TOPOLOGICAL OPTIMIZATION OF METALLIC DAMPERS APPLIED TO VIBRATION CONTROL IN STRUCTURES

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Abstract. *The construction of taller and slender buildings have become quite common in large cities, thus challenging the structural engineers to develop more efficient designs so that the adopted arrangement can make best use of the characteristics of materials. The use of devices that add stiffness and damping to structures subjected to dynamic actions such as wind and earthquake loads, has become quite common in civil structures. One of these mechanical devices that has been widely used is the type of Added Damping and Stiffness (ADAS), which if correctly installed, can significantly increase the strength, stiffness and energy dissipation capacity of the structures of the buildings. ADAS type devices are basically energy dissipators installed in the structure in order that the dissipation occurs in these elements in a concentrated way, thereby protecting the main structure from further damage. Once the dynamic action that damages these elements occurs, they can be easily replaced without major costs.*

In the present study, as an alternative to ADAS, is performed the topology optimization of a metallic dissipator applied to the reduction of vibration in buildings subject to random environmental actions, raising through numerical analysis the appropriate device type format.

Keywords: *Structural dynamics, Vibration Control, Topology Optimization.*

1 INTRODUCTION

Typically, the seismic performance of structures has been improved by the addition of structural elements that increase strength and stiffness of the system. These elements reduce strains, however, this reduction often leads to an increase of seismic forces, because of the reduction of the vibration period. These reductions also causes an increase on structure base accelerations, increasing that way damage to structural components. (Kelly, 2007)

In the last years, an alternative to stiffening all the structure that called attention of many researchers and engineers was the installation of structural control devices, specifically on mitigating damages caused by wind and earthquakes in building and bridges.

Metallic dampers are passive control devices that during severe winds and earthquake episodes can reduce amplitude vibrations of the structure through energy dissipation due to inelastic deformation. Because of its simplicity, reliable performance and easy application, researchers around the world have conducted theoretical and experimental studies for the development of various structural shapes of these dampers in a way that each one meets a specific problem.

In this work a topological optimization is performed searching an alternative geometry to a hysteretic damper widely used called ADAS (Added Damping and Stiffness). The resulting device is called Bottle Shape. A nonlinear dynamic analysis is performed attaching this damper to a building subjected to a seismic excitation and verifying its efficiency. The analysis were performed on Ansys® and SAP2000® software.

2 STRUCTURAL CONTROL

The emergence of densely populated urban centres has led engineering solutions towards vertical integration. The development of techniques for structural analysis and design, coupled with the advances in the science area of construction materials and techniques has made it possible to build higher and higher structures, slender and therefore more flexible. These structures are vulnerable to the occurrence of excessive vibration caused by dynamic loads such as earthquakes, winds, waves, traffic, human settlement, among others (Avila, 2002).

To reduce excessive vibrations a structural control system can be used to dissipate the energy absorbed by the structure improving its performance when subjected to dynamical loadings. In recent years, there has been employed efforts in research and development of structural control devices, especially in response mitigation of buildings in relation to winds and earthquakes.

2.1 Passive Control

Passive control system do not need external source of energy to operate, the energy added to the structure by the external load is transferred to or absorbed by the control device.

A passive control system consists of an installation of one or more devices incorporated to the structure that absorb some of the energy transmitted to the structure by the dynamic load reducing this way the energy absorbed by the structural members of the main structure.

One of the passive control systems widely used is the hysteretic damper, the basis of the energy dissipation mechanism is the metal inelastic deformation, usually a soft steel or even lead alloy, or also more complex ones. By the action of small earthquakes a hysteretic damper act as stiffness member that increases global structural resistance to deformations, when subjected to a more severe earthquake, it acts as an energy absorber.

In general, hysteretic dampers exhibit stable behavior on a large number of load cycles, have negligible effects on the usage time and stand up to environmental actions and temperature effects (Maldonado, 1995).

2.2 Metallic Dampers

One of the more effective way to dissipate the energy added to the structure during an earthquake is through inelastic deformation of metallic devices Soong e Dargush (1997).

A great contribution regarding to metallic dampers was Whittaker *et al*,.(1989) work that investigated the behaviour of parallel plates with an “X” shape called ADAS (*Added Damping and Stiffness*) in a way to find the degree of effectiveness to general seismic applications. A schematic representation of ADAS is shown on Fig. 1.

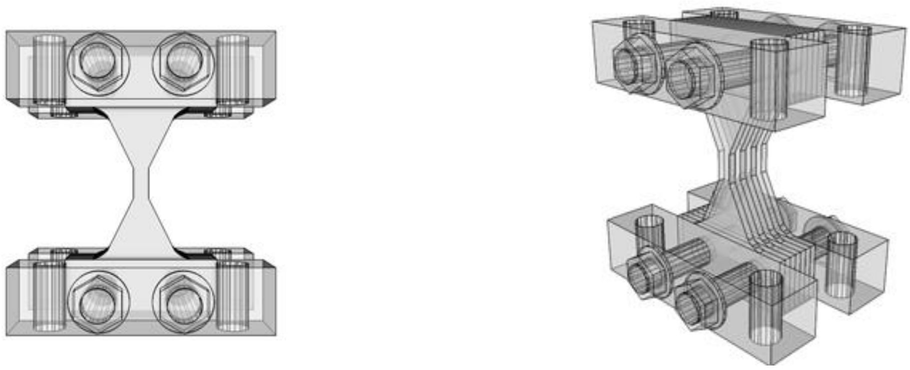


Figure 1. ADAS device

Although Whittaker *et al.* not specifically present the expressions they used to set the yield displacements, Tena-Colunga (1997) presents these displacements calculated from the double integration of the mean plastic curvature. The displacement of the metal plate yields given by the following equation:

$$\Delta_y{}^{PL} = \int_0^{l/2} \int_0^{b_{eq}} \frac{M_{px}(z)}{EI_x(z)} dxdz \tag{1}$$

being $M_{px}(z)$ and $I_x(z)$given by:

$$I_x(z) = \frac{b(z)t^3}{12} \tag{2}$$

$$M_{px}(z) = \sigma_y \frac{b(z)t^2}{4} \quad (3)$$

being:

$\Delta_y{}^{PL}$: Yield displacement of the metallic plate

l: Height of the plate X

b: Width of the plate X

b_{eq}: Equivalent width of the plate X

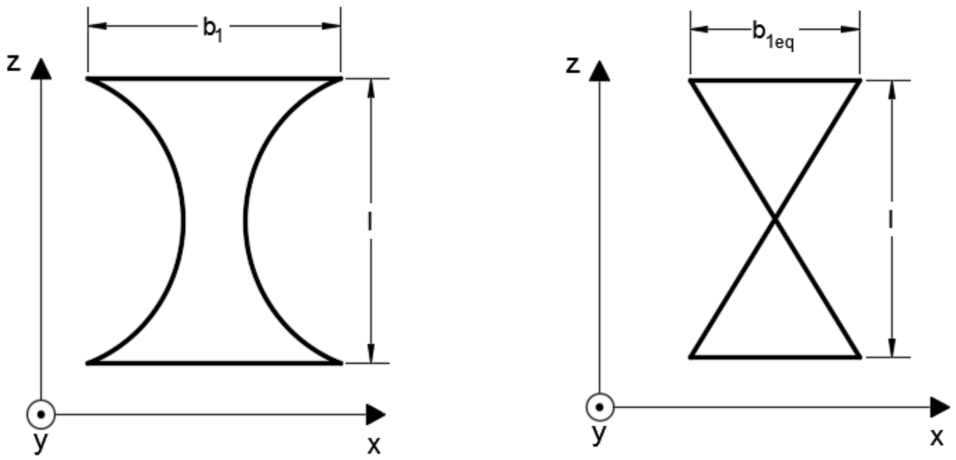
M_{px}: Plastic moment capabiliity

I_x: Moment of inertia of cross section of the plate X around x axis

t: Thickness of the plate X

σ_y: Yield stress material

The dimensions considered by Tena-Colunga (1997) are presented on Fig. 2.



(a) Idealized model type "Hourglass" (b) Equivalent "X" shape

Figure 2. Idealized shapes for ADAS device (Tena-Colunga, 1997)

Therefore, the yield displacement flow of the metal plate is given by:

$$\Delta_y{}^{PL} = \frac{3\sigma_y l^2}{4Et} \quad (4)$$

The equivalent shear plastic capability of the plate X (${V_{px}}^{PL}$) of ADAS is calculated through the equilibrium equation based on the plastic moment capability given by Eq.5.

$${V_{px}}^{PL} = \frac{2M_{px}}{l} = \frac{\sigma_y b_{eq} t^2}{2l} \tag{5}$$

Thus the shear elastic stiffness of each plate X is given by:

$$K_{PL} = \frac{{V_{px}}^{PL}}{{\Delta_y}^{PL}} = \frac{2Eb_{eq}t^3}{3l^3} \tag{6}$$

If it is adopted a number n of plates on a metallic device, the elastic shear stiffness of ADAS is given by:

$$K_{ADAS} = n\frac{2Eb_{eq}t^3}{3l^3} \tag{7}$$

In the same way, Bayat & Abdollahzaden (2011) presented an elastic shear stiffness of a TADAS (*Triangular-plate Added Damping and Stiffness*) given by:

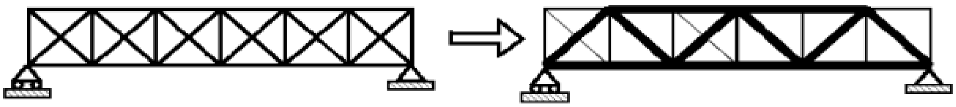
$$K_{ADAS^{\Delta}} = n\frac{Eb_{eq}t^3}{6l^3} \tag{8}$$

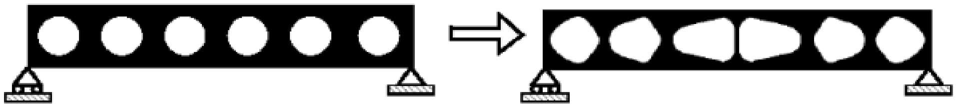
3 OPTIMIZATION

With increasing competition between global markets pressing the reduction of production costs and the reduced availability of raw materials, more and more necessary it becomes that optimization methods are developed for engineering design economical and efficient.

According to Rao (2009), optimization consists on obtain the best solution under given circumstances. Thus, when dealing with such problems, always seek to maximize a benefit or even minimizing damage, whether or not subject to any restriction.

Fig. 3 presents structural optimization types: (a) it is shown the parametric optimization where the structure present fixed shape and topology varying the constitutive characteristic of the material and/or the structural member dimensions; (b) shows the shape optimization in a way that the structure present a fixed topology, varying only its shape with no voids insertion and finally on (c) it was observed that voids were formed within the beam until all the truss shape be determined, thus characterizing the topology optimization, whose main feature is the inclusion of voids in a pre-established field.


(a) Parametric optimization


(b) Shape optimization

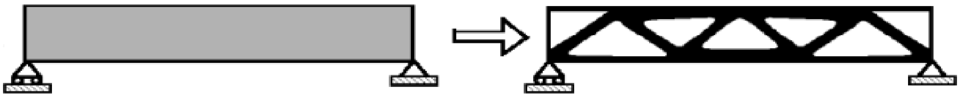

(c) Topological optimization

Figure 3. Structural Optimization Types (Bendsøe & Sigmund, 2003)

3.1 Topological Optimization

In a topological optimization design of a structure it is interesting to define the optimal location of every material fraction, setting this way where it will have to be material as well where it will not. *Sigmund et. al*. (2003) shows that if the geometric surface proposed is designed as rendered image, every pixel matches an element given by the finite element mesh.

One of the most used criteria in topological optimization problems is to minimize the internal strain energy with a volume restriction, which in linear problems is the same of minimization of external work. The loadings applied to the structure are constant, so minimizing external forces work is the same to minimize displacements, in other words stiffening the structure (Pantoja, 2012).

The aim is to determine the optimal subset (Ω_{mat}) of points with material. The admissible stiffness subset E_{ad} is that of those that attend the following equations:

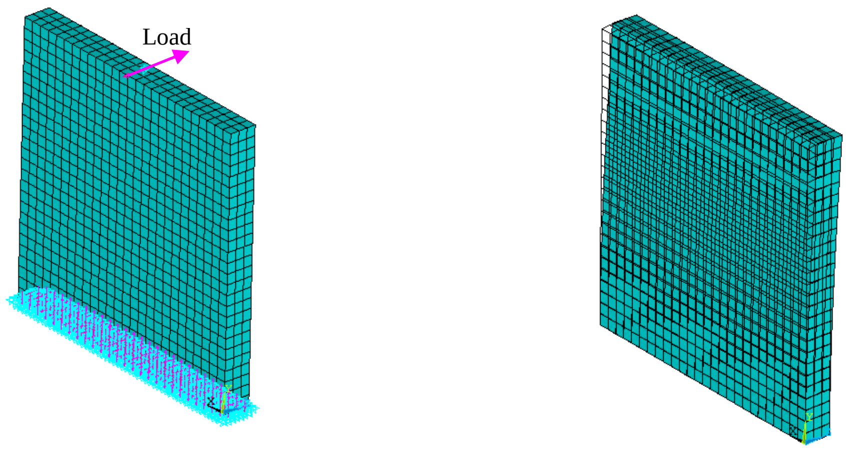
$$E_{ijkl} = 1_{\Omega^{mat}} E^0_{ijkl}, \qquad 1_{\Omega^{mat}} = \begin{Bmatrix} 1 & if\ x \in \Omega^{mat} \\ 0 & if\ x \in \Omega \backslash \Omega^{mat} \end{Bmatrix} \tag{9}$$

$$\int_\Omega 1_{\Omega^{mat}} d\Omega = Vol(\Omega^{mat}) \leq V \tag{10}$$

It can be observed that equation (9) formulates a discrete problem type [0,1], and inequation (10) express a total volume V limit of available material, in this way the lower designed stiffness is limited by a fixed volume.

In this work, through topological optimization, the behavior of metallic dampers with an alternative geometry is investigated.

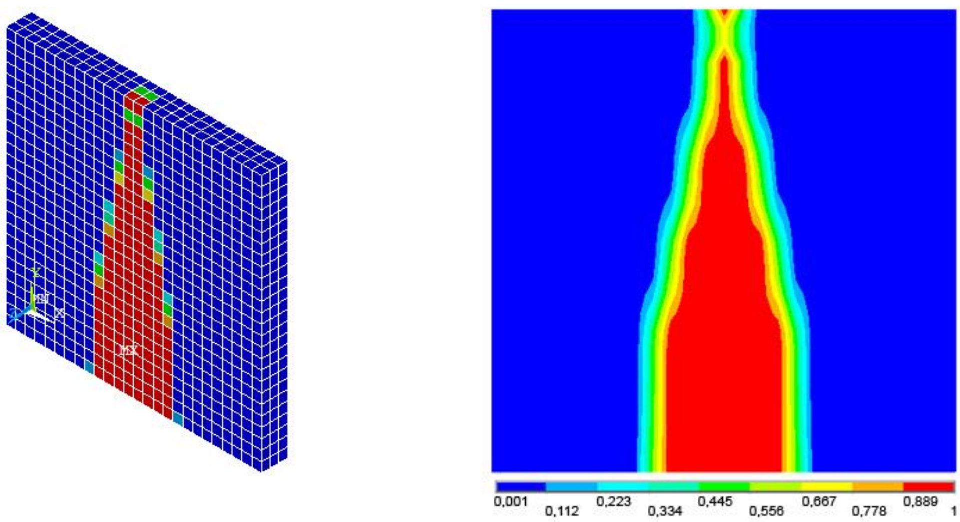
In a way to reproduce numerically experimental conditions so all the piece strain with the same curvature related to its middle point and present yielding all over its height, we chose to analyse a smaller size plate to the presented geometry by Whittaker *et. al*. (1989) with different restraint conditions. The structure was fixed at the base, with the loadings applied on top, to simulate double curvature an horizontal symmetry axis was considered and to consider an horizontal geometry gain it was adopted also a vertical symmetry axis. The detailed finite element model as well as the deformed structure after the loading are presented on Fig.4.



(a) Load application (b) Deformed structure

Figure 4. Metallic plate finite element model

After the load appliance, the topological optimization algorithm has been processed searching for an optimal material distribution within the boundaries of the plate model. This algorithm tries to find out the points where there should be material and the points where should not. After several iterations, the model presented on Fig. 5 is obtained, where by rendering an image, the model is generated sought by the distribution densities. The density $\rho=1$ indicates that should have material on that place, now those values less than one indicate absence of material on the considerate proportion. To the model studied here, the density value $\rho=0,001$ was considered as absence of material.



ρ distribuition acording to discretization Rendered image of the density distribution

Figure 5. Plate density distribution

As described above, two symmetry axis were considered, one horizontal to guarantee the piece to deform on double curvature and another vertical to provide a geometric gain on the piece dimensions. The piece details, already considering the symmetry axes are shown on Fig. 6. Due to the similarity of the piece geometry with a bottle it was called Bottle Shape.

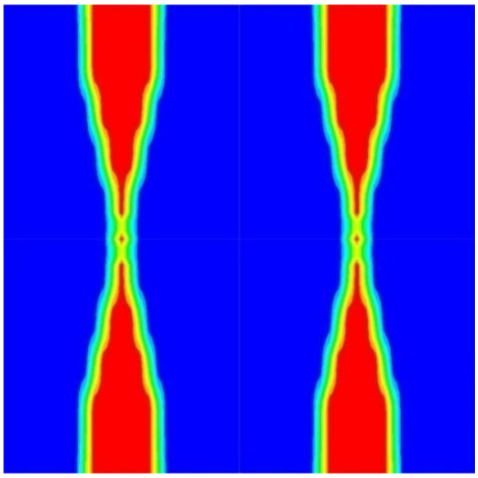
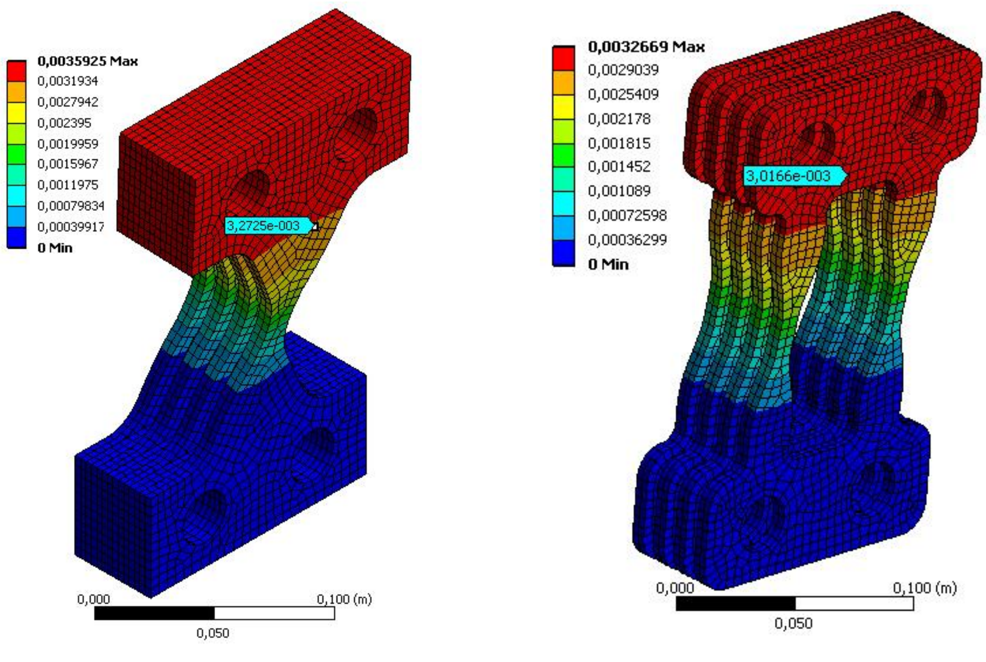


Figure 6. Topology proposal in accordance with the density distribution

4 NUMERICAL ANALYSIS

First an ADAS device with four plates was analysed. A shear force of *Vy=11.69kN* was applied to the system. In the same way a numerical analysis of a metallic damper with the Bottle Shape was also performed applying the same load. Both damper deformed shapes are presented on Fig. 7.



X Shape Bottle Shape

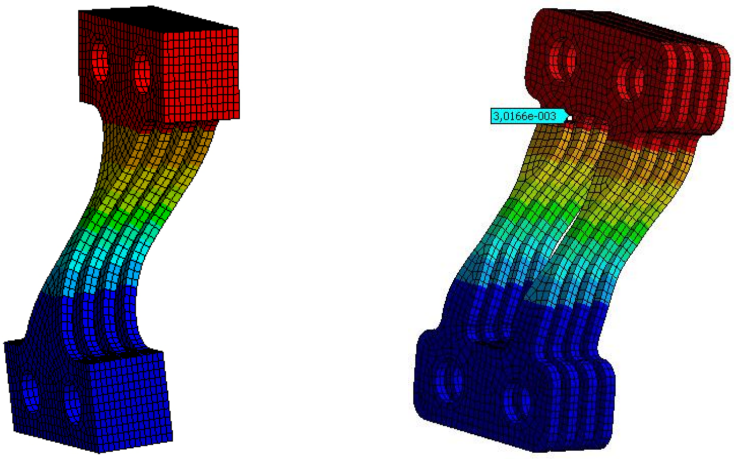
Figure 7. Deformed shape of the metallic dampers after load application.

From the numerical results it was observed that for the same loadings, the *Bootle Shape* damper presented satisfactory behavior when comparing displacements of both dampers, presenting a performance 8.5% greater. It notes that both pieces have practically the same amount of material. Displacement and shear elastic stiffness for both dampers are presented on Table 1.

Table 1. Shear elastic stiffness of X Shape and Bottle Shape

Formato	N° of Plates	$V_y(kN)$	$\Delta_y(cm)$	*k (kN/cm)*	Δ_k (%)
X Shape	4	11.69	0.33	35.72	0.00
Bottle Shape	4	11.69	0.30	38.76	8.48

As it can be observed on Fig. 8, as it was expected, the dampers deformed with double curvature related to its middle point. Note that the scale was expanded five times for better visualization.



X Shape Bottle Shape

Figure 8. Double curvature deformation

After proposing Bottle Shape topology and evaluating its elastic stiffness, its performance compared to X Shape is done attaching the dampers to a structural model like a plane frame. Consider the plane frame studied by Tena-Colunga (1997), presented on Fig. 9. The structure was subjected to North-South acceleration component of El Centro 1940 earthquake, data were normalized to a maximum design acceleration of 0,33g.The time history acceleration is shown on Fig. 10.

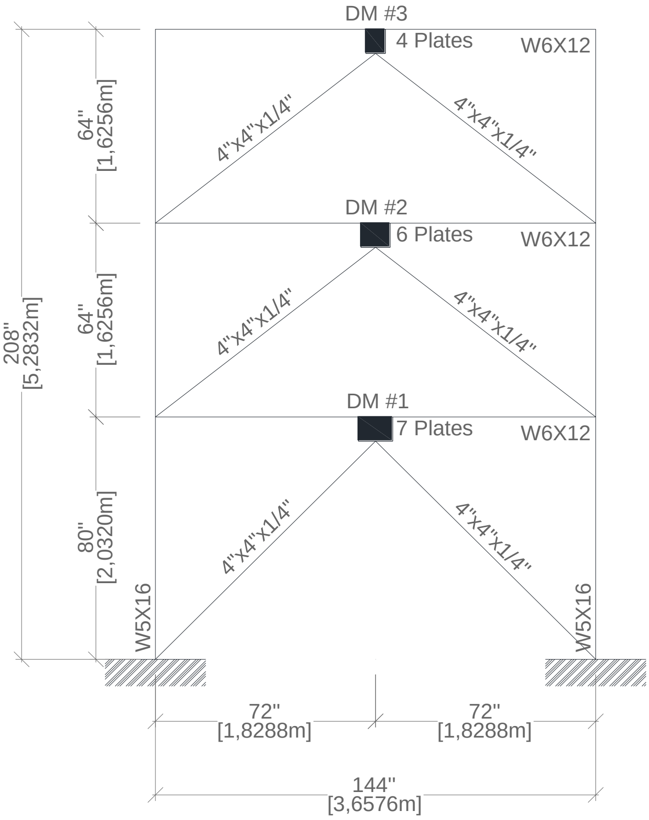


Figure 9. Plane frame (Tena-Colunga, 1997)

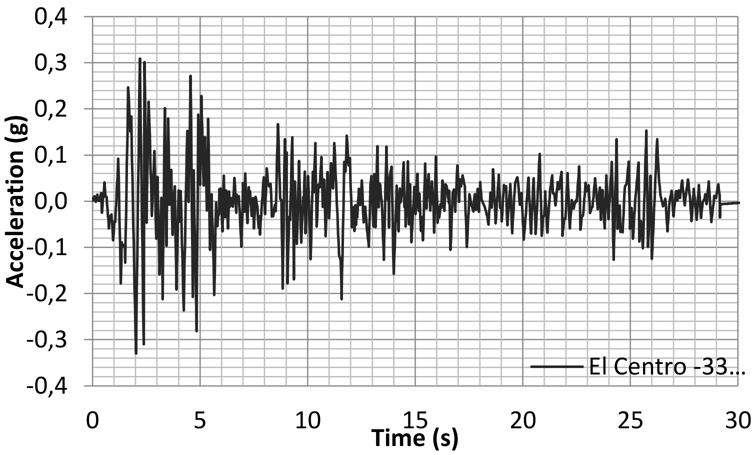


Figure 10. El Centro 33 N-S accelerogram

Numerical results of the nonlinear dynamic analysis of the structural system subjected to seismic excitation were analysed considering displacements on points A, B, C, DM#1, DM#2 and DM#3 as shown on Fig.9. Forces on dampers were also evaluated on points DM#1, DM#2 and DM#3.

Table 2 present displacements on points A, B e C for the structure without control and connecting dampers Bottle Shape and X Shape. Fig. 11 shows displacement time history for the same three cases. It can be observed that an excellent reduction was achieved.

Table 2. Plane frame displacements with and without control

Displacement		Without control (m)	X Shape (m)	Bottle Shape (m)	Δ(%) (1)/(2)	Δ (%) (1)/(3)
		(1)	(2)	(3)	(4)	(5)
Node C	RMS*	0.18048	0.01242	0.01204	1353.29%	1399.44%
	Maximum	0.30128	0.07377	0.07203	308.39%	318.25%
Node B	RMS	0.12880	0.00905	0.00880	1322.60%	1363.27%
	Maximum	0.22139	0.04884	0.04766	353.32%	364.49%
Node A	RMS	0.05344	0.00401	0.00391	1232.47%	1266.39%
	Maximum	0.09216	0.02027	0.01950	354.58%	372.55%

*RMS: Root Mean Square

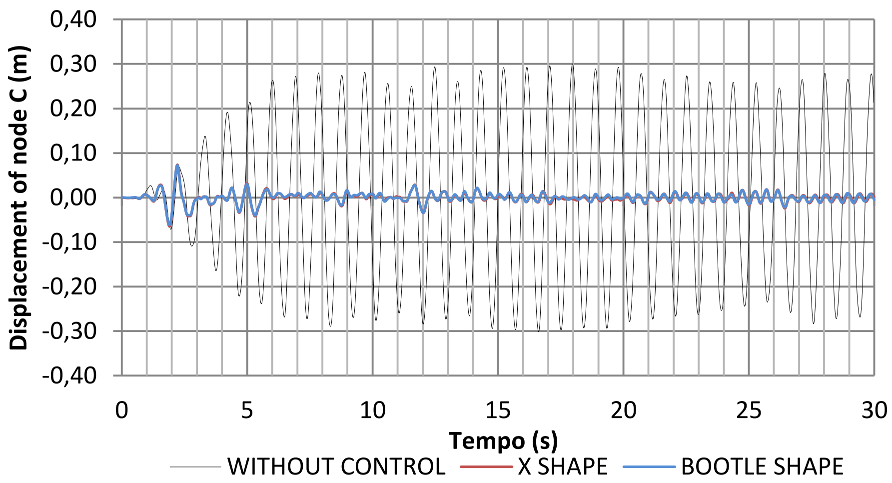


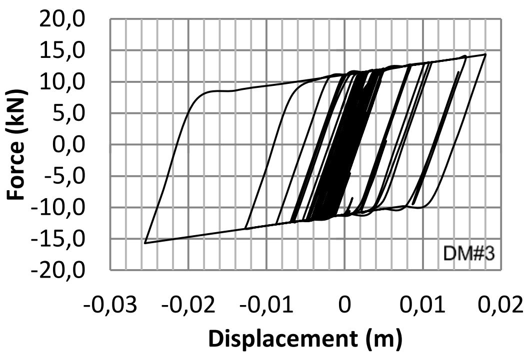
Figure 11. Displacement time history of node C with and without control

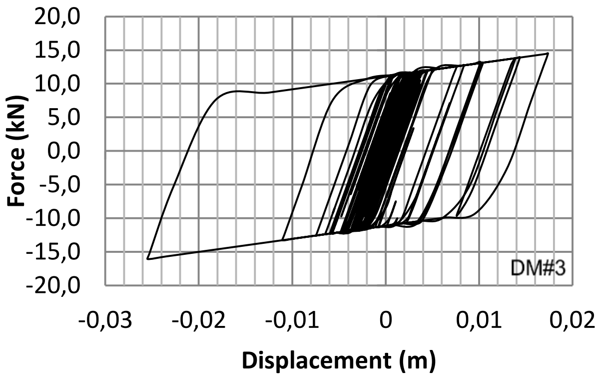
Maximum displacements obtained in each case are presented on Table 3. It can be observed that the difference between maximum displacements vary from 0,41% a 3,95%, the difference is greater for lower nodes.

Table 3. Maximum displacements of the plane frame

	X Shape(m)	Bottle Shape(m)	Δ(%)
	(1)	(2)	(3)=(2)/(1)
Node C	0.07377	0.07203	2.41
Node B	0.04884	0.04766	2.46
Node A	0.02027	0.01950	3.95
DM#3	0.02559	0.02548	0.41
DM#2	0.02967	0.02868	3.44
DM#1	0.02009	0.01933	3.95

In order to verify how the dampers are being requested, the hysteretic curves of each damper are presented on Fig. 12(a) e 12(b) for the Damper placed on DM#3.





(a) X Shape (b) Bottle Shape

Figure 12. Hysteretic behavior of the metal damper DM # 3 when the structure is subjected to seismic excitation

It can be observed from hysteretic curves that both them are very similar, a careful analysis indicates that maximum absolute forces absorbed by the metallic dampers X Shape are lower than those ones from the Bottle Shape type, with differences varying from 1,08% to 2,32%. On Table 4 the maximum absolute forces are presented, it is verified that dampers located at the bottom of the frame are more requested, needing more stiffness, which justifies a greater number of metallic dampers at the base of the structure.

Table 4. Maximum absolute force on dampers

	X Shape (kN) (1)	*Bottle Shape* (kN) (2)	Δ(%) (2)/(1)
DM#3	15.685	16.057	2.32%
DM#2	24.599	24.995	1.58%
DM#1	25.719	26.000	1.08%

5 CONCLUSIONS

Through topological optimization an alternative geometry for hysteretic metallic dampers, like ADAS, was proposed. The device modelled through this optimization was called Bottle Shape. The effectiveness of the damper was studied coupling it to a structural frame subjected to a seismic excitation. A nonlinear dynamic analysis was performed, where the dynamic response without control and with ADAS Damper was compared to the one with Bottle Shape Damper. Also the forces acting on the devices were verified in order to compare the performance of the two dampers.

Based on the obtained results it can be concluded that the Bottle shape geometry achieved satisfactory performance, being an alternative to control excessive vibration on buildings subjected to Seismic episodes. Both metallic dampers, ADAS and Bottle shape can dissipate energy added to the structure by earthquakes reducing excessive vibrations.

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