Available online at www.eccomasproceedia.org
Eccomas Proceedia COMPDYN (2021) 4248-4261

ECCOMAS
Proceedia

COMPDYN 2021
8th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Streamed from Athens, Greece, 28 - 30 June 2021

SEISMIC RESPONSE OF SEVEN EXISTING REINFORCED CONCRETE CHIMNEYS EQUIPPED WITH TUNED MASS DAMPERS UNDER FIVE STRONG SEISMIC EVENTS

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Abstract

The seismic response of seven existing reinforced concrete chimneys equipped with optimized Tuned Mass Dampers (TMDs) are investigated under five acceleration time histories recorded during different important European seismic events. For each chimney, the features of the TMDs are detected by nonlinear dynamic analyses, starting from the investigation about the optimum mass ratio (between the optimum mass of the TMD and the mass of the chimney without the TMD involved in the most representative vibrational modes). By the application of sinusoidal forces, the contribute of the TMDs are evaluated by the estimation of the equivalent damping ratio.

Keywords: Tuned Mass Damper, RC chimney, Seismic Response, Non-linear analysis.

ISSN:2623-3347 © 2021 The Authors. Published by Eccomas Proceedia.
Peer-review under responsibility of the organizing committee of COMPDYN 2021.
doi: 10.7712/120121.8782.18732

1 INTRODUCTION

All over the world many industrial plants are characterized by the presence of chimneys. Starting from the '50 of the 20th century, in the new manufacturing and chemical plants reinforced concrete (RC) chimneys were built instead of the masonry traditional ones, due to plants requirements derived from the industrial developments and environmental reasons. From the middle of the 20th century, thanks to the new concrete techniques in use, it was possible to satisfy the new industrial processes requirements by reducing the environmental impacts with a significant height increasing (up to about 400 m), thus defining a wide range of possible heights from 100 m to 400 m. It is remarkable many RC chimneys were designed without specific earthquake-resistant provisions, considering only the wind as horizontal force [1] even if in some European countries, e.g. in Italy, many chimneys were built in areas only nowadays considered as seismic regions [2]. It represents an evident structural negligence for the seismic performance of many existing RC chimneys in terms of resistance and ductility and for economic aspects. Under seismic loads, the chimneys are characterized by an inelastic response, different from the elastic behavior. The domain of higher modes vibration and large natural period vibration consistently drives to a complex global dynamic response during earthquake events, reporting extremely increase of structural stress states, possible brittle collapse [3–10].

A recent study [11] has pointed out 6 major chimney failures causes, from 739 study cases, statistically summarized. The damage of these RC chimneys was mainly caused by seismic and wind action, temperature stress and construction defect [9].

Several researches have made relevant considerations in the earthquake engineering field [12,13] which revealed a sort of crack pattern of these slender constructions. In particular, they identified a failure-prone region at 1/3 to 2/3 also 0.8 of the height of a standard designed chimney, which concentrates inelastic deformations. It may occur when remarkable inertial force takes place in hazard earthquake, observing fractures in the horizontal, vertical, and inclined directions depicted after the strong motion. A predominance of cracks with 20–30 mm widths according to [11] was noticeable in many seismic events. It was observed the specific wind design cannot allow an adequate seismic response [12] in particular in terms of concrete stiffness with respect the concrete strength [14]. The increase of the height over 130 m exposes chimneys to large displacements wreaking cracks which demand extensive rehabilitation. Moreover, the radius-thickness ratio feature has also relevant influence in the dynamic response that decreases the displacement with the growth of the radius-thickness. It can be observed in chimney tapered from bottom to top lesser displacement values than chimneys which are tapered from the bottom then becomes uniform at one-third height. Shell stress as well decreases with the increase of radius thickness ratio in a fully tapered chimney in respect of partially tapered chimney. Chimneys with heights ranging from 325 m to 350 m are vulnerable against seismic forces especially tin case of elliptical cross-section. However circular chimneys have higher displacement than the elliptical section ones with higher accelerations under the seismic events. For improving the seismic response an adequate representation of the chimneys and the earthquakes is mandatory as it is explained in [9,10]. In these studies, the efficiency of passive tuned mass dampers is also proposed as a valid cost-benefits solution[15]. In several cases, the use of a single TMD represents a valid solution in terms of structural and economic convenience. The contribute of the single TMD can be described by shifting period coupled to the damping increase characterized the new system represented by the chimney with the TMD are easily detected.

2 STRUCTURE OF THE PAPER

In Section 3, starting from the features of the chimneys (3.1) and the ones of the seismic actions (3.2), for each chimney the parameters of the Tuned Mass Dampers (TMDs) are detected (3.3). In the Section 4 the contribute of the TMDs in terms of equivalent damping is evaluated whereas the energetic contributions are shown in Section 5 (where a comparison between the cases chimneys without TMDs and chimneys with TMDs is shown as well). Finally, Section 6 contains the remarks about the results characterized Section 4 and Section 5,

3 IDENTIFICATION OF THE TUNED MASS DAMPERS FEATURES

3.1 Chimneys

The seven RC chimneys here investigated were built from the '60 to the first half of the '80 years. They are classified considering four main geometrical features: the height (H), the geometrical slenderness $\lambda = H/D_{base}$, the taper ratio $t_d = D_{top}/D_{base}$ and the mass distributed along the height (q_h), depending on the chimney materials and the structural configuration and where D_{top} represents the external diameter at the top of the structure while D_{base} indicates the external diameter at the base of the structure. In Table 1 the main information about the chimneys are shown.

Chimney	D_{base} [m]	D_{top} [m]	H [m]	t_d	λ	t_h [cm]	q_h [kN/m]
CH_1	4.8	2.5	60	0.52	12.50	30	76.50
CH_2	16.1	13.6	100	0.85	6.21	40-30	100.00
CH_3	10.3	6.6	115	0.64	11.17	45-20	71.00
CH_4	15.0	14.8	120	0.99	8.00	35-26.5	29.00
CH_5	15.7	9.4	183	0.60	11.66	60-30	56.00
CH_6	16.0	8.5	220	0.53	13.75	76-20	76.50
CH_7	26.0	16.8	245	0.65	9.42	70-35	80.00

Table 1. Main characteristics of the seven chimneys. Note: D_{base}=diameter at the base; D_{top}=diameter at the top; H=height; t_d=taper ratio; λ=slenderness; t_h=thickness of the circular hollow section; q_k=distributed mass along the height.

The finite element model (FEM) of each chimney is implemented by MIDAS Gen software [16]. Each FEM has beam elements with a perfect restrain at the base. The self-weight and the dead loads are converted to mass in order to carry out the eigenvalue analyses for evaluating the periods, the related modal participation mass and the deformed shapes. The nonlinear material property of the concrete is attributed by Kent-Park property [17] and the ones attributed to the steel rebars is described in [18]. Eigenvalue results are shown in Table 2.

Chimney	T_I [s]	M_1 [%]
CH_1	1.63	58.48
CH_2	0.90	66.51
CH_3	1.77	54.24
CH_4	1.33	63.82
CH_5	2.55	53.87
CH_6	3.21	48.02
CH_7	3.79	45.23

Table 2. Eigenvalue analysis results. Note: T_1 is the first fundamental period and M_1 is the related involved mass

3.2 Seismic actions

The seismic actions are represented by five acceleration times histories recorded during different European seismic events (Greece, Amatrice, L'Aquila, Friuli and Montenegro), included in the European Strong-Motion Database. The features of the seismic inputs are shown in Table 3. The seismic inputs have been selected in order to obtain Magnitude between 6 and 6.9 and a PGA value between 0.35 g and 0.53 g: however, they are characterized by different integral parameters values, gaining a large variability of the ground motion characteristics , [19,20].

Event	Event id	Stat.	Year	PGA	PGV	PGD	M_w	Arias Int.
[-]	[-]	[-]	[-]	[g]	[cm/s]	[cm]	[-]	[cm/s]
Friuli (Acc1)	IT-1976-0030	FRC	1976	0.35	23.7	5.3	6	84.5
Montenegro (Acc2)	ME-1979-0003	PETO	1979	0.45	38.5	6.9	6.9	455.7
Amatrice (Acc3)	EMSC-20161030_0000029	AMT	2016	0.53	37.9	7.5	6.5	156.4
Greece (Acc4)	GR-1995-0047	AIGA	1995	0.52	51.3	8.3	6.5	117.1
L'Aquila (Acc5)	IT-2009-0009	AQG	2009	0.49	35.8	6.0	6.1	132.4

Table 3. Characteristics of the seismic inputs.

3.3 Tuned mass dampers parameters

Once the vibration mode shapes and the main frequencies of the structures are known, the features of the TMDs can be evaluated according to [21,22] and the seismic response can be analyzed by introducing the TMDs in the FEMs of each chimney (system 2). The TMD is implemented through a nodal mass connected to the chimney with a spring and linear dashpot characterized by horizontal stiffness (k_{TMD}) and damping coefficient (C_{TMD}). The boundary conditions of the node representing the TMD are set to allow only the horizontal displacements of the mass. The horizontal stiffness (k_{TMD}) and the related damping coefficient (C_{TMD}) are evaluated considering the following relations [23]:

$$k_{TMD} = m \cdot \alpha_{opt}^2 \cdot \omega_s^2 \tag{1}$$

$$C_{TMD} = 2 \cdot \xi_{opt} \cdot \sqrt{(k_{TMD} \cdot m_d)} \tag{2}$$

From [24] the values of k_{TMD} and C_{TMD} are obtained starting from the definition of the ratio (μ) given by the ratio of the mass of TMD (m_d) and the mass of the chimney (m) involved in the main vibrational mode (already explained in Phase A) and ω_s defined as the pulsation depending by the main frequency (f_I corresponding to the frequency value of the first and second mode shapes of the chimney without TMD) by the equation (3):

$$\omega_s = 2\pi \cdot f_I \tag{3}$$

The TMD mass ratio is given by the Eq.4 to obtain concerning the fundamental mode (μ_1) is given by:

$$\mu_1 = \frac{m_d}{\alpha_1 . m} \tag{4}$$

where α1 is the participant mass ratio of the fundamental mode of the structure without the TMD. The general mass ratio μ is expressed as:

$$\mu = \frac{m_d}{m} = \frac{\mu_1 . \alpha_1 . m}{m} = \mu_1 . \alpha_1 \tag{5}$$

In order to define k_{TMD} and C_{TMD}, the optimal coefficient for the frequencies (αopt) and the optimal equivalent viscous damping ratio (ξ_{opt}) are evaluated as it comes out from the following expressions, where ξ is the equivalent damping ratio for the structure:

$$\alpha_{opt} = \left(\frac{\sqrt{1-0.5\mu}}{1+\mu} + \sqrt{1-2\xi^2} - 1\right) - (2.375 - 1.034\sqrt{\mu} - 0.426\mu) \cdot \xi \cdot \mu - (3.730 - 16.903 + 20.496\mu) \cdot \xi^2 \cdot \sqrt{\mu} \tag{6}$$

$$\xi_{opt} = \sqrt{\left(\frac{\sqrt{3\mu}}{8(1+\mu)(1-0.5\mu)}\right)} + (0.151\xi - 0.175\xi^2) + (0.163\xi + 4.98\xi^2) \cdot \mu \tag{7}$$

Basing on the previous relations the values of mass the TMD can be taken in the range 1%÷5% of the mass of the chimney excited in correspondence of the main frequency (related to the first and second mode shapes). Testing different values of the TMD's mass, the related values of k_{TMD} and C_{TMD} (see relation (1) and (2)) can be detected and the different seismic response of "chimney with TMD" (system 2) can be evaluated in the FEMs where displacement, shear and moment variations are graphically shown in Figure 1. Once the average trends are detected for each chimney, the mass ratios optimizing the sizes of the TMDs are evaluated. The optimized size must minimize the mass of the damper but it must allow to reduce as far as possible the displacements, the base shear and base bending moment [4,25]. Therefore, for each chimney when the optimum mass ratio (μ_{OPT}) is chosen, the features of each TMD are evaluated as well in terms of horizontal stiffness (k_{TMD}) damping coefficient (C_{TMD}) and pulsation (ω_s) by the previous equations (1÷3), see Table 4.

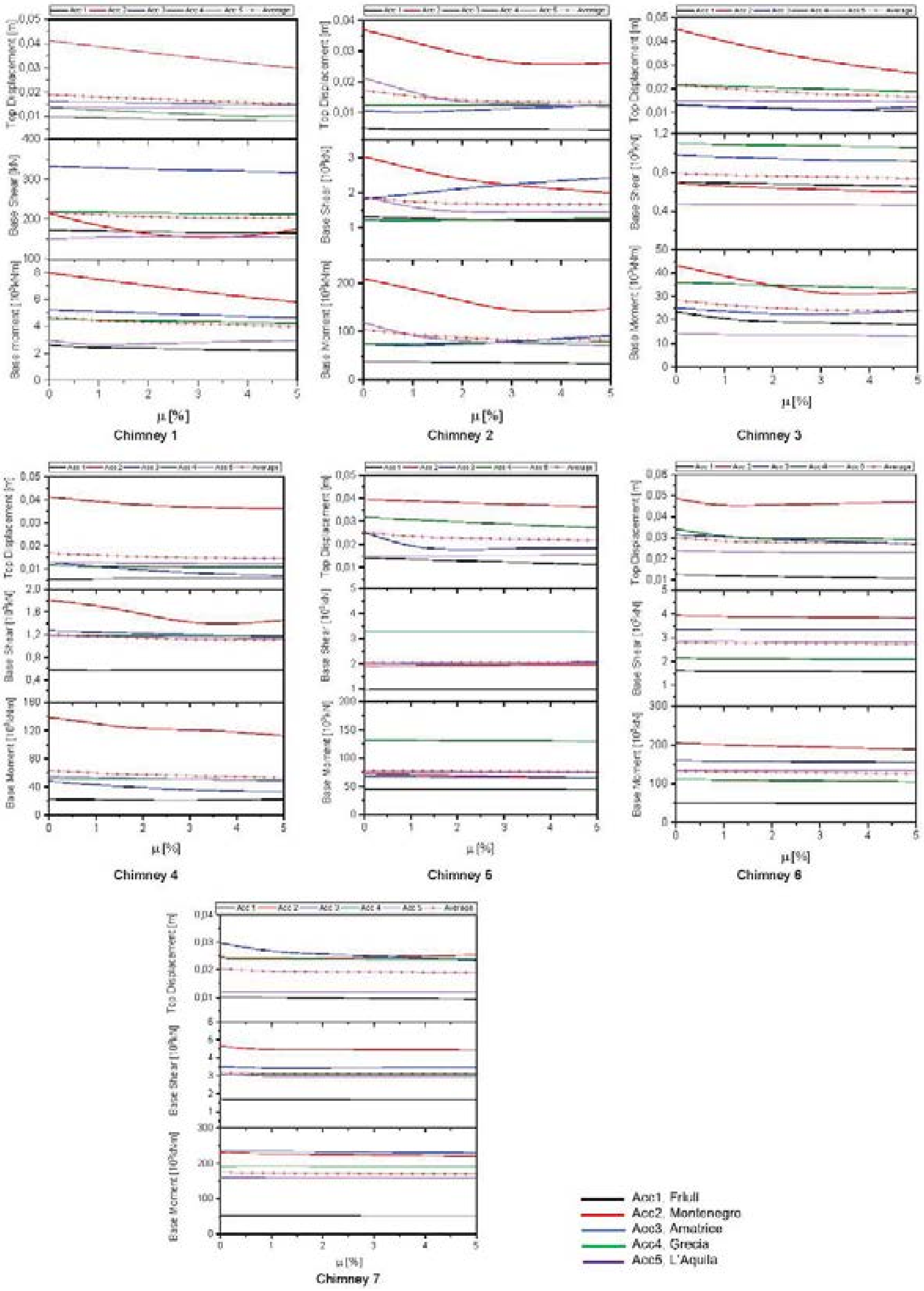

Figure 1. Optimization of the TMDs features in terms of top displacement, base shear and base moment in relation to the mass ratio for the seven existing chimneys

Optimum TMD Properties	CH_1	CH_2	CH_3	CH_4	CH_5	CH_6	CH_7
μ_{opt}	4%	1.5%	3%	3%	3%	5%	3%
ω_{TMD}	0.58	1.08	0.54	0.72	0.38	0.29	0.26
m_{tmd} [kN/g]	22.19	48.53	53.17	88.96	148.81	344.61	233.33
k_{TMD} [kN/m]	293.22	2224.90	613.50	1812.41	828.56	1148.62	589.11
c_{TMD} [kNs/m]	20.47	52.56	40.00	88.92	77.77	177.43	82.11

Table 4. Properties of the optimum tuned mass dampers selected for the seven chimneys (CH_ identifies the chimneys).

4 EQUIVALENT DAMPING EVALUATION

The contribution of the mass dampers of each chimney in terms of equivalent damping (ξ_e) is here estimated starting from the dynamic amplification factor (H) given by the ratio between X_s and X_d , where X_s is the top displacement under seismic action and X_d is the dynamic top displacement under forces with frequencies included in the range $(0.8\div1.2)\cdot f_I$ where f_I corresponds to the frequency to smooth (this value is obviously different for each chimney). The ratio between the frequencies of the forces and the frequency to smooth is called ρ (the variation of H by ρ is shown in Figure 2) . The equivalent damping (ξ_e) due to the TMDs can be detected as well from H because ξ_e is given by the relation (7) and it can be plotted once again in relation to ρ. The final value of the equivalent damping corresponds to the average one of the two lower peaks of the diagrams ξ_e-ρ (Figure 3):

$$\xi_e = \frac{H}{2} \tag{7}$$

It is worth nothing the influence of the main frequency of the chimney in the TMD's contribution in terms of equivalent damping given to the main structure. The results plotted in the Figure 2 and Figure 3, respectively in terms of dynamic amplification factor (H) and equivalent damping (ξ_e), are useful in order to appreciate the smooth effects given by the TMDs for each chimney under the five seismic events. The equivalent damping values are summarized in Table 5; the variation of the equivalent damping in relation to the frequencies of the chimneys is shown in Figure 4.

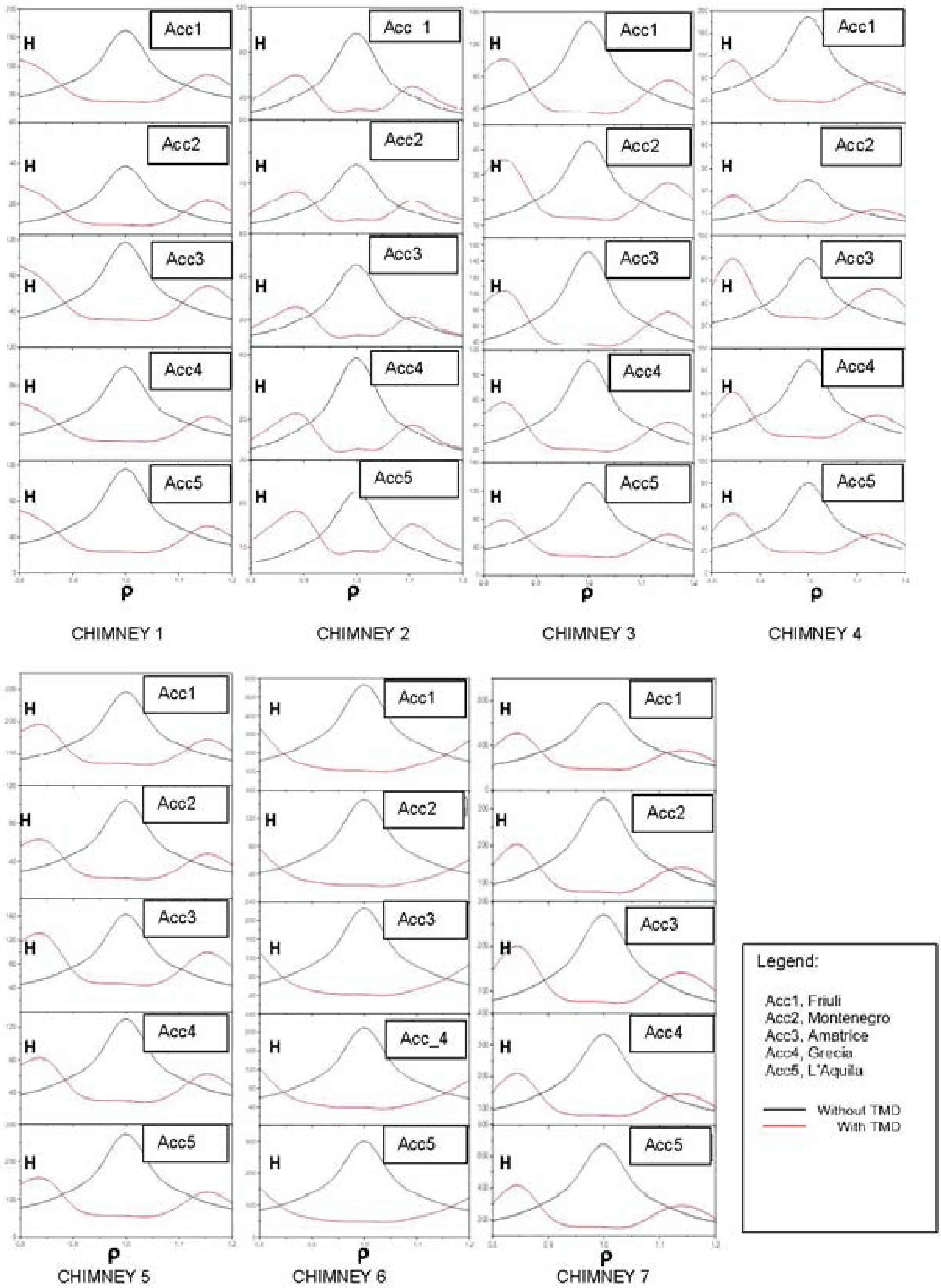

Figure 2. Dynamic Amplification Factor (H) in relation to the frequency ratio (ρ)

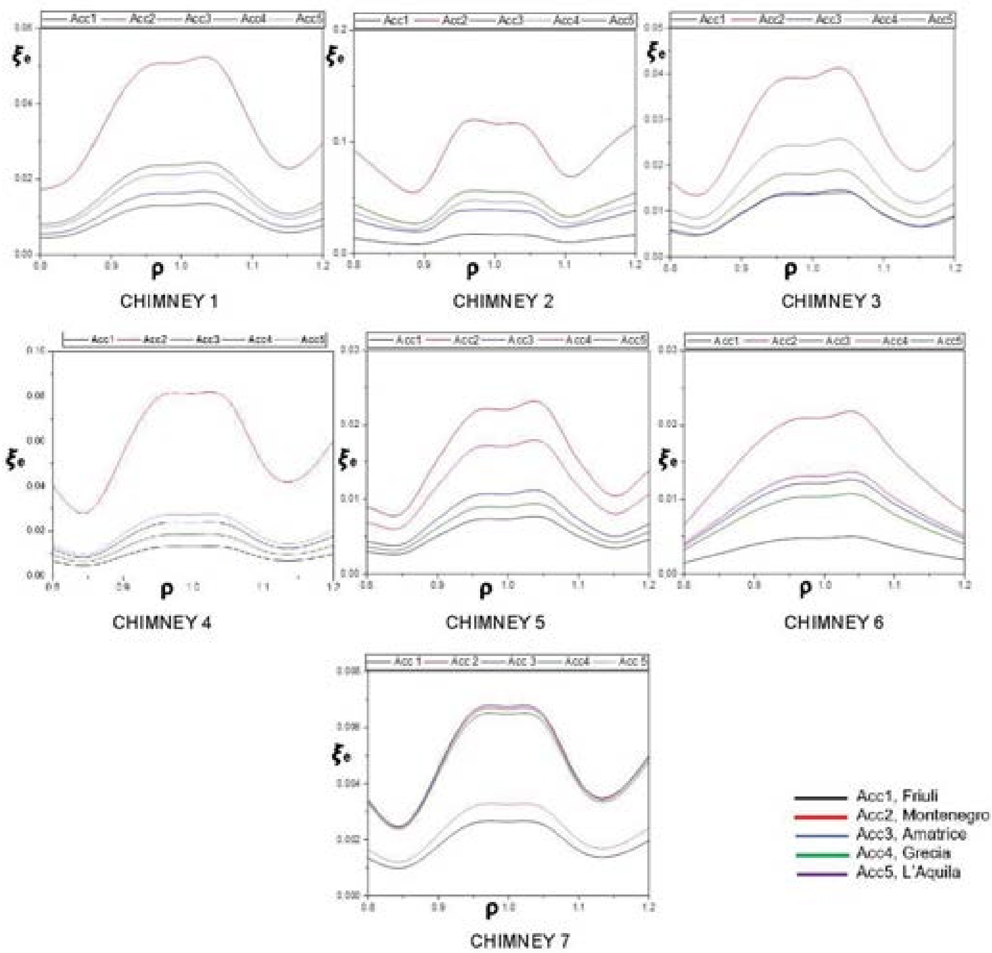

Figure 3. Equivalent Damping (ξ_e) in relation to the frequency ratio (ρ) for the five earthquakes

	Chimney 1	Chimney 2	Chimney 3	Chimney 4	Chimney 5	Chimney 6	Chimney 7
Acc	ξ_e	ξ_e	ξ_e	ξ_e	ξ_e	ξ_e	ξ_e
1	0.0076	0.011	0.008	0.007	0.004	0.003	0.001
2	0.0309	0.077	0.026	0.047	0.012	0.010	0.004
3	0.0101	0.023	0.008	0.013	0.007	0.007	0.004
4	0.0128	0.027	0.013	0.013	0.009	0.007	0.004
5	0.0112	0.041	0.009	0.015	0.005	0.005	0.002

Table 5. Equivalent damping ξe for the seven chimneys in correspondence of the five seismic events

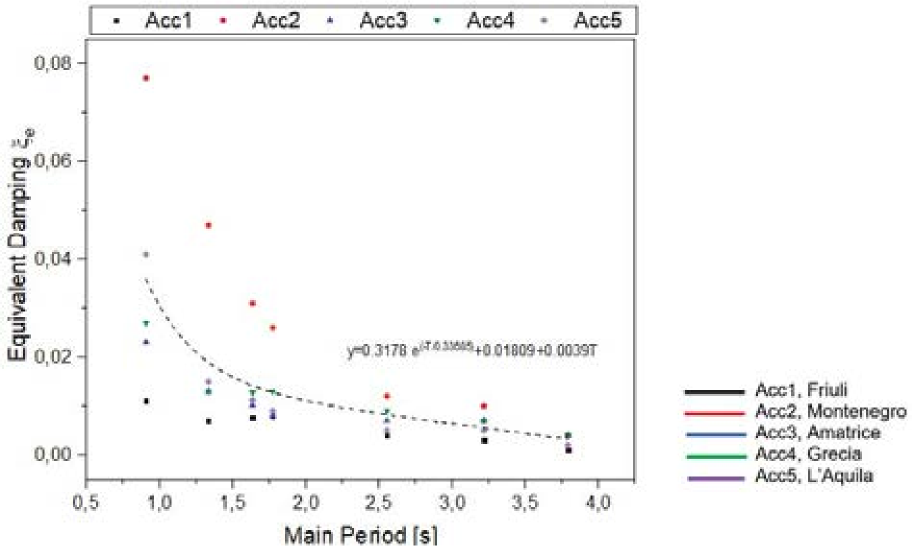

Figure 4. Variation of the equivalent damping with respect to the main periods of the seven chimneys.

5 ENERGETIC CONTRIBUTION OF THE TUNED MASS DAMPERS

In the present phase the dynamic behavior of the five case studies (chimneys with TMDs) is deepen in terms of energy damping starting from the assumption that for the generic chimney the input energy (E_i) due to the seismic action is the work done by the ground motion on the construction. Considering the time dependent conservation of the energy, (E_i) is given by the summation of the kinetic energy (E_k), the elastic strain energy (E_s), the energy dissipated by the structure throughout the inelastic features (E_h) and the damped dissipative energy of the building and the mass damper if present (E_d). Formulations about the energies are present in [26,27]. The aim of this phase is the evaluation of the damping energy during each seismic event for the seven chimneys either in the case chimneys without TMD and chimneys with TMDs. In Figure 5, for each chimney, the damping energy (E_d) is plotted for the five accelerograms. The output of the energetic analyses represents the variation of the damping energy during the seismic events therefore the results of this kind of analysis is plotted by time histories in both cases (chimneys without and with TMDs). Each time history represents the percentage of the damping energy with respect to the input energy.

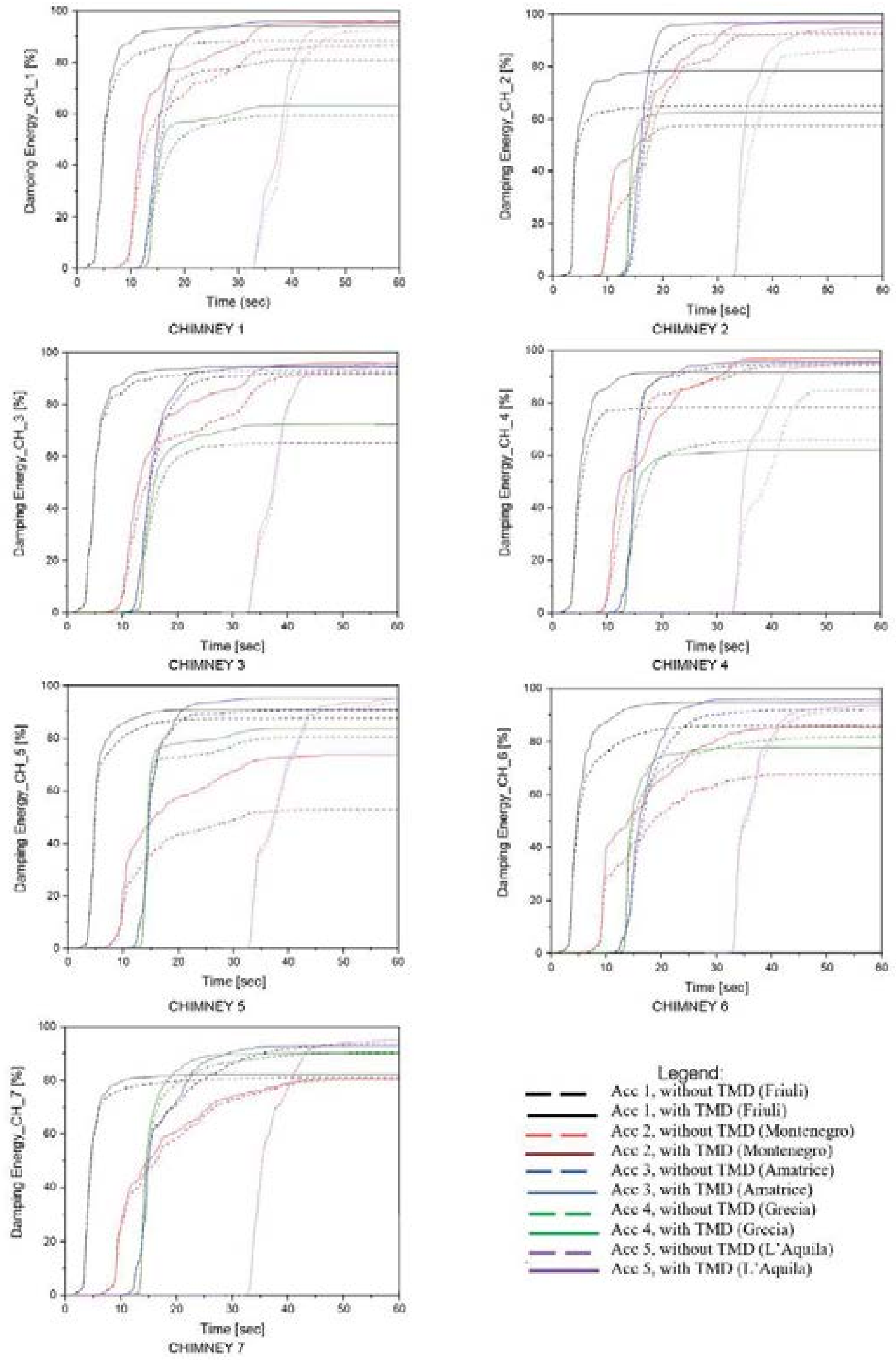

Figure 5. Evaluation of the percentage of the damping energy (Ed)with respect the input energy (Ei)

6 REMARKS

- The use of the Tuned Mass Dampers for existent Reinforced Concrete chimneys represents a valid solution for improving the seismic response of this kind of construction especially if originally built in areas only nowadays classified as seismic areas;
- The size of the TMD is influenced by the geometrical features of the chimneys: in fact, chimneys with high slenderness values need TMD with optimum mass ratio μopt higher than the ones with low slenderness. For slenderness value around $\lambda = 10$ the optimum mass ratio μopt is around 3% but for higher slenderness values, as it is for CH_6 with λCH_6 = 13.75, higher mass ratio μopt -CH_6 = 5% is adopted; vice versa CH_2 with slenderness λCH_2 = 6.21 needs lower mass ratio μopt-CH_2 = 1.5%; similar consideration may not be valid about the effect of the taper ratio td on the size of the TMD because chimneys with different td , as CH_1 with td = 0.52 and CH_4 with td = 0.99, are characterized by mass ratio values very close themselves (e.g. μopt-CH_1 = 4% and μopt-CH_4 = 3%);
- In the seismic events here adopted, the most important variations with the TMDs occur in terms of top displacement for each chimney; although, the base shear variation is not appreciable for each chimney especially in comparison to the displacements and moment variations;
- the equivalent damping does not appear dependent by the individual features of the chimneys (even if for high value of the geometrical slenderness - as it is for chimneys 1, 5 and 6 respectively with $\lambda_{CH\_1} = 12.5$, $\lambda_{CH\_5} = 11.66$ and $\lambda_{CH\_6} = 13.75$ – the equivalent damping values are very similar themselves); it is worth nothing the equivalent damping due to the TMD depends on the characteristics of the seismic event combined to the natural frequency of each single chimney, thus the seismic response is a correlation between the chimney's features (as the height, taper ratio, slenderness and dead loads) and the ones of each seismic event shacking the construction. A relation between the equivalent damping and the main periods of the chimneys (T) is expressed in the relation shown in Figure 4 where the equivalent damping ξ_e here estimated exhibits exponential variation growing for the lower values of T; vice versa, the intensity of the strong motion becomes irrelevant when the main period increases.

$$\xi_e = 0.3178 \cdot e^{-\frac{T}{0.33685}} + 0.01809 + 0.0039T \tag{8}$$

- under the five earthquakes the damping energy for the seven chimneys increases thanks to the TMDs; the contribution of TMDs is much evident in the asymptotic branch of the curves, especially under accelerograms 1 and 2 (drawn by black and red lines. In the case chimneys with TMDs, the damping energy increases. Generally, the dissipation of the input energy due to the seismic event occurs for damping contribute whereas the one due to the strain energy is practically zero. At the same time the TMD slightly reduces the contribute of kinetic energy in the dissipation of the input energy.

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