



A NEW HYSTERETIC DISSIPATIVE COLUMN PROVIDING ADDITIONAL STIFFNESS AND DAMPING

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ABSTRACT

A new replaceable hysteretic damper to better control seismic building damage consisting of two or more adjacent steel vertical elements connected to each other with continuous mild/low strength steel shear links, is proposed and investigated in this paper. New Dampers called Dissipative Columns (DC), continuously linked through X-shaped steel plates, provide additional stiffness and damping to a lateral system by using a basic and minimally invasive construction element: the column. Working in a way similar to coupled shear walls, the proposed element behavior is theoretically analyzed in linear and non-linear range. In fact, a parametric analysis is developed in order both to evaluate the effect of the main geometrical and structural parameters and provide the design capacity curves of this new damper. The DC can be considered as a new damping device easy to be installed to new as well as existing buildings in order to protect them from seismic damage.

INTRODUCTION

Strong earthquakes have shown that a large percentage of buildings in the affected areas, even if properly built and designed according to the most advanced codes, have suffered such severe damages that have been demolished after the quake since it would have been expensive to repair. As known, the acceptance of such level of damages under severe earthquakes is related to the ductility based design criteria that assume design seismic actions decreased by reduction factors. This approach may lead to high social and economic costs to the affected communities even for the long recovery time of essential services and production activities. Inspired by new performance criteria, there is a growing believe that code design criteria could not be sustainable for the high level of the accepted damage, impossible to repair, and that common buildings should be designed with higher performance level. At the beginning of this century, the performance based engineering (OES, 1995) introduced new principles with the scope to select more articulated targets better corresponding to different building role and use, defining a variety and most complex subdivision of performance objectives for seismic events having different intensity and frequency of occurrence. “Direct Displacement Based Design” philosophy (Priestly, 1993) provides to relate the specified performance level to the strain or drift limits, for a specified seismic intensity.

With the scope of minimizing structural damage, several dampers were developed in order to dissipate seismic input energy outside of the primary structure (Wada and Watanabe, 1992; Symans et al., 2008) and new replaceable hybrid composite steel devices (Pampanin, 2005) have recently been

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proposed. Dampers can absorb a significant portion of the input energy reducing the hysteretic energy demand to the primary structural elements.

The aim of this paper is to propose and investigate a new replaceable hysteretic damper having a basic form of the art of building, minimally architecturally invasive, consisting of two or more dissipative steel columns directly connected to two consecutive floors linked to each other through X-shaped low/mild steel plates. It will be shown that the new element is able to add significant stiffness and damping to the structural system in order to reduce seismic response and damage in primary structural members under severe earthquakes.

THE DISSIPATIVE COLUMN CONCEPT

The proposed Dissipative Column models are shown in Figure 1 for two different end cases (models A, B). The elements can be considered as a sort of framed bi-pendulum, connected in parallel to the primary structure, able to react to the story drift Δ with a lateral force Q_D adding stiffness, strength and damping. The design concept of the DC element aims to obtain a lever mechanism by which a small inter-storey drift provides an amplified vertical drift in the X-plate ends reacting with shear forces, (Figure 2). X-shaped steel plates made of mild or Low Yielding Strength (LYS) steel are also used as shear links between coupled elements (Kim and Seo, 2004; Susantha et al., 2004). The top ends of the three models are linked to the upper floor through slotted bolted connections to allow large vertical displacements. As known, well designed hysteretic dampers in framed structures should dissipate large rates of seismic input energy to control inter-storey drift and damage in the primary structure.

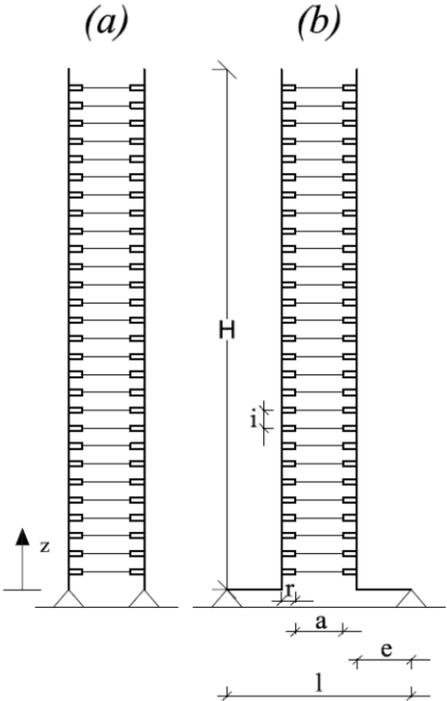


Figure 1. Dissipative Column Model: (a) Model A: Hinged at the ends; (b) Model B: Eccentrically Hinged at the base

By yielding a large volume of steel, the shear devices dissipate substantial input energy under earthquake or strong wind also increasing damping in the entire system. The limit values of Inter-Storey Drift Angle (ISDA) corresponding to different structural performance levels of a r.c. structure are suggested by Ghobarah (2004). The great advantages of DC elements, if compared with classical dissipative brace, are the reduced architectural invasiveness so that they are able to be integrated in any building, the easiness of installation everywhere, their replacement after earthquakes and the stable behavior in cyclic reversal deformation. Axial forces should be designed in order to be transferred locally to a proper structural element.

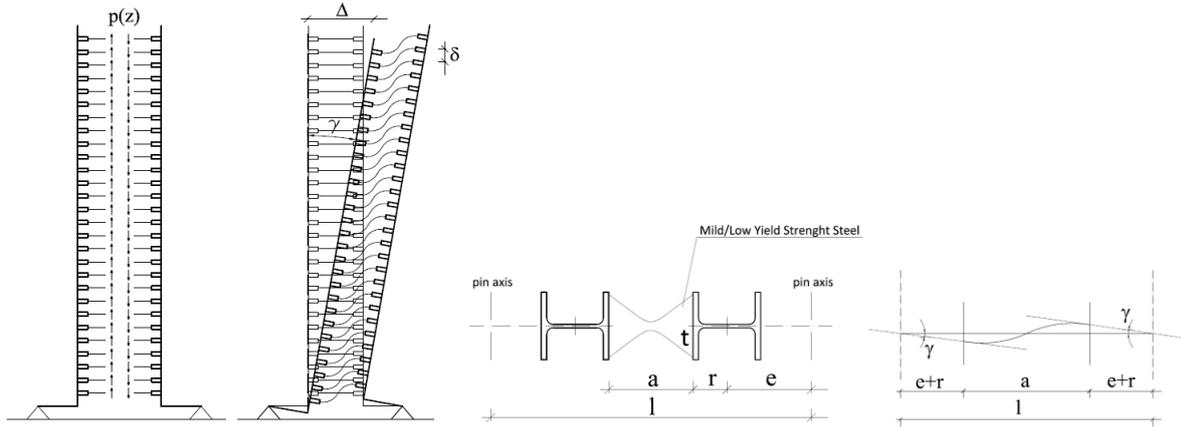


Figure 2. Eccentric Dissipative Column Model: dissipative amplified mechanism

SIMPLIFIED NON-LINEAR ANALYSIS OF DOUBLY-HINGED DC

The vertical drift δ between the ends of a generic shear link in the elastic range, being the curvature χ constant along each half plate, is related to shear force V_d developed by each X shaped plate, as:

$$\delta = 2 \int_0^{a/2} \int_0^{a/2} \chi(x) dx = \frac{3}{2} \frac{a^3}{Ebt^3} V_d \quad (1)$$

where a , t , b , E are, respectively, the X-plate length, thickness, width at the ends and Young's modulus of steel plates. Hence, the single X-plate vertical stiffness is equal to $K_d = V_d / \delta$. With reference to the model A, a simplified analysis of the DC behavior subjected to relative displacement can be easily carried out assuming that the column flexural deformation is negligible respect to the one of flexible inextensible links. Building inter-story drift produce a shear drift angle " γ " and vertical drifts " δ " in the X-shaped steel plate. Under such simplified assumptions the top-base relative displacement Δ of a DC element of height H is related to the drift angle " γ " as $\Delta = \gamma \cdot H$. Therefore, the uniform distributed vertical load due to shear drift angle γ applies:

$$p = \frac{2}{3} \frac{Ebt^3}{a^3 i} (l-a) \frac{\Delta}{H} \quad (2)$$

where i , l , $(l-a)/2=r$ are, respectively, the plates vertical distance, pin axes distance and a small lever arm. The lateral force-displacement relationship and the expression of K_D , representing the lateral stiffness of the DC, are respectively expressed as:

$$Q_D = \frac{2}{3} \frac{Ebt^3}{a^3 i} l \frac{\Delta}{H} (l-a) = K_D \Delta \quad (3)$$

$$K_D = \frac{2}{3} \frac{Ebt^3}{a^3 i} \frac{l}{H} (l-a) \quad (4)$$

According to experimental tests (Whittaker et al., 1989, 1991; Aiken et al., 1993), the load-deformation curve of the X-shaped mild steel plates can be idealized as a bilinear curve with a ratio of post yielding stiffness to the initial one equal to 0.03 and available displacement ductility ratio $\mu = \delta / \delta_y$ in the range between 3 and 5. Since yielding strength f_y is reached almost uniformly along

the device, the lateral yield strength of the doubly hinged DC element and the yielding displacement can be evaluated as:

$$Q_{Dy} = f_y \frac{blt^2}{2ia} \quad (5)$$

$$\Delta_y = \frac{3}{4} \frac{f_y}{E} \frac{a^2 H}{t(l-a)} \quad (6)$$

The dimensionless theoretical force-displacement relationship of a DC element consisting of two HE220 steel columns with $H=3.5$ m linked to each other through X-shaped mild steel plates having $a=200$ mm, $b=200$ mm, $t=10$ mm, $i=50$ mm, $l=480$ mm, is plotted in Figure 3. Considering X-shaped LYS steel plates having yield strength 97.9 MPa at 0.2% offset strain with Young's modulus equal to 200 GPa, a parametric analysis of DC element is developed in order to evaluate the effect of flexible devices for different values of i and t . The results of the parametric analysis (Figure 4) show that lateral stiffness and strength increase with greater values of t and lower values of i .

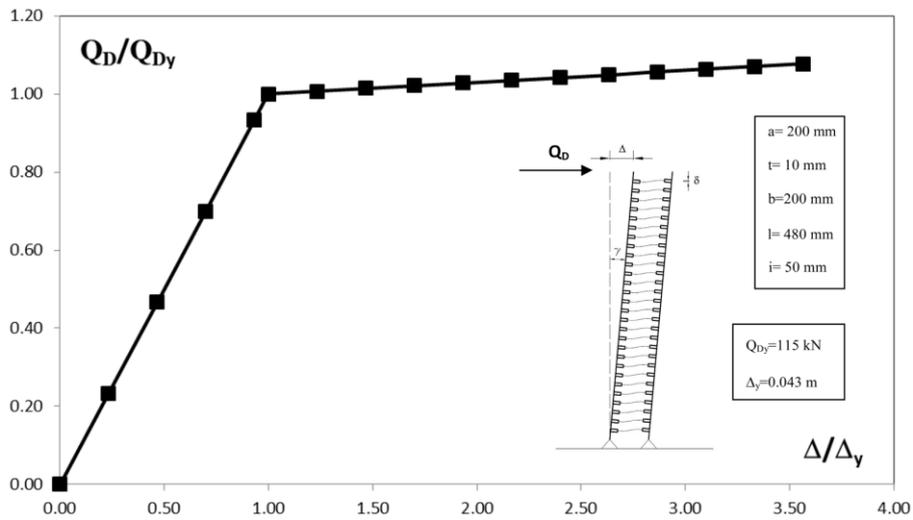


Figure 3. Model A: Theoretical Force-Displacement Relationship

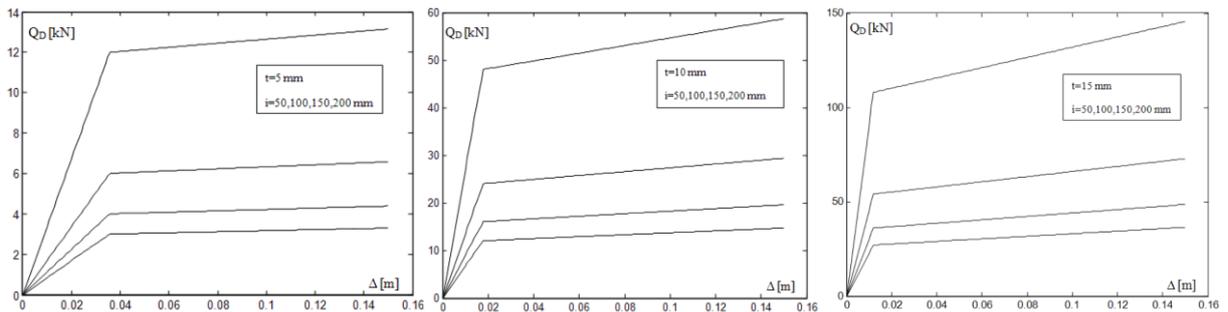


Figure 4. Model A: parametric analysis for different values of i and t

Differently to the previous case, in presence of a significant eccentricity the column flexural deformation should not be neglected, therefore, the top-base relative displacement Δ of the DC element results being:

$$\Delta = \gamma \cdot H + Q_D \left(\frac{eH^3}{3EI_c l} + \frac{e^2 H^2}{2EI_e l} \right) \quad (7)$$

and each X-plate undergoes a vertical drift $\delta(z)$:

$$\delta(z) = \gamma(l-a) + Q_D \left(2 \frac{H}{l} \frac{e^3}{3EI_e} + \frac{H}{l} \frac{e^2}{EI_e} r + \frac{e}{l} \frac{z^2}{EI_c} r \right) \quad (8)$$

where E , I_c , I_e and $(l-a)=2(e+r)$ are, respectively, Young's modulus, inertia of each column, lever arm with the eccentricity e . In the same way to previous case, the lateral force can be expressed as:

$$Q_D = \frac{N_c l}{H} = \frac{\frac{2 Ebt^3}{3 a^3 i} \gamma(l-a) H \frac{l}{H}}{1 - \left[\frac{2 Ebt^3}{3 a^3 i} \frac{l}{H} \left(2 \frac{H^2}{l} \frac{e^3}{3EI_e} + \frac{H^2}{l} \frac{e^2}{EI_e} r + \frac{e}{l} \frac{H^3}{3EI_c} r \right) \right]} \quad (9)$$

Being the fraction (9) denominator less than 1, the eccentricity causes an increase of the stiffness and lateral yield strength of the DC element.

RESULTS OF NON LINEAR PUSHOVER ANALYSES

The responses of the DC elements have been analyzed by static pushover analyses using SAP2000 software (Computers and Structures, 2010). The displacement-controlled pushover analyses have been performed until to reach 150 mm of relative displacement by modeling the non-linear response of the steel plates through Ramberg-Osgood (RO) curve with a ratio of post yielding stiffness to the initial one equal to 0.03. The analysed dampers are composed of two steel columns with different X-plates varying width, thickness and yield stress. Mechanical and geometrical properties of tested models (models A and B) are shown in Table 1.

Table 1. Geometrical and structural properties of the DC elements

Model	Height H (mm)	Column distance l (mm)	X plate length a (mm)	Plate thickness t (mm)	Plate distance i (mm)	Plate width b (mm)	Plate yield stress f_y (N/mm ²)	Eccentricity e (mm)	Column Profile
A_1	3500	480	200	5	50	200	240	0	HE220B S235
A_2				10					
A_3				15					
A_4				20					
B_1	3500	360	200	5	50	150	100	0 100 200 300	HE160B S460
B_2		560		10					
B_3		760		15					
		960							

With reference to model A, the displacement-controlled pushover curves of the DC models until to reach 150 mm for different thickness values are illustrated in Figure 5. The model A_4 collapses before due to excess of non-linear deformation.

In Figure 6, the diagrams of column bending moment, axial force, link bending moment related to model A_2 ($t=10$ mm) are represented. The axial force distribution along the columns is linear, in a manner consistent with the simplified assumptions previously examined. Both columns remain quite far from their elastic limits (Figure 7) (CEN, 2005) while shear links immediately enter in plastic range as the lateral force increases.

Comparisons between theoretical and numerical DC behavior of models A are plotted in Figures 8 and 9. Force - displacement relationships result comparable and consistent with the assumption that the column deformation can be considered as a rigid neglecting the small curvature respect to the shear links' one. The maximum ductility factor $\mu = \delta / \delta_y$ demanded to model A X-plates, at the last considered step (150 mm), is shown in Figure 10.

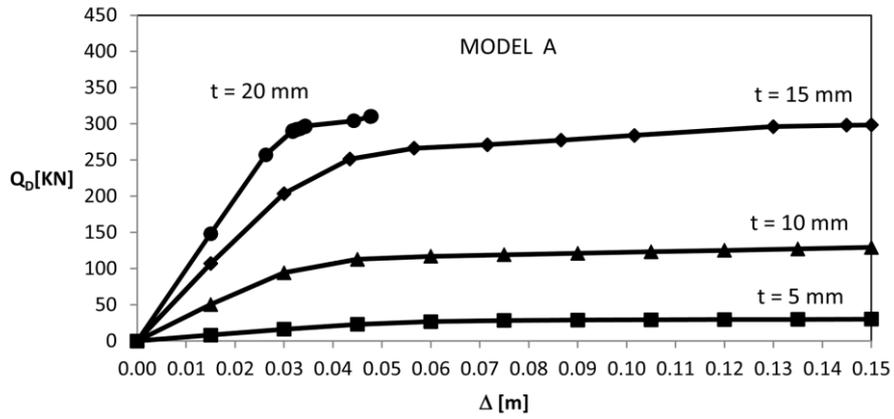


Figure 5. Model A: Pushover Curves for different plate thickness

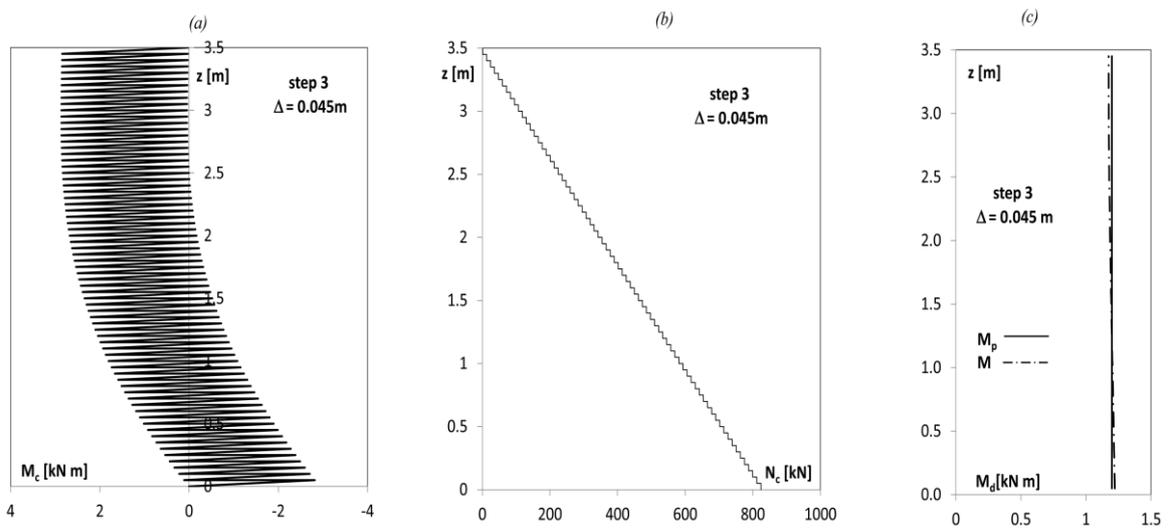


Figure 6. Model A_2: Column Bending Moment (a); Axial Force (b); Link Bending Moment (c)

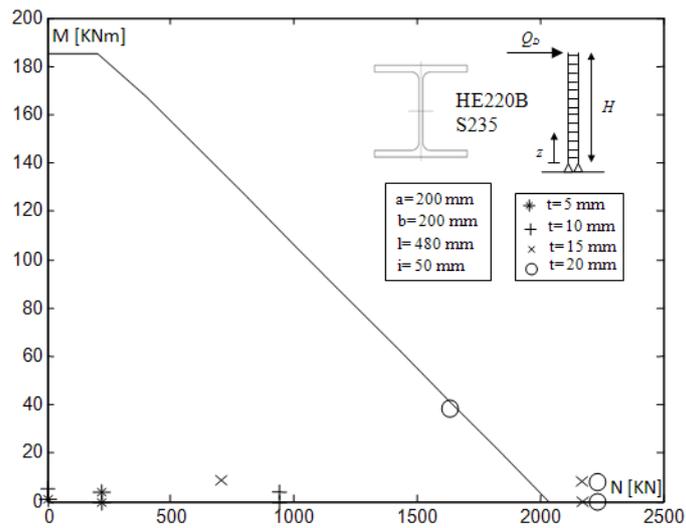


Figure 7. Model A_2: Stress Points on MN Domain at last pushover step

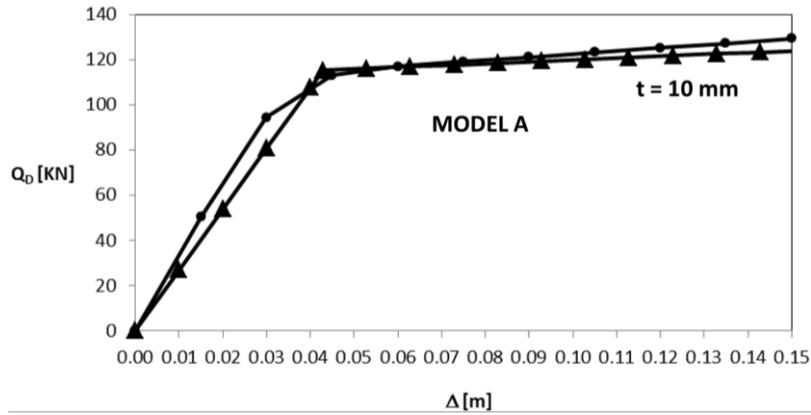


Figure 8. Model A_2: Theoretical vs Pushover Analysis Force Displacement Relationship

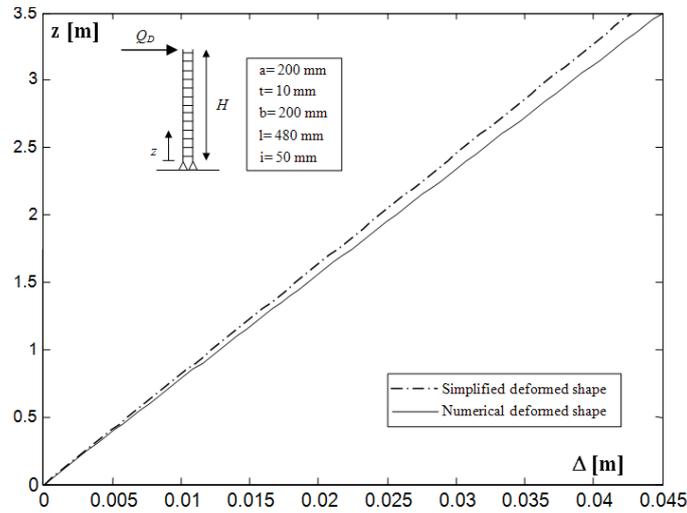


Figure 9. Model A_2: Simplified vs numerical deformed shapes

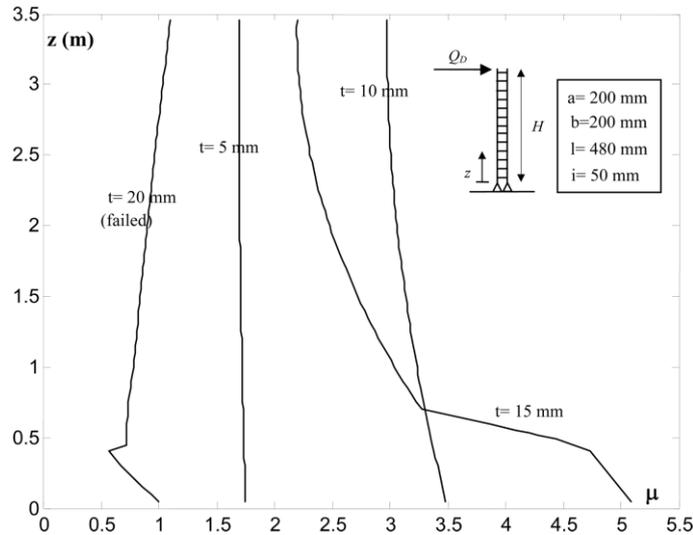


Figure 10. Model A: Displacement Ductility requirements for steel plates at the last step

With reference to model B, model with eccentricity, the pushover curves for different X-plate thickness and eccentricity values, are shown in Figure 11 (a)-(c). Results show that the higher value of the eccentricity, produces an increase both stiffness and lateral strength while X steel plates yield for lower displacement Δ . It follows that the DC element with significant eccentricity is able to add more stiffness and lateral strength to the primary structure and dissipate more energy than the small eccentricity case under the same displacement Δ .

Figure 12 shows the displacement ductility factor along the height of the model B_2, required at displacement Δ equal to 0.045 m for different values of eccentricity.

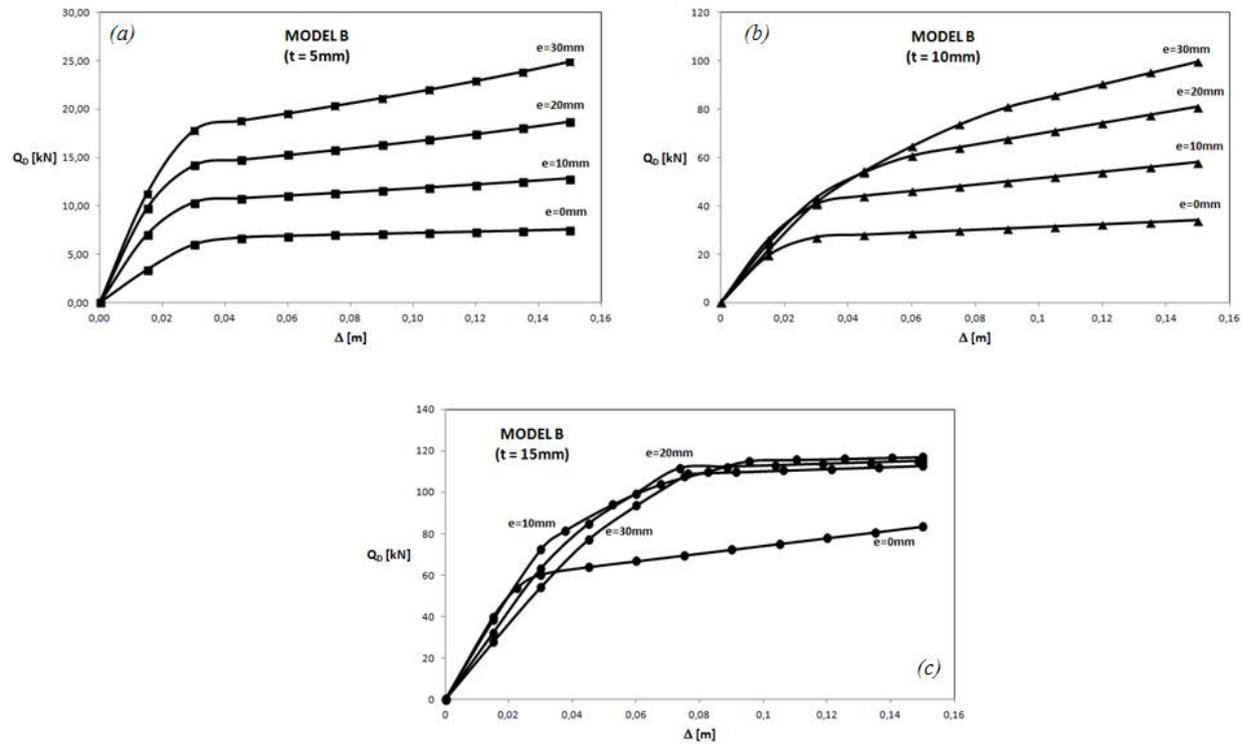


Figure 11. Model B: Pushover Curves for different plate thickness and eccentricity

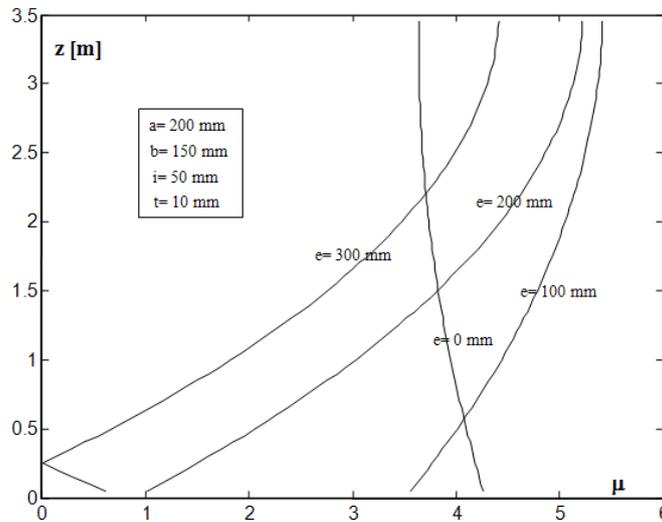


Figure 12. Model B_2: Displacement Ductility requirements for steel plates at 4th step

MULTI-BAY DISSIPATIVE COLUMNS

With reference to double-hinged model, in several cases it is possible to adopt multi-bay dissipative columns organized as represented in Figure 13. Let's consider the case of an assembled n DC elements, assuming the same simplified hypothesis used for the two adjacent columns case. The assembled system story drift is related to the shear drift angle γ as:

$$\Delta = \gamma \cdot H \quad (10)$$

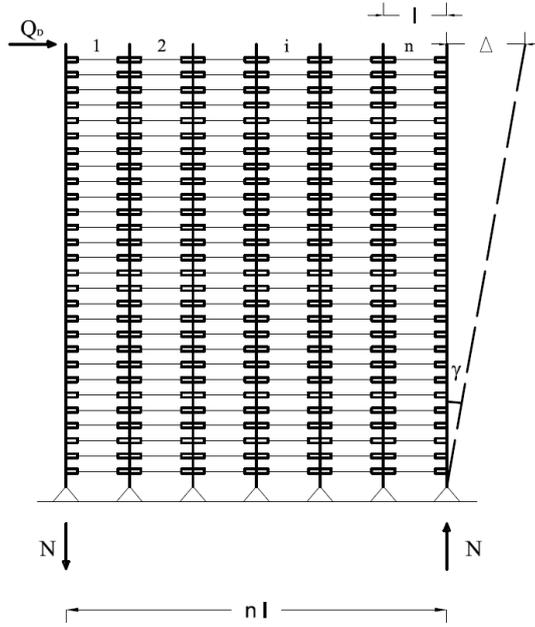


Figure 13. Multi-bay Dissipative Columns

The \$i\$-th bay transmits to the column a uniformly distributed load \$p_i\$ given by:

$$p_i = \frac{2}{3} \frac{Ebt^3}{a^3i} \gamma(l-a) \quad (11)$$

Therefore internal columns are not subject to axial force while only the two external ones react at the base through an axial force, expressed by:

$$N = \frac{2}{3} \frac{Ebt^3}{a^3i} (l-a)\Delta \quad (12)$$

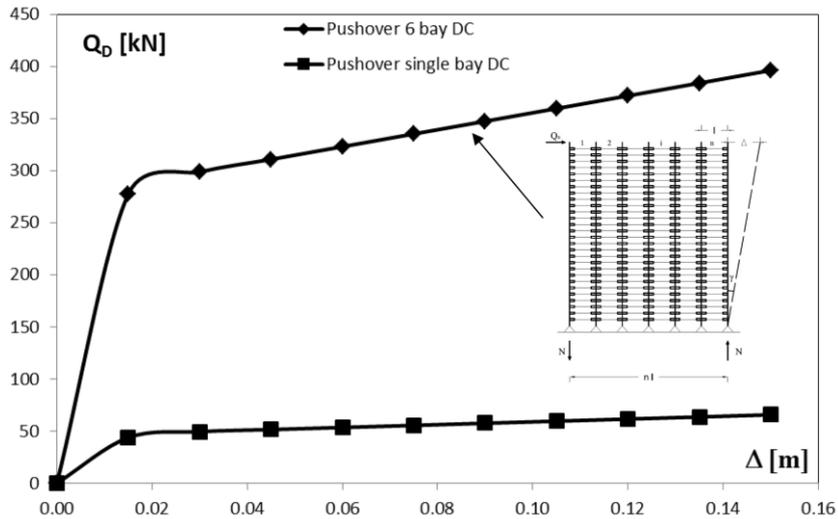


Figure 14. Six bays vs single bay DC Pushover Curves

The \$n\$-bays assembled dissipative columns react through a shear force given by:

$$Q_D = \frac{2}{3} \frac{Ebt^3}{a^3i} nl \frac{\Delta}{H} (l-a) = K_D \Delta \quad (13)$$

where K_D is the sum the lateral stiffness developed by the links of each bay. Also the post yield stiffness of the multi-bay element is equal to the sum of the single-bay one.

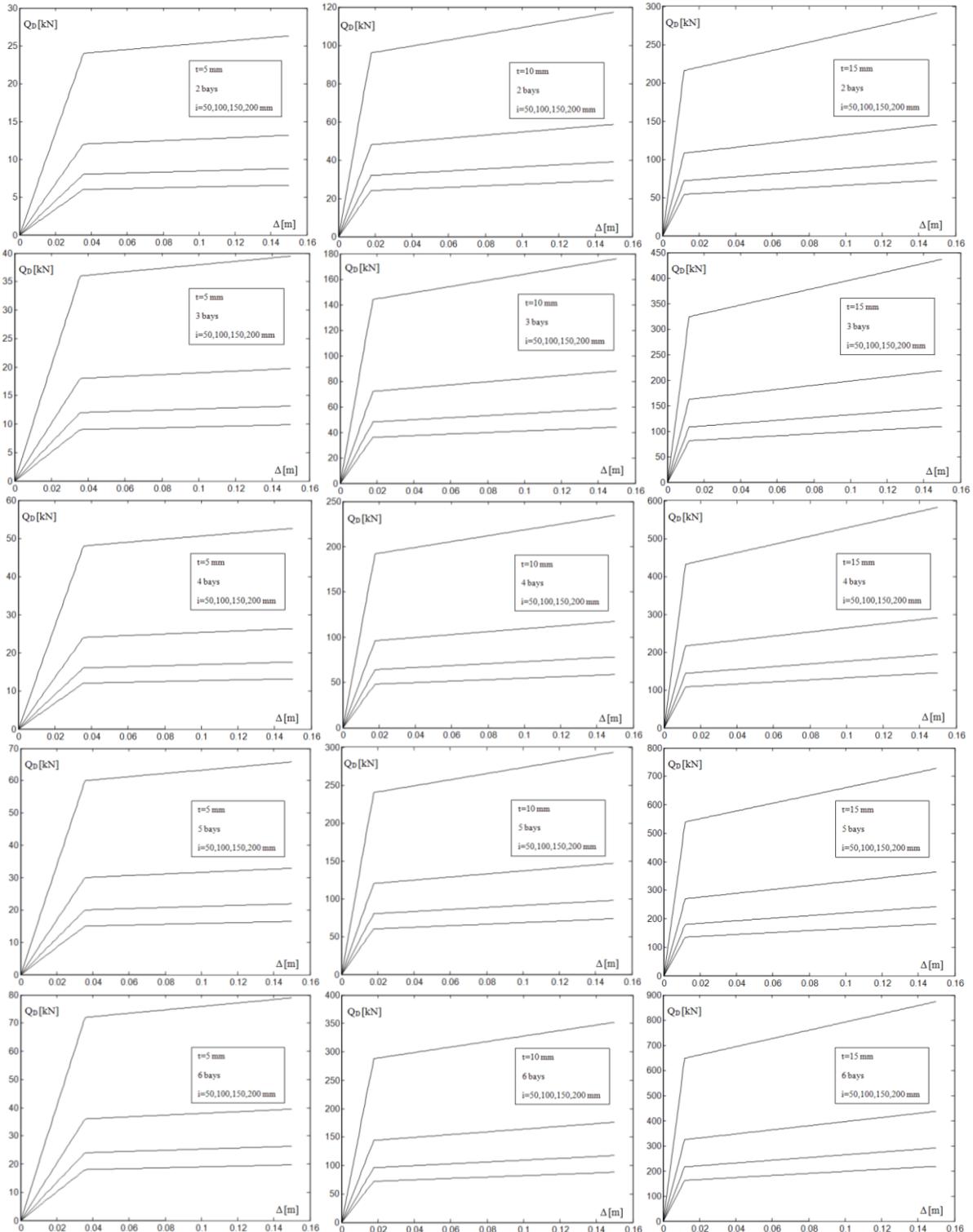


Figure 15. Parametric analysis of the force-displacement relationships of the model for different values of the thickness t , number of bays and plates distance i

The responses of some multi-bay DC elements have been analysed through static pushover analyses. Adopting X-shape plate made of LYS steel, the yielding displacement and lateral strength obviously decrease as well as the axial force in both columns.

Multi-bay dissipative columns with X-shape plate made of LYS steel represent a design solution to obtain higher lateral stiffness and low strength. Figure 14 comparatively shows the response curves for the case of 6-bays and 1-bay DC elements equipped with LYS steel X-shape plate between S235 HE220 steel columns having properties reported in Table 2.

Table 2. Geometrical and structural properties of the n-bay DC elements with YLS steel plate.

Model	Height H (mm)	Column distance l (mm)	X plate length a (mm)	Plate thickness t (mm)	Plate distance i (mm)	Plate width b (mm)	X plate yield stress f_y (N/mm ²)	Restrains
1-bay DC	3500	480	200	10	50	20	100	model A
6-bays DC	3500	480	200	10	50	20	100	model A

Then a parametric analysis has been carried out in order to define the force-displacement relationship of the model for different values of the thickness t , number of bays and plates distance i (Figure 15). As shown in Figure 15, adopting X-shape plate made of LYS steel, the lateral stiffness and strength of the Multi-bay dissipative columns increase for lower values of i and for more bays. The yielding displacement decreases as device thickness increases.

CONCLUSIONS

A new replaceable hysteretic steel damper to control seismic building damage consisting of two or more adjacent steel Dissipative Columns (DC) connected to each other through continuous mild/low strength steel X plates, has been proposed and investigated.

The behavior of the proposed DC element with two different end configurations has been investigated in linear and non-linear range developing several parametric analyses in order to evaluate the hysteretic performances.

Numerical tests showed that doubly-hinged DC elements with small eccentricity can fully yield along their length while columns are subjected to axial strain and so small bending moment that flexural deformation can be neglected.

In the presence of significant eccentricity, large bending moments have been observed that affect the section size. Eccentricity acts as a mechanical lever arm in order to amplify energy dissipation increasing plate drift producing easy yielding conditions in hysteretic dampers.

In any case lateral stiffness increases for greater values of the X plate thickness and for lower values of their distance and for greater eccentricities between bearings and column axes. For greater values of the device thickness, the yielding displacement decreases as well as for lower values of link steel strength. Strongly coupling dissipative affects can be obtained by using mechanical lever to amplify X-plate drift. Greater eccentricity higher bending moment.

Multi-bay dissipative columns with X-shape plate made of LYS steel represent a design solution to obtain higher lateral stiffness and lower strength also strongly reducing the axial force in the internal columns. The number of DC elements should be designed for the buildings where are to be installed.

The DC elements can be considered as new low-yield, ductile replaceable and minimally invasive dampers easy to be installed to new as well as existing buildings providing significant additional stiffness, strength and damping to a structural system potentially capable to reduce building seismic response and damage in primary structural members under severe earthquakes.

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