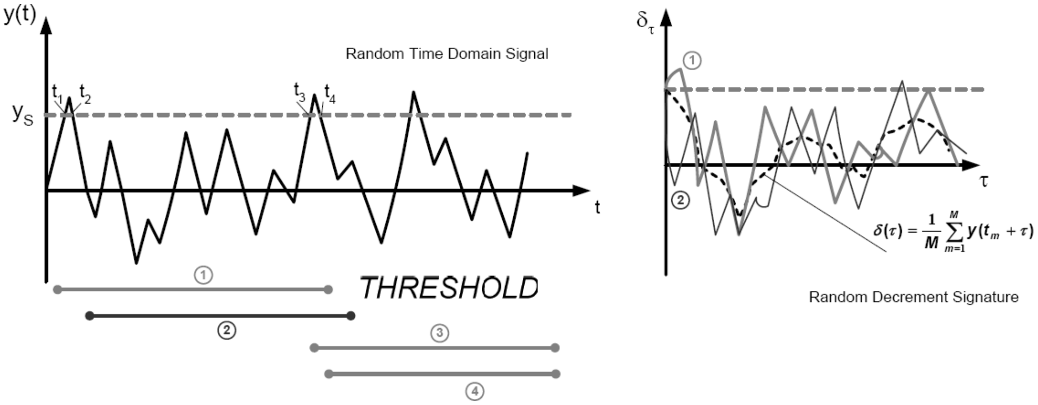


Figure 21. Principle of the random decrement method.

Several methods can be used to assess the damping using the ambient vibration records. For damping assessment, the random decrement method will be applied. The principle of this method is presented in Figure 21.

Based on the theory that the random excitation consists of a deterministic component which corresponds to free vibration terms and a random component which corresponds to forced vibrations, the random part can be eliminated by averaging a large number of blocks that fulfill a certain threshold criteria and are extracted from the time domain signal with a certain length τ. The random decrement signature (RDS) results from the formula

$$\delta(\tau) = \frac{1}{M} \sum_{m=1}^{M} y(t_m + \tau), \tag{8}$$

and the resulting damping ratio can be derived by the known logarithmic decrement, whereas the quality of the RDS strongly depends on the selection of the segment duration τ and the threshold y_S.

The structural response for ambient excitation (wind and traffic) usually occurs in several modes. To withdraw the damping ratio for a single mode, the time records have to be processed with a bandpass filter for each relevant natural frequency. The random decrement method has been commonly accepted for system identification analyses of structures and buildings. The design of the TMCS and the excitation due to traffic with a comparatively high energy input allows the assessment of the TMCS effectiveness by comparing the structural damping with blocked and with activated TMD.

To assess the structural damping of the bridge structure with the random decrement method, recorded time histories of the vibration velocities in lateral direction with blocked and activated TMCS will be consulted. The signatures for several variations of the threshold will be normalized and averaged to achieve a stochastically approved damping ratio.

5. Project example: TMCS for a building

5.1. ***Introduction.*** The structure of the Palatul Victoria (see Figure 22) consists of 6 different parts, which are separated by joints. The clearance is very small and in case of an earthquake high interstory

Figure 22. The Palatul Victoria in Bucharest, Romania.

drift ratios as well as hammering effects can be expected. Damages could result for columns, walls and panelling and the necessary repair work would be tremendous. As a consequence the building could experience a period of downtime, not acceptable due to the importance of this venue for the Government of Romania.

In order to prevent this scenario a suitable sequence of interventions was designed. In a first stage some of the building slabs were coupled in order to reduce relative motions between portions of the building. In order to reduce the interstory drift ratios traditional strengthening techniques were considered. Among them, the insertion of additional shear walls was decided even though limited in number and size by the existing structural configuration. The installation of shear walls had to be complemented by additional measures.For this purpose a suitable TMCS was developed.

5.2. ***Specification of TMCS: calculations.*** The building consists of reinforced concrete members, as well as of brickwork. The total length is about 95 m, the width about 52 m and the height of the main parts about 24 m. The total mass of the building is assessed at about 35,000 tons and the main frequencies are about 2.0 Hz in the longitudinal direction and 1.8 Hz in the transverse direction. These values vary slightly according to the different parts of the whole structure.

Using the finite element software SAP2000 a three dimensional model of the structure was prepared. The computer model was validated against the measured eigenfrequencies of the building. Altogether three different computer models were 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 slabs.
- Model C: System with additional shear walls, with some connected slabs and with TMCS.

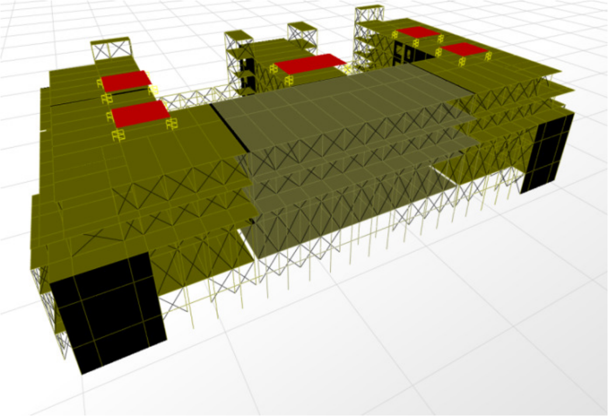


Figure 23. Computer model.

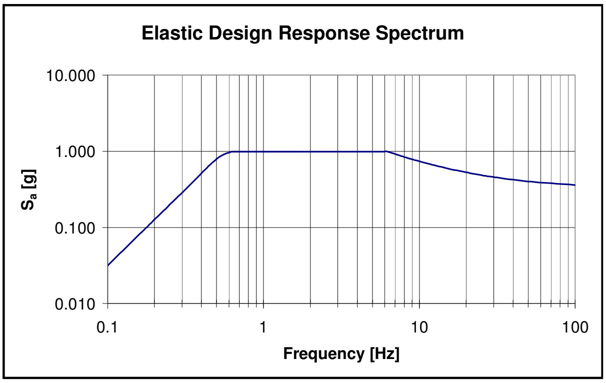


Figure 24. Design spectrum ($D = 5\%$).

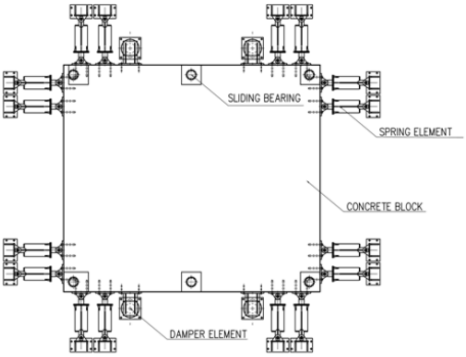
After implementation of the measures the weight of the total structure is increased to about 38,800 tons. A plot of the Model C is shown in Figure 23.

The elastic response spectrum (see Figure 24), which has to be taken into account, 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

Several calculations (response spectrum analyses and time history analyses) were performed to define the optimal parameters for the TMCS. A TMCS — located on the roof top of different building segments — consisting of the following elements was chosen:

- 5 concrete blocks (each one has a mass of about 96 tons) / supported by sliding bearings.
- Each block is connected with spring elements to the roof in both horizontal directions.
- Damper elements are arranged.



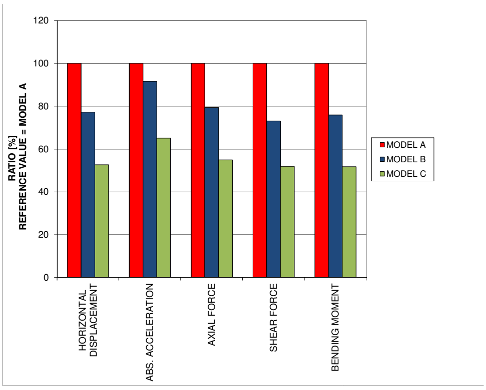


Figure 25. Left: principle of TMCS. Right: efficiency of TMCS.

A principle sketch of one block of the TMCS is presented in Figure 25, left.

The results of the calculations show that the TMCS significantly reduces the top story displacements, interstory drifts, response accelerations and consequently induced internal stress responses due to earthquakes. In Figure 25, right, the corresponding efficiency of the proposed measures are shown, by comparing some important values.

The first step (Model B = additional shear walls and connected floors) lead only to an improvement of about 10 to 20%. This was not sufficient in regard to the demands of the important structure.

The additional implementation of the TMCS (Model C) was required to achieve an improvement of more than 35%.

5.3. ***Manufacturing of devices.*** The required devices (spring elements and Viscodamper® from GERB Vibration Control Systems) are developed and manufactured. Due to the uncertainties of the conventional stiffening of the building structure by adding the new shear walls and the connection of some slabs, a special kind of spring element was required. It is possible to use different kind of springs inside the spring element. Thus, it is possible to adjust the stiffness of the element very easily. The spring elements (see Figure 26) are tested in axial direction to check the stiffness of the elements.

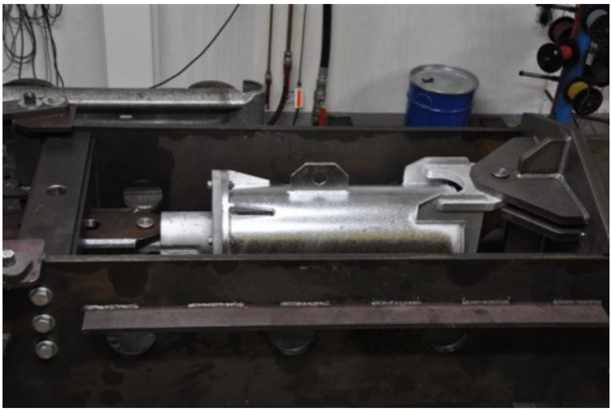


Figure 26. Spring element in test rig.

Figure 27. Viscodamper® in test rig.

Figure 28. New shear wall.

The Viscodamper® units (see Figure 27) were tested to verify the required damping resistance values. Due to the very high seismic excitation, a suitable damper had to be developed and tested.

5.4. ***Installation works and in situ tests.*** At the moment the installation process is nearly completed. The Romanian construction company started with the implementation of the new shear walls (Figure 28) and the connection of the slabs.

Afterwards the five concrete blocks were poured and the required embedded parts for the connection between spring element / damper element and the roof were fabricated and installed. As a next step one of the blocks was equipped with spring and damper devices (see Figure 29).

Prior to the final installation of all spring elements, vibration measurements were performed and are currently being analyzed. The objective of these initial ambient vibration measurements is to verify the calculated resulting natural frequencies of the building structure after the implementation of the shear walls, connection of the slabs and arrangement of the masses of the TMCS. Additionally, also the specific

Figure 29. TMCS at roof of building.

parameters of the TMCS in their current setup were determined In a next step the final specification of the required spring stiffness and damping properties will be derived and the TMCS will be adjusted accordingly to complete the installation process (scheduled for summer 2011).

6. Conclusion and outlook

Experimental shaking table tests and theoretical investigations have shown that the application of passive control systems can lead to a significant reduction of the dynamic response to seismic loading. While the experimental investigations showed that a reduction can be achieved for several examined time histories, theoretical analyses showed that 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.

To achieve the highest effectiveness possible for tuned mass control systems (TMCS) for earthquake protection that are installed at an elevated bridge structure in Guadalajara, Mexico, and a building in Bucharest, Romania, theoretical approaches have been introduced and several numerical studies have been done to verify the optimum specification of the control system. Depending on the free-vibration participation of the structural response, the optimum reduction can be achieved with the Den Hartog Criteria or with recommended higher internal damping ratios of the TMCS.

Practical considerations showed that a higher internal damping leads to a more robust specification in terms of varying structural stiffness and inherent damping. Additional numerical calculations of the bridge and the building discussed here, verified the chosen TMCS parameters.

Both TMCS devices that are introduced in this contribution have been installed. In-situ tests are currently being performed to determine structural and TMCS parameters. The dynamic loading of the bridge structure due to traffic and the design of the TMCS allow a direct verification of the effectiveness of the system, once the test data have been analyzed. The test results of the TMCS for the RC structure/masonry wall building and of the building itself will be used for model updating to perform a final theoretical analysis.

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