FEM SIMULATIONS OF A NEW HYSTERETIC DAMPER:
THE DISSIPATIVE COLUMN

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SUMMARY: A new replaceable hysteretic damper to better control seismic building damage, consisting of two adjacent steel vertical elements connected to each other with continuous X-shaped mild/low strength steel shear links, is investigated in this study. New Dampers, called Dissipative Columns (DC), provide additional stiffness and damping to a lateral system by using a basic and minimally invasive construction element: the column. The Dissipative Column has been conceived or as a device installed within a frame either external damper to provide macro-dissipation. In fact, considering different configurations, a parametric analysis, based on FEM simulations, is developed in order to evaluate the effect of the main geometrical and structural parameters as well as provide the design capacity curves of this new damper. In particular, non-linear pushover and cyclic analyses have been carried out in ABAQUS in order to characterize the local and global behaviour of the device also considering different steel grades.

KEYWORDS: Replaceable hysteretic damper, dissipative column, FEM simulations, low yielding point steel, damage control, lever arm

1. 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, suffer such severe damages [De Iuliis et al., 2010] that they need to be demolished after a strong earthquake, since they would be expensive to repair. As is known, the acceptance of such level of damage due to severe earthquakes is related to the ductility-based design criteria that assume design seismic actions decreased by corresponding reduction factors. Inspired by new performance criteria, there is a growing belief that code design criteria are not sustainable for the high level of accepted damage and that common buildings should be designed with a higher performance level. At the beginning of this century, performance based engineering0 [Vision, 2000] introduced new principles with the scope to select more articulated targets better corresponding to different building roles and use, defining a variety and complex subdivision of performance objectives for seismic events with different intensities and frequencies of occurrence. The “Direct Displacement Based Design” philosophy [Priestley, 1993] relates the specified performance level to the strain or drift limits for a specified seismic intensity. With the scope of minimizing structural damage, several frictional isolation devices [Castaldo et al., 2015; Castaldo and Tubaldi, 2015; Palazzo et al. 2014a; Castaldo et al. 2016a; Castaldo et al. 2016b] and dampers [Symans et al., 2008; Wada et al., 1992], new replaceable hybrid composite or

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steel or aluminium devices [Brando et al., 2013; Castaldo et al. 2016c; De Matteis et al., 2007; Formisano and Mazzolani, 2015; Formisano and Sahoo, 2015; Formisano et al., 2006; Formisano et al., 2010; Montuori, 2014; Pampanin, 2005; Pampanin, 2013; Palazzo et al., 2014b; Palazzo et al., 2015; Piluso et al., 2014] have been recently proposed as well as integrated design approaches [Castaldo, 2014; Castaldo and De Iuliis, 2014] and new strategies, i.e., based on the collapse mechanism control [Longo et al., 2014; Montuori and Muscati, 2015; Montuori et al., 2014; Montuori et al., 2015; Montuori et al., 2016; Nastri, 2016; Nastri and Paciello, 2016] or energy balance [De Iuliis and Castaldo, 2012], have been developed in order to dissipate seismic input energy outside of the primary structure. Dampers should absorb a significant portion of the input energy reducing the hysteretic energy demand to the primary structural elements. Another damper employed to dissipate energy dynamic energy through stable hysteretic behavior [Kim and Seo, 2004] consists in the buckling-restrained braces (BRBs). Low Yielding Strength (LYS) steel is investigated by [Susanta et al., 2004] for improving the ductility capacity of box-shaped steel bridge piers carrying out an experimental work for four specimens having different thickness and sectional configurations under cyclic loads. The test results reveal that the LYS steel portion with longitudinal stiffeners greatly improves the strength and ductility capacity of box columns and it is observed that LYS steel has a great cyclic strain-hardening characteristic. The advantage of use of LYS steel is that it can effectively use large plastic deformation in component plates and the failure of column is concentrated at the LYS steel segment and the energy dissipation occurs far beyond the yield point. The aim of this paper is to 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 floors linked to each other with X-shaped low/mild steel plates. 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 Columns (DC) element will be investigated through non-linear pushover and cyclic analyses useful to characterize the yielding properties of the damper depending on the steel grades, the characteristics of the primary structure and the expected performance as discussed by [Oviedo et al., 2010].

2. THE DISSIPATIVE COLUMN: MECHANICAL PRINCIPLES

The Dissipative Column model, shown in Fig.1, can be considered as a sort of framed biperiodum with height equal to \( H \), connected in parallel to the primary structure, able to react to the story drift \( \Delta_0 \) with a lateral force \( Q_0 \) adding stiffness, strength and damping [Palazzo et al., 2014b; Palazzo et al., 2015]. The design concept of the DC element aims to obtain a lever mechanism by which a small inter-story drift provides an amplified vertical drift between the X-plate ends (Fig. 1) reacting with shear forces. The X-shaped steel plates made of mild or Low Yielding Strength steel, having length \( a \), thickness \( t \), width at the ends \( b \) and vertical distance \( i \), are also used as shear links between coupled elements. Each lever arm is characterized by an eccentricity \( e \), while, \( r \) is the rigid element representing half section of each column (Fig. 1). The top ends of the model are linked to the upper floor through slotted bolted connections to allow large vertical displacements.
By yielding a large volume of steel, the shear devices are able to dissipate substantial input energy during earthquakes, while also increasing damping in the entire system in order to reduce the damage in the primary system. With reference to reinforced concrete structures, the limit values of Inter-Story Drift Angle (ISDA) corresponding to different structural performance levels are suggested by Ghobarah [Ghobarah, 2004]. The great advantages of the DC, if compared with classical steel dissipative braces [Kim and Seo, 2004], are the reduced architectural invasiveness, so that it is able to be integrated in any building, the ease of installation everywhere, replacement after earthquakes and the stable behavior in cyclic reversal deformation. In fact, in [Castaldo et al., 2016], an example of a r.c. building, modeled without considering specific constitutive laws [Etse et al., 2016; Mroginski et al., 2015; Ripani et al., 2014; Vrech et al., 2015], with the DC is described.

3. Simplified mechanical behaviour of the DC

As extensively discussed in [Palazzo et al., 2015], the vertical drift $\delta$ between the ends of a generic shear link in the elastic range, being the curvature $\chi$ constant along each half plate, is related to shear force $V_d$ developed by each X-shaped plate, as:

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

where $a$, $t$, $b$ are, respectively, the X-plate length, thickness, width at the ends and $E$ is Young’s modulus of the steel plates. The axis $x$ represents the barycentric axis of a generic steel plate. Hence, the single X-plate vertical stiffness is equal to:

$$K_d = \frac{V_d}{\delta} = \frac{2}{3} \frac{Ebt^3}{a^3}$$

In the case of small eccentricity, a simplified analysis of the DC behavior subjected to relative displacements can be easily carried out assuming that the column flexural deformation is negligible respect to the case of flexible inextensible links. An inter-story drift produces a shear
drift angle $\gamma$ and vertical drifts $\delta_D$ along the X-shaped steel plate. Under such simplified assumptions, the top-base relative displacement $\Delta_D$ of a DC element with height $H$ is related to the drift angle $\gamma$ as:

$$\Delta_D = \gamma \cdot H$$

(3)

Therefore, each X-plate undergoes a vertical drift equal to:

$$\delta_D = (l-a) \frac{\Delta_D}{H}$$

(4)

where $l$ represents pin axes distance (Fig.1). Therefore, the uniform distributed vertical load, along the vertical axis having origin in the hinge (Fig.1), due to the shear drift angle $\gamma$ applies:

$$p = \frac{2}{3} \frac{E b t^3}{a^3} (l-a) \frac{\Delta_D}{H}$$

(5)

where $i$ represents the plates vertical distance. The term $(l-a)/2 = r$ represents a small lever arm that can be amplified using eccentricity $e$ between the vertical axis and the supports as will be shown in the following. The axial force at the base of each column is equal to:

$$N_c = \frac{2}{3} \frac{E b t^3}{a^3} (l-a) H \frac{\Delta_D}{H}$$

(6)

For the equilibrium, lateral force-displacement relationship is expressed as:

$$Q_D = \frac{2}{3} \frac{E b t^3}{a^3} \frac{\Delta_D}{H} (l-a) = K_D \Delta_D$$

(7)

where $K_D$ represents the lateral stiffness of the Dissipative Column given by:

$$K_D = \frac{2}{3} \frac{E b t^3}{a^3} \frac{l}{(l-a)}$$

(8)

According to experimental tests [Aiken et al., 1993; Whittaker et al., 1989], 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 $\mu = \delta_D/\delta_{Dy}$ varying in the range between 3 and 5 [Whittaker et al., 1991]. Since yielding strength $f_y$ is reached almost uniformly along the device, the yielding vertical load $p_y$ can also be expressed as:

$$p_y = \frac{2M_{d,y}}{ia} = \frac{f_y b t^2}{2ia}$$

(9)

while, the relative yielding displacement of each link can be written as:

$$\delta_{D,y} = \frac{V_{d,y}}{K_f} = f_y \frac{3a^2}{4Et}$$

(10)

Therefore, the lateral yield strength of the doubly hinged DC element can be evaluated as:

$$Q_{D,y} = f_y \frac{b t^2}{2ia}$$

(11)

and the yielding displacement applies:

$$\Delta_{D,y} = \frac{3}{4} f_y \frac{a^2 H}{E t(l-a)}$$

(12)

Moreover, in presence of a significant eccentricity the column flexural deformation should not be neglected, therefore, as extensively described in [Palazzo et al., 2015], the top-base relative displacement $\Delta_D$ and lateral force of the DC element can respectively be expressed as:
\[ \Delta_D = \gamma \cdot H + Q_D \left( \frac{eH^3}{3EI_l} + \frac{e^2H^2}{2EI_l} \right) \]  

\[ Q_D = \frac{N_l}{H} = \frac{2}{3} \frac{Ebt^3}{a} \gamma (l-a) \frac{H}{H} \left( \frac{2}{3} \frac{H^2}{EI_e} + \frac{H^2}{l - 3EI_e} + \frac{e^2}{EI} + \frac{e^3}{l^2EI_e} + \frac{e^3}{l^3EI_e} \right) \]  

4. **Non-linear Analysis of the X-Shape Steel Plates**

Non-linear analyses in ABAQUS [ABAQUS, 2010a; ABAQUS, 2010b] are performed in order to characterize the non-linear behavior of the X-shape steel plates. In Table 1, the geometric and mechanical properties are reported with reference to two different steel grades: S235 [CEN, 2007] and LYP [Saeki et al., 1998; Susantha et al., 2004].

<table>
<thead>
<tr>
<th>Plate Length (a mm)</th>
<th>Plate Thickness (t mm)</th>
<th>Plate Width (b mm)</th>
<th>Plate Yield Stress (fy) (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>15</td>
<td>120</td>
<td>132</td>
</tr>
<tr>
<td>150</td>
<td>15</td>
<td>120</td>
<td>235</td>
</tr>
</tbody>
</table>

Figure 2. Geometric shape (a) and deformed shape (b) of a X-shaped steel plate

Figure 3. Pushover curves of the X plates: (a) LYP [Susantha et al., 2004; Saeki et al., 1998]; (b) S235 [CEN, 2007]
Fig. 2 shows the geometric shape as well as the deformed shape of the steel plates. A FE model has been defined in ABAQUS [ABAQUS, 2010a; ABAQUS, 2010b] with means of 3D elements with nonlinear stress-strain behaviour. The geometric model proposed by [Tena-Colunga, 1997] has been adopted for the X-shape steel plates. The displacement-controlled pushover analyses of the X plates have been performed until to reach 50 mm in terms of relative displacement and the corresponding curves related to the two different steel grades are plotted in Fig. 3.

4.1 Cyclic analysis and fatigue life curves

In order to obtain the fatigue life curves of the X-shape steel plates, a database of several experimental data developed by [Chang-Hwan et al., 2014; Chang-Hwan et al., 2015; Latour and Rizzano, 2012; Teruna et al., 2015] has been previously defined. The experimental data, related to the different configurations of steel plates and hysteretic devices with different steel grades, are shown in Fig. 4, demonstrating that the data of the different typologies of the devices can be fitted through different linear regressions in the logarithmic scale having the same slope. The dashed line, illustrated in Fig. 4, represents both the average linear regression of all data tests as well as a good fitting of the data [Latour and Rizzano, 2012]. By this way, the abovementioned average regression curve has been adopted as the fatigue life curve characterizing the S235 X-shape steel plates. Regarding LYP steel plates [Saeki et al., 1998; Susantha et al., 2004], the damage properties have been set to be equal to the S235 [CEN, 2007] steel plates. Next, regarding both LYP [Saeki et al., 1998; Susantha et al., 2004] and S235 [CEN, 2007] steel, it has been possible to develop a parametric analysis for different thickness values of the steel plates and for increasing the imposed displacement $\delta_D$. In Fig. 5, with reference to a thickness of the LYP steel [Saeki et al., 1998; Susantha et al., 2004] plate equal to 15 mm, the cyclic curves with imposed ultimate displacements $\delta_D=\delta_{D,u}$ equal to 12, 16, 20 and 24 mm, respectively, are shown. In Fig. 6, the fatigue life curves related to the plate thicknesses equal to 5, 10, 15 and 20 mm, respectively, are illustrated for both LYP [Saeki et al., 1998; Susantha et al., 2004] and S235 [CEN, 2007] steel showing that the number of cycles decreases for higher thickness values.

![Figure 4. Fatigue life curves points of the experimental data and the average fatigue life curve](image_url)
5. **Non Linear Analysis of the Dissipative Column**

Defined the non-linear behavior of the X-shape steel plates, non-linear static and dynamic analyses of the whole Dissipative Column have been performed in ABAQUS [ABAQUS, 2010a; ABAQUS, 2010b]. In Table 2, the main geometric and mechanical properties of the DC are reported. A FE model has been also defined in ABAQUS [ABAQUS, 2010a; ABAQUS, 2010b] with means of 3D elements with nonlinear stress-strain behaviour.
Figure 7. Pushover curve of the DC and its deformed shape in ABAQUS [ABAQUS, 2010a; ABAQUS, 2010b]

Figure 8. Cyclic curves of the DC for increasing the imposed displacement $\Delta_0$
Fig. 7 shows the geometric shape as well as the deformed shape of the DC. The displacement-controlled pushover analyses of the DC has been carried out until to reach 200 mm in terms of relative displacement as plotted in Fig. 7, showing a yielding point at about 20 mm (0.17%). The cyclic curves with an imposed ultimate displacement $\Delta D = \Delta D_u$ equal to 120, 150 and 180 mm, respectively, are shown in Fig. 8. In Fig. 9, the fatigue life curve of the DC is illustrated showing a good agreement with the ideal fatigue life curve of the DC supposed to be characterized by a rigid deformed shape as described in section 3. For low displacements $\Delta D_u$, the fatigue life curve demonstrates a higher number of cycles respect to the ideal case due to a lower energy rate dissipated by the steel plated located at the base of the DC.

6. CONCLUSIONS

A new replaceable hysteretic steel damper, defined ad Dissipative Column (DC), to control seismic building damage consisting of two adjacent steel columns connected to each other with continuous mild/low strength steel X-shape plates, has been proposed and investigated. The behavior of the proposed DC element has been investigated at linear and non-linear ranges, developing several parametric analyses in order to evaluate the hysteretic performances. Numerical tests of the DC elements showed that the eccentricity acts as a mechanical lever arm in order to amplify energy dissipation increasing plate vertical drift producing easier yielding conditions in hysteretic dampers. In any case, lateral stiffness increases for greater values of the X-shape 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. The number of DC elements should be designed for the buildings where they are installed. The DC elements can...
be considered as new low-yield, ductile replaceable and minimally invasive dampers easy to install to new as well as to 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.

7. REFERENCES


LA COLONNA DISSIPATIVA COME UN NUOVO DISPOSITIVO ISTERETICO

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SOMMARIO: Un nuovo dissipatore isteretico sostituibile per migliorare le prestazioni di un edificio in caso di sisma, costituito da due elementi verticali in acciaio adiacenti collegati tra loro con continui piatti in acciaio dolce/bassa soglia di snervamento, è proposto e studiato. I nuovi dispositivi, chiamati Colonne Dissipative (DC), connessi con piatti in acciaio a forma di X, offrono maggiore rigidezza e smorzamento ad un sistema strutturale utilizzando l’elemento base e poco invasivo della costruzione: la colonna. In analogia alle pareti di taglio accoppiate, il comportamento dell’elemento proposto è teoricamente analizzato sia in campo lineare che non lineare. La Colonna Dissipativa è stata concepita come dispositivo installato all’interno di una maglia di piano o dissipatore esterno per ottenere una macro-dissipazione. Infatti, considerando diverse configurazioni, un'analisi parametrica è sviluppata al fine sia di valutare l'effetto dei principali parametri geometrici e strutturali che di fornire le curve di capacità per la progettazione di questo nuovo dispositivo. In particolare, analisi statiche non lineari e cicliche sono state effettuate in SAP2000 che in ABAQUS per caratterizzare il comportamento locale e globale del dispositivo. La Colonna Dissipativa può essere considerata un nuovo dispositivo isteretico, facile da installare sia in edifici nuovi che esistenti al fine di garantire un'adeguata protezione sismica.

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