DESIGN OF NEW OPTIMAL PASSIVE NON-DETUNING MASS DAMPER

L. Martinelli[1], G. Grillo[2]

[1] Politecnico di Milano, Department of Civil and Environmental Engineering (DICA), Milano, Italy,
luca.martinelli@polimi.it

[2]Self-employed professional engineer, Vienna, Austria

Abstract: *In this paper a tentative manual design strategy for the "NextGenTMD" is proposed. The NextGenTMD is a new incarnation of Tuned Mass Dampers (TMD) passive structural control devices, introduced in a previous work of the authors. Differently from its linear counterpart version, the Linear Tuned Mass Damper (L-TMD), the NextGenTMD has a hysteretic-behaviour. In the proposed design strategy the parameters controlling the behaviour are selected so to enhance the effectiveness of the NextGenTMD by minimizing the negative effects related to the loss of tuning. This is what would normally occur for L-TMDs when the protected structure yields during a severe earthquake. The tuning problem is overcome by implementing a hysteretic version of the dynamic absorber, able to remain tuned to the primary structure despite its non-linear response. The proposed design method was applied on a simplified model of a four story building of which full scale pseudo-dynamic test results were available. The test results were used to set up a reduced numerical model of the building that was adopted in the assessment of the proposed design procedure with a set of spectrum compatible time histories, according to Eurocode 8.*

1. Introduction

In the past years, earthquakes were among the deadliest and more expensive natural disasters, resulting in a large number of casualties worldwide and causing expensive damages. Despite all what has been already done to increase the seismic performance of buildings, many strategies can still be implemented, especially for low rise Reinforced Concrete (R/C) buildings which are among the most diffused in Europe.

In this paper, which is derived from a MSc. thesis work (Grillo (2021)) jointly developed at Politecnico di Milano and TU Wien by the second author, co supervised by the first author, a new design strategy for a new incarnation of the well-known Tuned Mass Dampers (TMD) passive structural control devices is presented.

The proposed "NextGen-TMD" is a variation of the linear tuned mass damper (L-TMD) that includes the hysteretic-behaviour of the same.

As it is well known L-TMDs, properly tuned on a natural frequency of the main building, are able to oscillate with it, adsorbing part of the seismic energy that could otherwise cause structural damage. In order to be effective, however, they need to stay properly tuned to the principal structure even if this changes its vibration frequency. This is problematic for normal buildings, characterized by a nonlinear dynamic response during severe earthquakes.

The newly proposed NextGen-TMD aims to overcome the loss of tuning and effectiveness by implementing a specially designed hysteretic version of a TMD, broadening the use of TMDs beyond classical applications to buildings which behave in a relatively stable elastic way under seismic loading (e.g. high-rise one).

The promising results obtained so far from numerical simulations show that the NextGen-TMD can be effective in a seismic setting. This differs from what has been reported in some works of the literature, and encourage a further extension of the research efforts towards physical tests.

Indeed, if effective, the simplicity of the installation of this type of TMD could allow for a large-scale diffusion, helping to reach a wider reduction of the seismic vulnerability of the built environment.

2. Representative building

The “primary” structure on which the design method of the passive TMD control system, presented in this work, is focused, is the “dual frame” composite building. This is a four-story R/C building designed according to Panagiotakos and Fardis (2001) and tested in seismic conditions with the pseudo-dynamic technique at the ELSA Laboratory of the Joint Research Centre in Ispra (see Colombo et al. (2002)).

The building is a dual (walls-frame) structure, with an elevation of 12.5 m and a dimension, in the direction of testing, of 11.3 m.

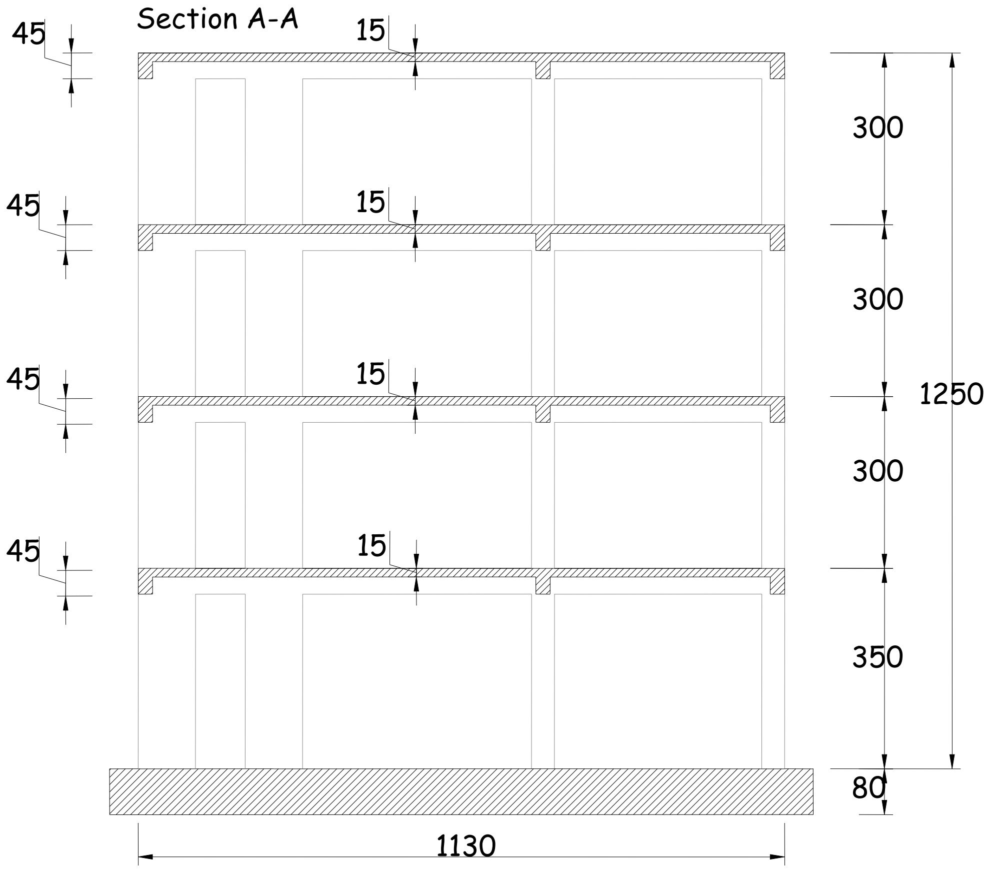

Figure 1. Elevation view of the “dual frame” building (measures in cm).

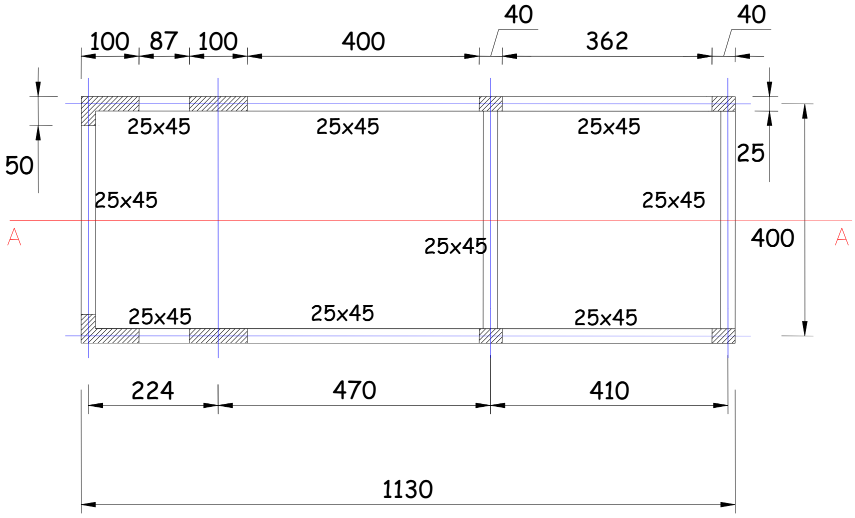

Figure 2. Plan view of the "dual frame" building (measures in cm).

3. Reduced model of the representative building

In order to numerically assess the design procedure that will be presented in Section 4, the main structure presented in Section 2 is modelled as a single degree of freedom nonlinear system (see Figure 3), in which the mass m_1, represents the mass of the main structure, and the nonlinear springs k_1 follows an appropiate hysteretic rule.

The hysteretic model chosen to represent the behaviour of the primary structure is the well known model by Takeda et al. (1971), originally developed on the base of experimental observations to reproduce the nonlinear behaviour of R/C structures under earthquake loading.

In this work, the simplest, original, version with large loops (see Figure 4) has been adopted, and implemented inside the Matlab (Matlab (2021)) environment including an independent set of parameters for the positive and negative values of the kinematic variable.

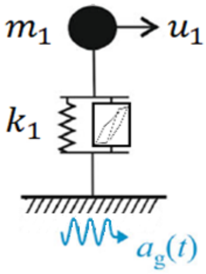

Figure 3. Reduced model of the building with NextGenTMD.

The parameters defining the properties of the nonlinear spring k_1 were calibrated with respect to the results of a pseudo-dynamic full-scale testing campaign (Colombo et al. (2002)) of the main structure. The parameters of the Takeda model (positive and negative yielding strength F_y^+ and F_y^-, amount of previous yielding that will be maintained upon reloading β, unloading stiffness parameter α, post-yielding stiffness parameter r) used to represent the structure were retrieved via a genetic algorithms-based identification procedure which relied on the minimization of the error between the measured response of the real structure and the calculated response of the single degree of freedom numerical model for the experimental data-set available from Panagiotakos and Fardis (2001). Further details can be found in Grillo (2021) and Grillo et al. (2023). The identified parameters of the Takeda model are reported in Table 1, were the subscripts “p” and “n” make reference to positive and negative values of the kinematic parameter.

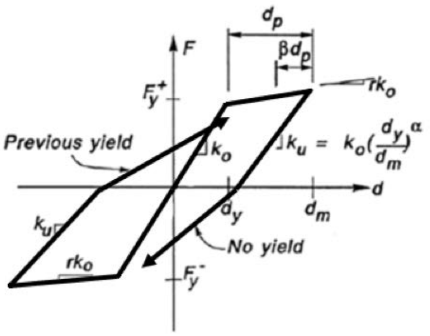

Figure 4. Takeda Hysteretic Model (redrawn from Carr (2004)).

Table 1. Identified parameters of the Takeda model.

Parameter	**Value**
r_p, r_n	0.009, 0.005
α_p, α_n	0.0, 0.0031
β_p, β_n	0.0, 0.0
F_{yp}, F_{yn}	766 kN, -674 kN
u_{1yp}, u_{1yn}	0.0348 m, -0.0307 m

4. Hysteretic model of the TMD and reduced model of the combined system

Regarding the hysteretic behaviour of the non linear spring connecting the TMD to the main structure, the modelling assumption in this work is that it follows the Bouc-Wen hysteretic law as presented in (Vestroni and Casini (2020)):

$$\begin{cases} F_d(u) = k_{e_l}u + z \\ \dot{z} = \{k_d - [\gamma_d + \beta_d sgn(z\dot{u})]|z|^n\}\dot{u} \\ k_e l = k_t * \delta_d \\ k_d = k_t - k_{e_l} = k_t(1 - \delta_d) \\ k_d > 0; \beta_d > 0; \gamma_d > 0; \\ \gamma_d + \beta_d > 0; \gamma_d - \beta_d \geq 0 \end{cases} \tag{1}$$

In Equation (2) u is the displacement across the spring, z is an internal state variable while $\beta_d, \gamma_d, \delta_d$, n and k_t are model parameters.

The Bouc-Wen model was selected for its good performance concerning its documented ability to reproduce the hysteretic behaviour of structural elements (e.g. rubber bearings, Bucher (2020)) and for the practical feasibility of a Bouc-Wen hysteretic Mass Damper to control linear viscous-elastic structures (Morelli (2019) and Vestroni and Casini (2020), Basili et al. (2021)). An illustration of how the key parameters modify the hysteresis cycles is shown in Figure 5.

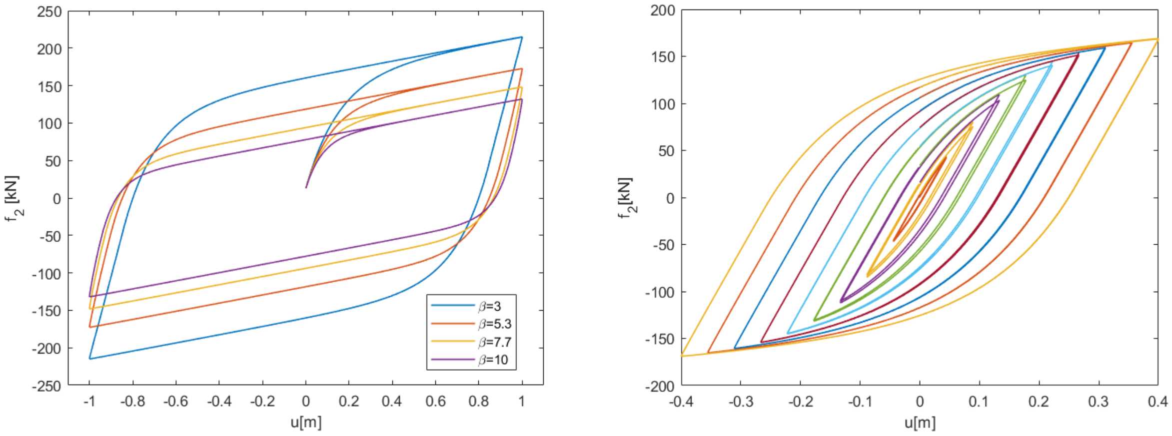

Figure 5. Features of the Bouc Wen Model. Right: variations of $\beta_d = \gamma_d$. Left: hysteresis cycles for n = 1; δ_d= 0:05 and different input peak displacements.

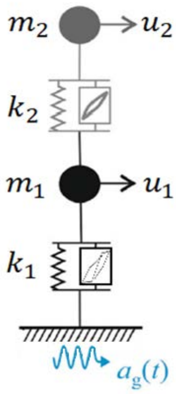

Figure 6. Reduced model of the building with the NextGenTMD.

The equations of motion of the combined system, composed of the main structure and the TMD, under horizontal seismic input, can be written as:

$$\begin{cases} m_1\ddot{u}_1 + c\dot{u}_1 + f_s(u_1) - f_d(u) = -m_s a_g(t) \\ m_2\ddot{u}_2 + f_d(u) = -m_2 a_g(t) \\ u = u_2 - u_1 \end{cases} \tag{2}$$

where u_1 and u_2 are relative displacements to the base of the structure, a_g is the ground acceleration, f_s and f_d are the non-linear restoring forces exerted by the non-linear springs k_1 (modelling the stiffness of the main structure) and k_2 (modelling the stiffness of the TMD), respectively.

5. Design strategy of the TMD

The design procedure here presented is based on setting a working point both for the main structure and for the non linear TMD: the main structure should reach, at most, a specified design value of displacement $u_{1\max}$ (design control displacement, here assumed equal to 0.07 m) while the TMD a design value of the drift with respect to the main structure u_{max} (design drift value, here assumed equal to 0.3 m).

In principle, because of the hysteretic nature of both the structure and the TMD, design must be carried out by keeping into account the level of the intensity of the motion and making sure that the damper and the structure are "optimally" tuned in the whole expected displacement field. While this aspect can effectively be granted by more advanced design approaches, such as the genetic algorithms-based design method presented in Grillo et al. (2023), the procedure here presented is a simplified one and it is based on the condition that the TMD is tuned to the structure at the beginning of the motion and when both the damper and the structure have frequencies of vibration corresponding to their secant stiffness at the respective working points.

Differently form the design method in Grillo et al. (2023), the proposed design approach does not consider the earthquake time histories as an input. Indeed, the degree of coupling described in Equation 2, that holds for the two degrees of freedom system, is here discarded and it is simply assumed that the TMD reaches its design drift value when the structure is at the design control displacement.

The TMD, taken as a single degree of freedom independent system, is "loaded" with a sinusoidal displacement time history so to be able to plot its hysteresis limit cycle (see Figure 5). Knowledge of the limit cycle is necessary to retrieve the TMD secant stiffness and damping factor, that depend on its drift value and force response. Once these are known, the additional damping provided to the main structure by the TMD can be estimated assuming the TMD as a linear one, characterized by the frequency associated to the secant stiffness and the damping factor just computed.

In the end, the algorithm presented in this work, allows to identify two design parameters among those $\beta_\mathrm{d}, \gamma_\mathrm{d}, \delta_\mathrm{d}$, n and k_t of the TMD by imposing that the desired tuning frequency and the desired damping ratio are provided by the TMD when it reaches its working point (i.e. the maximum design drift).

As it is known that (e.g. Vestroni and Casini (2020)) in a Bouc-Wen model the maximum dissipation occurs when $\beta = \gamma$ and $n = 1$, the search space for the design solution can be restricted by these conditions. The hardening coefficient δ of the model is fixed to a reasonable value, usually below 15% and here assumed at $\delta_d = 5\%$, considering that a zero value would lead to the largest possible effective damping ratio but the mass of the TMD would then be too loose and reach large values of displacement.

If the damping factor of the TMD is not optimal, iterations are required in which the parameters of the Bouc-Wen model are changed. However only one or two iterations are usually required to define the optimal TMD parameters, as the one reported in Table 2 for the structure at hand (set "Design solution A"). In the same table, the optimal ones identified with a genetic algorithm (set "Design solution GA-1", from Grillo et al. (2023)) by maximizing the control effect of the TMD during spectrum compatible time histories are reported as well for comparison.

In the iterative process, the elastic stiffness k_0 of the structure and the secant one k_s, correspond to those identified from a pushover curve of the main structure at zero displacement and using the design control displacement $u_{1\mathrm{max}}$.

Table 2. Parameters of the Bouc-Wen model obtained from the proposed design procedure and from Grillo et al. (2023) for procedure GA-1.

Parameter	**Proposed design procedure (set Design solution A)**	**Simulated time histories (set Design solution GA-1)**
δ_d	0.05.	0.05
f.	1	0.99
β_d	3.4	3.51

6. Numerical simulations

Using the Takeda model presented in Section 3, that represents the main structure, and a set of 8 simulated spectrum compatible accelerograms, the performances of the control strategy based on a non-linear TMD designed as presented in Section 5 are now compared to the outcome of using the same set of accelerograms with the TMD parameters coming from a different design solution (Grillo 2021, Grillo et al. (2023)), in which the problem of the control of the structural response by obtaining the Bouc-Wen parameters is solved as an optimization problem to spectrum compatible input accelerograms using a suitable objective function, related to the peak response of the main structure.

Based on the definition of the input time history, the design case here named GA-1 (spectrum-compatible simulated time histories), as also prescribed by the EC8, was obtained as the set of parameters that optimized, on average, the structural displacement resulting from a set of 8 simulated time histories. These were generated through the software SIMQKE_GR (Gelfi (2021)) to be compatible with the design spectrum of the real structure, which is described in Panagiotakos and Fardis (2001). A similar set of simulated design time histories was used for the assessment of the results both of the design case A and GA-1.

Results concerning the main quantities of interest for the response in terms of structural motion parameters are listed in Table 3 and 4. In such table A_{max} and A_{min} denote the maximum positive and negative horizontal acceleration, while the suffix “RMS” denotes the root mean square value of a response parameter. The case "UNC" refers to the uncontrolled situation, in which the TMD is not present and is the baseline to assess the effectiveness of the control effects due to the TMD.

The best results in terms of displacements of the main structure were obtained with the GA-1 design case, that was able to reduce, on average, the structural displacement of 0.039 m in the positive direction and of 0.0355 m in the negative one.

Table 3. Average of the peak response for the main structure kinematic parameters for the set of 8 time-histories.

Design solution	$\boldsymbol{u_{1,max}}$ [m]	$\boldsymbol{u_{1,min}}$ [m]	$\boldsymbol{u_{1,RMS}}$ [m]	$\boldsymbol{A_{max}}$ [m/s^2]	$\boldsymbol{A_{min}}$ [m/s^2]	$\boldsymbol{A_{RMS}}$ [m/s^2]
A	0.0775.	-0.0905	0.0269	11.4034	-107633	2.3711
GA-1	0.0751	-0.0834	0.0259	10.5611	-10.7826	2.4892
UNC	0.1165	-0.1260	0.0367	15.4316	-15.0856	N.A.

Table 4. Average of the peak response for the TMD kinematic parameters for the set of 8 time-histories.

Design solution	$\boldsymbol{u_{max}}$ [m]	$\boldsymbol{u_{min}}$ [m]	$\boldsymbol{A_{max}}$ [m/s^2]	$\boldsymbol{A_{min}}$ [m/s^2]
A	0.2715.	-0.2573	36.782	-37.7703
GA-1	0.3524	-0.3651	47.4294	-45.8586
UNC	N.A.	N.A.	N.A.	N.A.

The best solution concerning the TMD displacement is provided by the design case "A", that requires the minimum amount of free space for on the building to host the TMD oscillation.

7. Conclusions

In this work, which summarizes part of the MSc thesis of the second author, co supervised by the first author, the dampers class of the passive TMDs is revisited and cast into a new design strategy that leads to interesting control performances without requiring a multi dimensional optimization process. The positive performances suggest that the new name, "NextGenTMD" mass damper, given to the proposed control strategy seems justified.

The hysteretic-behavior on which the NextGentTMD is based is carefully adapted to the structure on which it will operate on the base of the proposed design procedure, carried out without resorting to numerically expensive optimization procedures. This solves all the issues related to the difficulties connected to defining gradients, when the structural response is non-linear, and to the risk of being decoyed by local minima in the parameters' space.

The main structure is represented as a single degree of freedom non linear oscillator, on the base of the Takeda model. The parameters of the Takeda model have been identified, in the framework of the Genetic Algorithm class, by matching the available seismic experimental response of the dual frame-wall multistory reinforced concrete building tested under its design earthquake.

Differently from what has been sometimes reported in some literature sources, excellent results were obtained from the NextGenTMD damper designed with the proposed procedure. The simplicity of the design and installation could allow for its large-scale diffusion and, in the end, for a more effective reduction of the seismic vulnerability of the built environment.

8. References

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