STUDIES AND RESEARCHES – V.34, 2015
Graduate School in Concrete Structures – Fratelli Pesenti
Politecnico di Milano, Italy

A TMD APPLICATION IN THE SEISMIC IMPROVEMENTS OF AN HISTORICAL CHIMNEY

Nicola Longarini[1] , Marco Zucca[1], Antonio Migliacci[2]

ABSTRACT

The paper analyzes the seismic improvement of an historical masonry chimney by the tuned mass dumper (TMD) application.

The chimney was built at the beginning of XX century in the northern region in Italy and the mechanical characteristics of the masonry, in terms of elastic modulus and compressive strength, used in the finite element models (FEMs) has been determined by a set of experimental tests. A first FEM is implemented by element beam (FEM 1) a second FEM is implemented by solid elements (FEM 2); in both, two configurations are studied: the chimney without TMD and the chimney with TMD. By a time history analysis the main characteristic of the TMD in the terms of mass, stiffness and damper values are valued and optimized for different positioning of the oscillating mass. Finally, a structural solution for the support of the TMD is proposed.

Keywords: historical construction, TMD, chimney, seismic improvements

---

[1] PhD Candidate - Dept. of Architecture, Built Environment and Construction Engineering – ABC, Politecnico di Milano, Milan (Italy).

[2] Former Full Professor at Politecnico di Milano, president of CISE Consortium

1. INTRODUCTION

In order to improve the structural seismic response of an existent construction, two ways could be considered: modifying the original structure by the introduction of steel (or fiber) reinforcements or changing the dynamic characteristics of the structure by an auxiliary system. In this case the second option is considered, opting for a removable solution representing by the TMD.

2. CHIMNEY CHARACTERISCS

The chimney is characterized by an inner and an outer cylindrical skins (thickness, t = 27 cm) linked themselves by a no. 8 meridians and no. 11 parallels structure. The chimney's height is about 50 m and the thickness of the skins, meridians and parallels is 0.27 m.

The mechanic characteristics of the masonry are deduced from the surveys carried out by flat jacks tests in some positions of the chimney's masonry. In particular: modulus of elasticity E = 12.185 MPa and ultimate compression strength value f_d = 4.96 MPa. In the analysis the value of the ultimate compression strength is reduced to 3.55 MPa considering the Italian Structures Regulations [1], [2] and [3] by the application of two coefficients related to the number of the carried out tests and the eccentricity of the loads, in relation to the geometrical slenderness (in particular see the Section C.8.A.1.A.4 in [2].

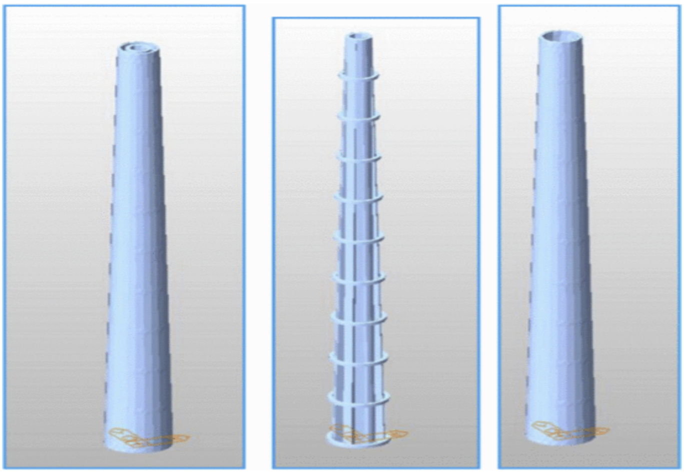

Figure 1. A representation of the chimney's structure: parallels system.

3. DEFINITION OF THE TMD'S PARAMETERS IN FEM 1

A first FEM 1 representing only the chimney is implemented by tapered beam elements (from the base to the top) with perfect join as a base boundary condition. The loads combination applied on the structure are the summation of dead loads and the seismic actions by the application of seven spectrum-compatible accelerograms. Thus, stress actions are evaluated like the average actions to the accelerograms (as explained in Section 7.3.5 [1]).

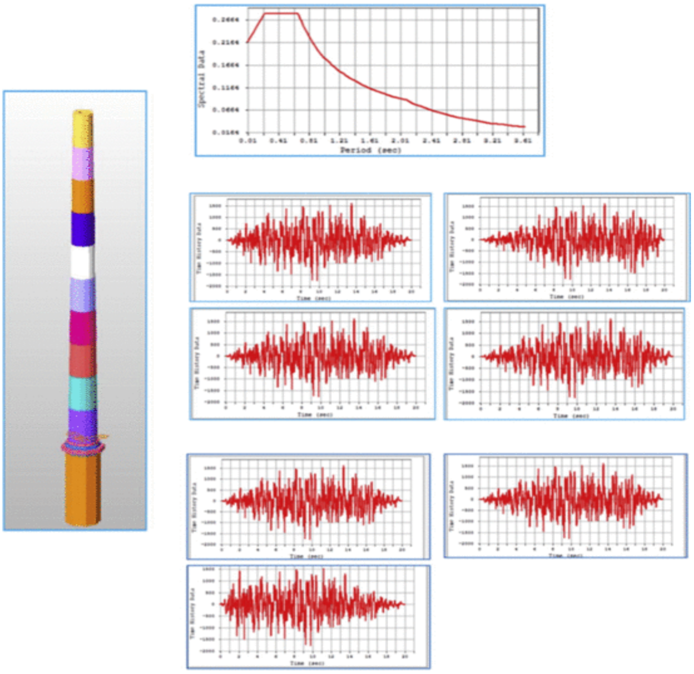

Figure 2. FEM 1, site spectrum and spectrum-compatible accelerograms.

The structural Ultimate Limit State (ULS) verifications are not fulfilled because the maximum compression stress under the seismic action is $f_{c,s} = 4.29$ MPa, major the $f_{dc,rid} = 3.55$ MPa, the maximum base shear is $V_d = 893$ kN major than the ULS $V_d = 723$ kN and the maximum top displacement is $\Delta_{top} = 0.10$ m.

At the same time an eigenvalue analysis is carried out to identify the main vibrational mode shapes and the relative percentage of the mass associated to each modes. The value of the mass related to the main mode shapes is used to find thr the optimum values of the TMD's mass. From the value of the TMD's mass, the stiffness and damping are valued too.

The main parameters of the TMD are obtained by the relations explained and optimized in [5], [6]. In particular the parameters are:

- the ratio between the TMD's mass and the mass of the main structure (chimney) , $\mu = m_{TMD}/m_{structure}$;
- the optimal coefficient for the frequencies (considering the chimney and the TMD)

Knowing the vibrational mode shapes and the related masses from the eigenvalue analysis, the TMD mass value is optimized ([11], [13] and [14]) in 3.3% of the mass involved in the first vibrational mode. By the eigenvalue analysis, the first and second vibration modes (T_1 and T_2) are $T_{1A} = T_{2A} = 1.08$ s and the related masses (m_1 and m_2) are $m_{1A} = m_{2A} = 0.56\%$ of the total mass.

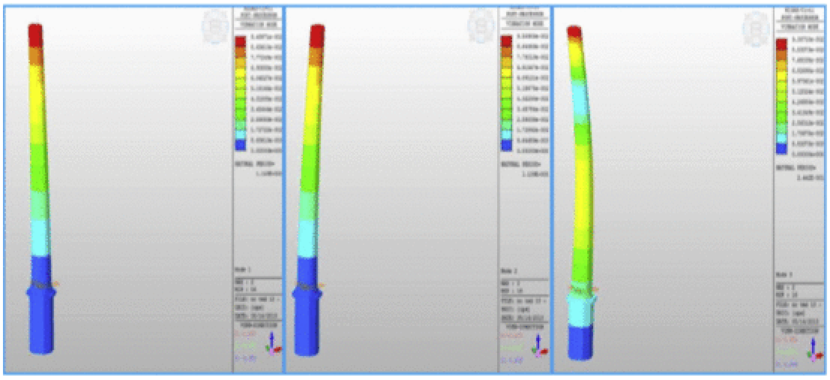

Figure 3. I,II and III vibration mode shapes.

4. TMD IN FEM 1

The TMD is implemented in the FEM 1 by a nodal mass constrained to move only horizontally linked to the chimney to the top displacement point by a general link (type spring and dashpot) with k_{tmd} and C_{tmd} evaluated by the previous relations. With the TMD the previous structural ULS verifications are fulfilled because the maximum compression value decreases to $f_{c,s} = 2.59$ MPa, minor the $f_{dc, rid} = 3.55$ MPa, and the maximum base shear decreases to $V_d = 582$ kN , minor than the $V_{d,ULS} = 723$ kN; moreover the maximum top displacement decreases to $\Delta top = 0.04$ m with the TMD's horizontal displacement $\Delta_{TMD} = 0.14$ m. Finally, by the eigenvalue analysis, the vibration mode shapes of the chimney with TMD shows the first four modes involve only the TMD, only from the fifth mode the chimney's structure begins to be involved.

5. TMD IN FEM 2

A solid elements FEM 2 is implemented by considering the seismic action as seven spectrum-compatible accelerograms application. In FE 2 a no-linear analysis (time history analysis) is carried out: the earthquake is represented by an accelerogram and the masonry is characterized by a non-linear behavior.

The effect of the nonlinearity to the behavior of masonry must be accurately taken into account analyzing the ultimate behavior of masonry chimney. The main concept of the nonlinear masonry model, adopted in the FEM implemented by the software MIDAS GEN, is based on the theory of Lee et al.[7], [8] and [9]. In fact, the failure of masonry bases on the micromechanical behavior. Using Midas, at every loading step, once the equivalent stresses/strains in the masonry structure are calculated, stresses/strains of the constituent materials can be derived on the basis of the following structural relationship:

$$\sigma_b = [S_b]\sigma_m$$
$$\sigma_{bj} = [S_{bj}]\sigma_m$$
$$\sigma_{hj} = [S_{hj}]\sigma_m$$

where subscripts b, bj and hj represent brick, bed joint and head joint respectively. The structural relationships for strains can similarly be established.

By using the function "Plastic Material" in Midas, the maximum principal stress is calculated in each constituent layer and is compared to the tensile strength defined by the user. If the maximum principal stress exceeds the tensile strength at the current step, the stiffness contribution of the constituent to the whole element is forced to become ineffective. For the nonlinear stress–strain relation of constituents, even the elasto-perfectly plastic relation could be simulated. This can be numerically implemented by substituting the stiffness of the constituent with very small value as $E = 0$ (of the brick, or bed joint or head joint).

The structural ULS verifies are conducted for the solid elements positioned at the base of the outer skins shown in the red circle in the following Figure 4.

The ULS verifies show the maximum compression stress $f_{c,s}$ is about 4 MPa, major the ultimate acceptable value 3.55 MPa, before mentioned.

The TMD is implemented in the FEM 2 by the introduction of a circular steel ring located close the top of the chimney and linked to the structure by four general link. For each link, the stiffness and the damping values are identical to the values before obtained in FEM 1, in fact the four links represents the four spring-dashpot systems of the real Tuned Mass Damper.

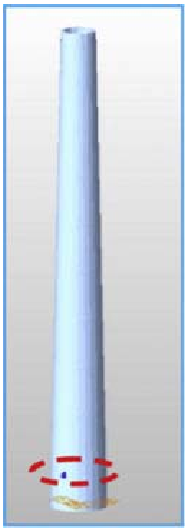

Figure 4. Outer skins elements considered for the ULS verifications.

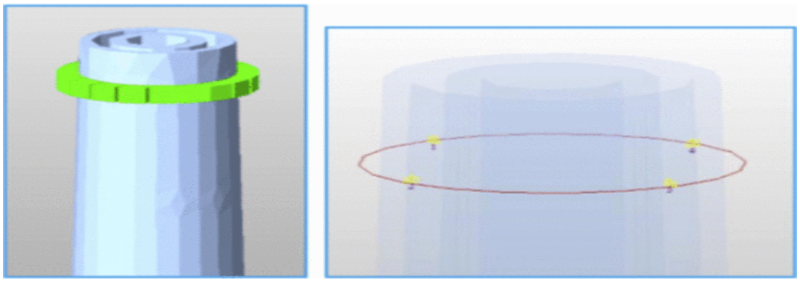

Figure 5. TMD implementation with the four spring-dashpot links.

In case of chimney with TMD, in FEM 2 the solid elements of the outer skin close the base of the chimney have maximum compression stress minor than 3.55 MPa because, with the TMD, the $f_{c,s} = 1.96$ MPa. At the same time, the top displacement decreases to $\Delta top = 0.05$ m.

Other depth study is conducted in FEM2, by modelling the TMD in solid elements with its support structure (see paragraph 7) like shown in the next Figure 6. The seismic response is practically equal to the case in which the TMD is implemented like before shown in Figure 5.

The slight differences between the results of FEM 1 and FEM 2 are probably due to the differences between the beam and the solid finite elements: in FEM 1 the structure is implemented by only tapered beam elements having an equivalent section and inertia values of the real ones, instead in the FEM 2 the chimney is represented by solids in order to reproduce the geometry more similar to the real one.

However, the FEM 1 analysis is necessary to calibrate and to optimize the values of the mass, stiffness and damping of the TMD; the optimized values are used in both FEMs.

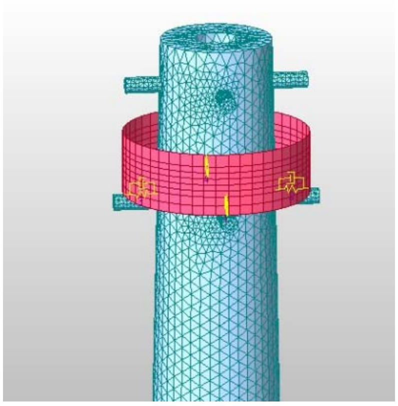

Figure 6. TMD in solid elements implementation.

6. TMD'S POSITIONING

In some applications, the TMD is well suited for steel chimneys because the mass value of the main vibration mode (from which to evaluate the TMD's mass) is lower in comparison to a concrete or masonry chimney cases. In a steel chimney it is very easy to realize the oscillating mass and its positioning is easy too, for example using a welded steel profiles system externally welded to the chimney's body. In a concrete or masonry chimneys, the dimensions of the oscillating mass could lead to large cross-section beams not easy to assemble. That is especially true in masonry chimneys where it is necessary not affect the actual stresses state of the masonry.

In this case the TMD support structure is represented by a steel structure to realize on two levels: the first (upper) level works for the positioning of the rops to which the circular steel mass of the damping system is attached, the second (lower) level supports the viscodampers.

The circular steel mass is hanging on the ropes and, it is supported by the dampers. The number of the dampers could be three positioned at 120° themselves.

Carrying out further structural and geometrical surveys in order to confirm the originally historical structural drawings, the original geometry described in the original drawings did not confirmed. In fact, the chimney shows an irregular geometry because the last 10m has only one skin. So, the analysis is recalibrated on the new geometry and to not afflict the masonry the TMD's positioning results more appropriate in the part of the structure with two skins. In this case, the seismic improvements change and other analysis are necessary.

In the following comparisons, the structural improvements are discussed naming:

- CA, chimney already studied in mentioned FEM 1 and FEM 2 with TMD positioned at the top (50 m);
- CB, chimney with new geometry and TMD located at 10 m down from the top (40m). Also a positioning in one skin part is considered too. The parameters of the TMD is recalculated like explained in the following.

The presence of two skins in the last 10m top changes a lot the vibration mode shapes and the seismic improvement by TMD. In fact, in CB the eigenvalue anlaysis shows new values of frequencies because $T_{1B} = T_{2B} = 0.82$ s and the related masses (m_1 and m_2) are $m_{1B} = m_{2B} = 0.85\%$ of the total CB's mass.

Like done in CA, in the CB case α_{opt}, ξ_{opt} and the k_{TMD} are optimized strating from μ value.

In case of the TMD is located at 40 m height, the best is $\mu_{2skin} = 0.0125$, thus $m_{TMD} = 33.9$ kN, $k_{TMD} = 189.48$ kN/m and $C_{TMD} = 4.17$ kNs/m. If the TMD is located in one skin part (at h = 45 m) the best μ is $\mu_{1skin} = 0.007$, so $m_{TMD} = 15.8$ kN, $k_{TMD} = 90.55$ kN/m and $C_{TMD} = 1.39$ kNs/m. For different μ values, V and M at the base of CB vary like showed in Figure 7. Choosing an average value $\mu = 0.01$ the improvements in Table 7 are obtained.

In every cases, for CA and CB, the TMD mass acceleration is always minor then the limit value $a_{lim} = 1$g.

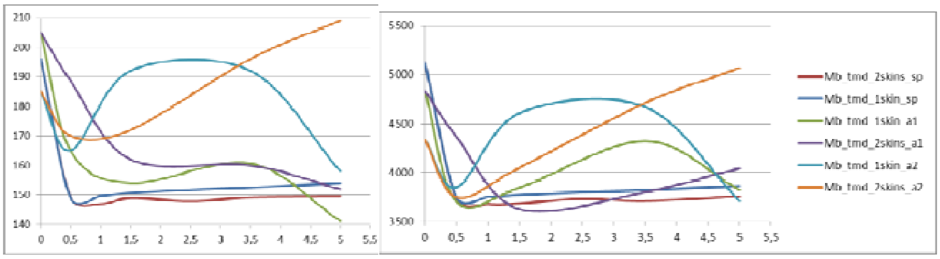

Figure 7. V and M with different μ , for seismic spectrum (sp) and 2 accelerogram (a1 and a2) application.

The seismic improvements for CA and CB cases (in CB two positioning of the TMD are considered: 45 m in the part with one skin and 40 m in the part with two skins) are summarized in the next Table 1.

7. SUPPORT STRUCTURE OF TMD

In a typical masonry historical chimney case, when it's possible to install the TMD in the part with two skins, the support system of the TMD could be the following, by considering features of the commercial dampers. The two levels could be positioned at about 2.70–3.50 m, depending by the length of the ropes (also variable between 0.80 and 1.40 m) to fix by dynamic test to investigate the real vibration modes of the chimney. The first level of the structure is characterized by an inner part realized by a cross of welded hollow circular profiles (diameter 193.7 mm and thickness 5.4 mm). At the end of each cross' arm n.4 hollow circular steel plates are welded. Each steel plate is bolted to another steel circular plate welded to hollow circular profile that reaches a length of 700 mm from the external chimney surface. Where the steel profiles cross the square holes (length sides 220 mm) in the masonry a steel box realized by n.6 4 mm thickness steel rectangular plates is previously welded on profiles. To perfectly close the square holes it is necessary use a suitable premixed cement mortar. The second level is equal to the first one but the cross' arms reach a length of 900 mm from the external surface of the chimney and at the end of each no. 4 arms the viscodampers are positioned on a n. 6 steel welded plates system characterized by no. 5 6 mm thickness vertical rectangular plates (sides 230 mm and 238 mm) and no. 1 8 mm thickness horizontal plate. The first and second levels are also connected by no. 4 AISI 316 cables linked at the inner hollow circular plate. A 3d representation of the TMD's structure is represented in the next Figure 8.

Table 1: Seismic improvements for CA and CB, with TMcS .

	μ [%]	TMD quote [m]	ΔV [%]	ΔM [%]	Δη [%]
CA	3.2	45	32	43	28
CB	1.0	45	24	27	22
CB	1.0	40	25	28	25

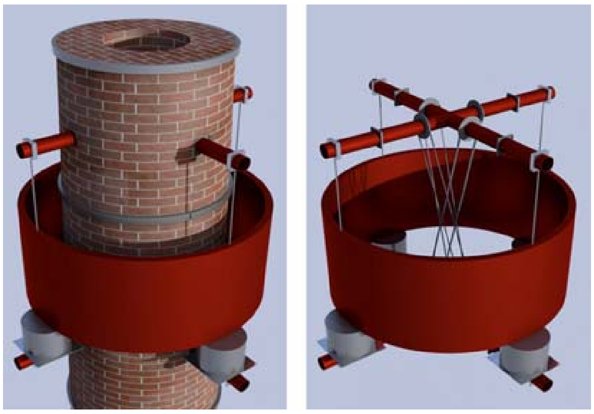

Figure 8. 3D representation of the structure for the TMD.

8. CONCLUSIONS

In the paper the TMD application is deeped to improve the seismic response. The main parameters of the TMD system is valued by the dynamic characteristics of the chimney (from the eigenvalue analysis). Some FEMs are implemented to understand the efficiency of the system. At the same time, in order to not afflict the masonry, different positioning are valued in terms of base shear, base moment and top displacements reductions. A possible solution to install the TMD is presented too.

REFERENCES

[1] D.M. Norme Tecniche per le Costruzioni; 2008.

[2] Circolare no. 617/2009.

[3] OPCM 3275/2003.

[4] Migliore G. Risposta delle ciminiere al distacco di vortici e controllo mediante smorzatori a massa accordata.

[5] Z.T. Rakicevivc, A. Bogdanovic, D. Jurukovski and P. Nawrotzki, *Effectivness of tune mass damper in the reduction of the seismic response of the structure*, Bull Earthquake Eng 10, 2012, 1049–1073.

[6] Chunxiang Li and Weilian An (2006), *Optimum properties of multiple tuned muss dumper for reduction of translational and torsional response of structures subjected to ground acceleration*, Eng Struct 28, 472–494.

[7] Garcia-Diéguez M, Koo K-Y, Middleton CM, Brownjohn JMW, Goddard C. *Model updating for a 183 m of reinforced concrete chimney. In: Dynamic of civil structure, conference proceedings of the society for experimental mechanics series*, vol. 4; 2011. p. 91–8.

[8] S. Lee, G.N. Pande, et al (1996) , *Numerical modeling of brick masonry panels subject to lateral loadings*, Comput Struct 61 (4).

[9] Analysis reference. Midas Gen.

[10] Chunxiang Li and Bilei Zhu (2006), *Estimating double tuned mass dampers for structures under ground acceleration using a novel optimum criterion*, J Sound Vib 298 (1–2), 280–297.

[11] Z. Zhang and T. Balendra (2013), *Passive control of bilinear hysteretic structures by tuned mass damper for narrow band seismic motions*, Eng Struct 54, 103–111.

[12] Chunxiang Li (2000), *Performance of multiple tuned mass dampers for attenuating undesirable oscillations of structures under the ground acceleration*, Earthquake Eng Struct Dynam 29, 1405–1421.

[13] Gebrail Bekdaş and Sinan Melih Nigdeli (2013), *Mass ratio factor for optimum tuned mass damper strategies*, Int J Mech Sci 71, 68–84.

[14] Chi-Chang Lin, Chi-Lun Chen and Jer-Fu Wang (2010), *Vibration control of structures with initially accelerated passive tuned mass dampers under near-fault earthquake excitation*, Comput-Aided Civ Infrastruct Eng 25 (1) , 69–75.

[15] K.F. Wong Kevin (2008), *Seismic energy dissipation of inelastic structures with tuned mass dampers*, J Eng Mech (ASCE) 134 (2), 163–172.

[16] N. Hoang, Y. Fujino and P. Warnitchai (2008), *Optimal tuned mass damper for seismic applications and practical design formulas*, Eng Struct 30 (3), 707–715.

[17] C. Li (2002), *Optimum multiple tuned mass dampers for structures under the ground acceleration based on DDMF and ADMF*, Earthquake Eng Struct Dynam 31, 897–919.

[18] Emiliano Matta (2013), *Effectiveness of tuned mass dampers against ground motion pulses*, J Struct Eng (ASCE) 139 (2), 188–198.

[19] J.P. Den Hartog (1956), *Mechanical Vibrations,* 4th Edition Ed .Dover Publication, NY.