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SEISMIC PERFORMANCE OF INNOVATIVE DISSIPATIVE REPLACEABLE COMPONENTS FOR STEEL BRACED FRAME (DRBrC)

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Abstract. The structural performance of a steel Concentrically Braced Frame (CBF) equipped with replaceable dissipative seismic components, called DRBrC, is presented. X-diagonal CBFs are an efficient structural solution for buildings in seismic prone areas, being conceived to dissipate the energy stored during the earthquake through plastic deformation of bracing elements; all the other components remain in the elastic field thanks to opportune design criteria. Of course, structural damages, even if voluntarily located in specific regions, need to be repaired after the seismic event to restore the functionality of the building, leading to relevant economic (and time) effort since the full replacement of damaged dissipative components is necessary after irreversible plastic deformations. Recently, research activities have been widely carried out to provide repairability of steel buildings by means of easily replaceable dissipative components. The Research Fund for Coal and Steel (RFCS) of European Commission, for instance, promoted and funded the research project DISSIPABLE - *Fully dissipative and easily reparable device for resilient buildings with composite steel-concrete structure",* with the aim of designing, producing, optimizing and testing several dissipative components for steel structures having, as fundamental feature, the full repairability after the earthquake without impacting on other components. In the present paper, the seismic performance of a steel braced frame equipped with a specific typology of dissipative replaceable device at the ends of braces is presented by means of nonlinear analyses.

1 INTRODUCTION

The use of steel structures in seismic prone areas is widely appreciated thanks to their good performance against horizontal actions. Steel braced frames, such as Concentrically Braced Frames (CBF) and Eccentrically Braced Frames (EBF), designed according to the capacity design rules [1][2] to avoid brittle and unexpected failures [3][4][5][6], usually highlight limited lateral displacements respect to Moment Resisting Frames (MRF), an excellent dissipative capacity and a higher easiness in realization thanks to diffused pinned connections [7][8]. Nevertheless, strong damages were observed after recent earthquakes, compromising the serviceability the buildings and requiring strong effort to restore the original conditions. This is the reason why, in the last years, the interest progressively increased in the concept, design and realization of structures equipped by Dissipative Replaceable (and repairable) Devices (DRD), allowing the full substitution of the damaged dissipative components without impacting on the other elements and connections. Several research works developed promoting the idea of introducing fully replaceable/repairable connections in the post-emergency/post-damage phase [2][10][11], allowing to simplify the restoration operations after the earthquake saving costs and time effort. Different solutions were deeply studied through both experimental and analytical analyses (to cite few: link in EBF structures [12], FUSEIS system [13], INERD connections [14], BRB systems [15], ADAS systems [16], self-centering systems [17]). Recently, the Research Fund for Coal and Steel (RFCS) of European Commission promoted and funded the research project DISSIPABLE *"Fully dissipative and easily reparable device for resilient buildings with composite steel-concrete structure"* (2018-2021) [18] with the aim of deeply analyzing the possible enhancement and the application of several already existing DRD to steel structures.

The present paper focuses on the analysis of a particular dissipative connection for concentric braced frames, called DRBrC (Dissipative Replaceable Bracing Connection), whose structural performance is presented by means of nonlinear analyses. Indications about the design of CBF structures with DRBrC connections are even provided.

2 DRBrC DISSIPATIVE COMPONENTS FOR STEEL BRACED FRAMES

The DRBrC device is a dissipative component located at the ends of bracings of X braced structures; the connection is studied and realized to opportunely create a pinned joint, typical configuration for CBF. The DRBrC device consists in a rectangular steel box with two external and two internal plates and a pin, representing the dissipative element, with a chamfered rectangular cross section (Figure 1) and the strong axis oriented along braces direction.

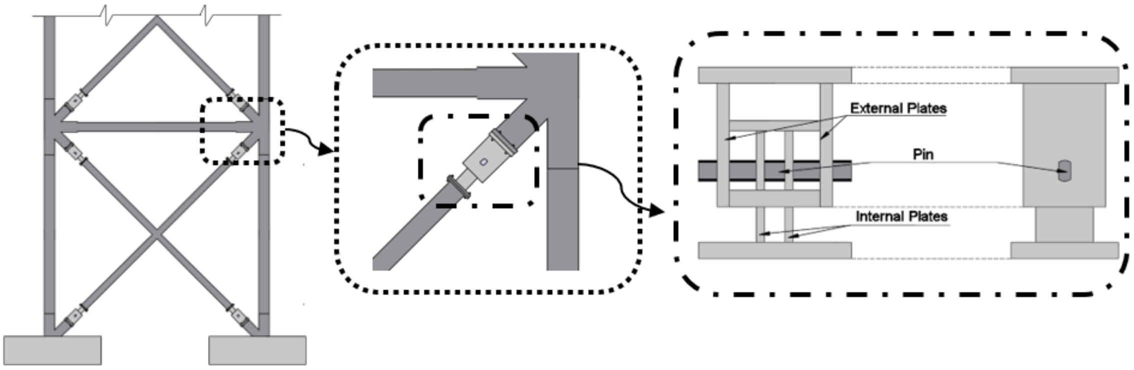
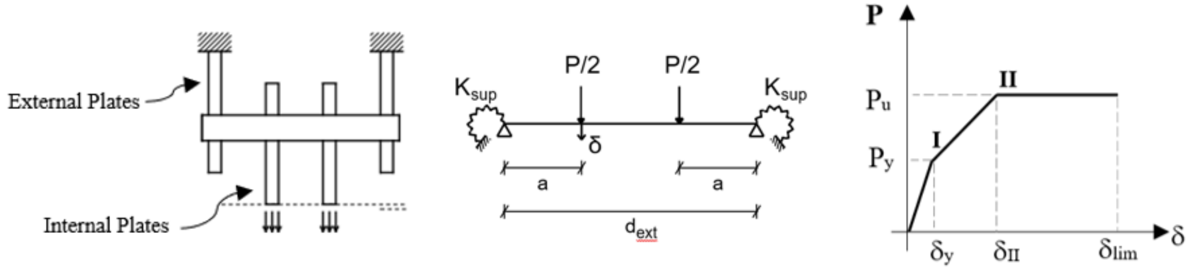


Figure 1: DRBrC dissipative component, scheme and position within the frame.

When DRBrC devices are introduced in a steel braced frame, the DRBrC devices are the only components devoted to seismic energy dissipation (i.e. the equivalent of the braces in a traditional CBF configuration). In particular, the pin element the only component devoted to develop plastic deformations, while all the other plates remain in the elastic field [19]. The mechanism adopted for seismic energy dissipation can be described as follows: when the seismic lateral force acts, an axial force in the braces occurs, then adsorbed by the DRBrC component and transferred through the internal plates in two points of the pin as two concentrated loads (Figure 2a). The behavior of the pin can be then schematized as a beam supported at the ends (in correspondence of external plates) under 3 or 4 points bending, where the external plates can be represented through elastic springs with a stiffness K_{sup} owning different values in relation to the effective loading condition. By assuming this static scheme, a trilinear axial force/displacement can be used to describe the behavior of the only pin (Figure 2b), being points I and II respectively associated to yielding and ultimate conditions [20].



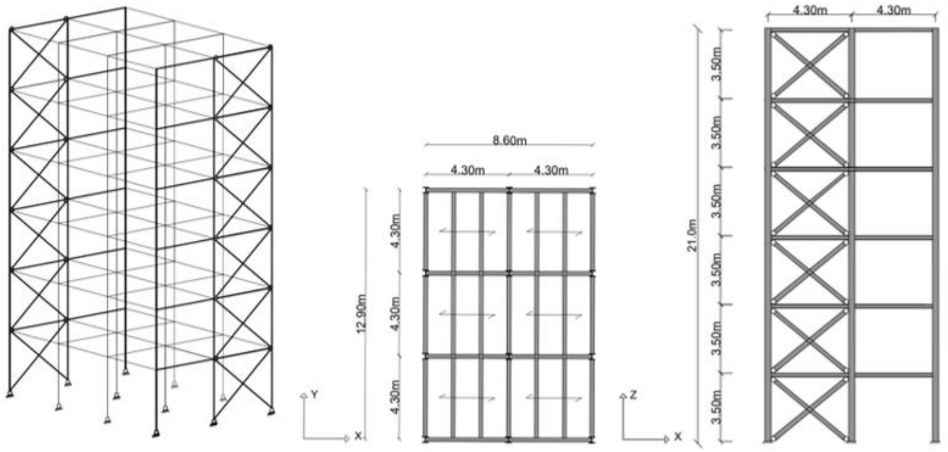
(a) (b)

Figure 2: Simplified pin model: a) equivalent static system, b) tri-linear axial force/deformation law [20].

3 DESIGN, MODELLING AND ANALYSIS OF DRBrC FRAME

3.1 Design indications

A case-study building, with a simple MRF scheme in the Y-direction and a braced scheme equipped with DRBrC devices at the ends of diagonals in X-direction, was designed and fully analyzed by means of nonlinear analyses. For the design of the MRF, the indications provided by Eurocode 8 [1] were followed, adapting specifically the capacity design approach for the braced frame in the other direction with the aim of optimizing the structural performance. The general layout of the case study building is presented in Figure 3; Table 1 shows the design loads adopted.



a) b) c)

Figure 3: Geometry of case study building: a) 3D view, b) plan and c) front view of the braced frame.

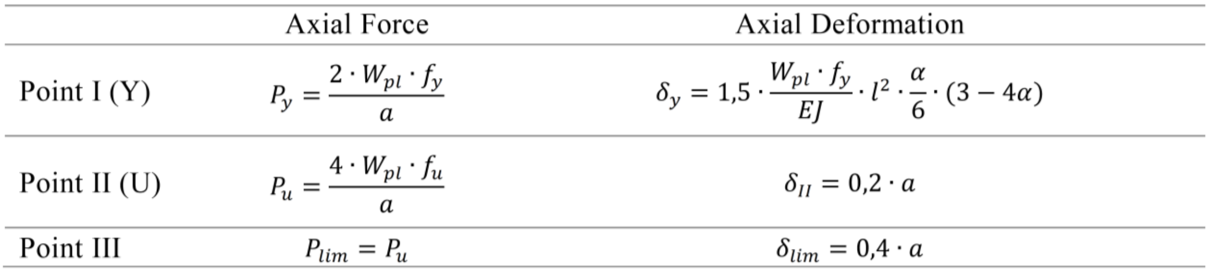
Table 1: Design loads.

Load Class	**Type of Load**	**(kN/m^2)**
Dead loads	Composite slab	2.75
Superimposed Loads	Services, ceilings and raised floor for intermediate floors	0.70
	Services, ceiling and raised floor for top roof floor	1.00
	Perimeter Walls	4.00
Live Loads	Offices (Class B)	3.00
	Movable partitions	0.80

The building was located in Reggio Calabria (Italy); for seismic action, a reference life equal to 50 years and soil category A were selected, adopting a spectrum type I and a unitary importance factor [1], leading to a Peak Ground Acceleration (PGA) equal to 0.36g for Significant Damage (SD) condition. A behavior factor equal to 4.0, coherently with the indications provided by [1] for CBF and with the results of experimental investigations and numerical analyses performed in [20], was adopted. The foundation system was assumed rigid and provided by adequate overstrength respect to the super-structure to remain in the elastic field. Steel grade S355 was adopted for beams, braces and columns; for the DRBrC devices, steel grade S460 was used for the box and steel grade S235 for the dissipative pin. For the horizontal storey slabs, double-crossed steel structure with 50 mm reinforced concrete C25/30 slab were adopted.

Linear dynamic response spectrum analysis was used on a three-dimensional model realized in SAP2000®; for the execution of nonlinear IDA [21][22] only the two-dimensional frame in X-direction (Figure 3) - equipped with DRBrC - was considered. Besides following the traditional rules of the capacity design approach for protected (elastic) members, for the preliminary design of DRBrC connections a simplified formulation derived from the static scheme of the pins before described (Figure 2) was used. Table 2 shows the relevant points describing the axial force/deformation trilinear law of the pins, being f_y and f_u the yielding and ultimate strength of the pin material, W_{pl} the plastic modulus of the pin section and J its inertia, l the distance between external plates, a the distance between supports of the pin and α the ratio between a and l. A 30% amplification of the ultimate load was considered for safety reasons. Table 3 shows the final dimensions of DRBrC components; Table 4 summarizes the profiles adopted for the different elements.

Table 2: Force and deformation values adopted for the preliminary design of pin.

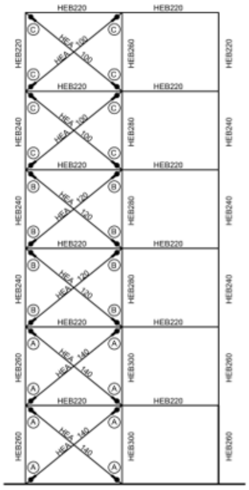


	Axial Force	Axial Deformation
Point I (Y)	$P_y = \dfrac{2 \cdot W_{pl} \cdot f_y}{a}$	$\delta_y = 1{,}5 \cdot \dfrac{W_{pl} \cdot f_y}{EJ} \cdot l^2 \cdot \dfrac{\alpha}{6} \cdot (3 - 4\alpha)$
Point II (U)	$P_u = \dfrac{4 \cdot W_{pl} \cdot f_u}{a}$	$\delta_{II} = 0{,}2 \cdot a$
Point III	$P_{lim} = P_u$	$\delta_{lim} = 0{,}4 \cdot a$

Table 3: Geometrical characteristic of the pins for the different building levels.

Type	Level	Pin section (mm^2)	a (mm)	l (mm)	t_{int} (mm)	t_{ext} (mm)
A	1-2	45x35	80	300	20	40
B	3-4	40x30	80	300	20	40
C	5-6	35x25	80	300	20	40

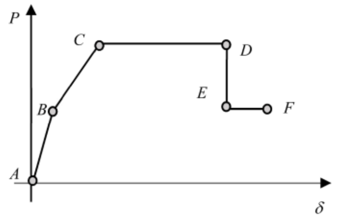
Table 4: Sections adopted for the different elements.

Level	DRBrC frame profiles			
	Columns	Beams	Braces	
1	HEB260 (ext) HEB300 (int)	HEB220	HEA140	
2	HEB260 (ext) HEB300 (int)	HEB220	HEA140	
3	HEB240 (ext) HEB280 (int)	HEB220	HEA120	
4	HEB240 (ext) HEB280 (int)	HEB220	HEA120	
5	HEB240 (ext) HEB280 (int)	HEB220	HEA100	
6	HEB220 (ext) HEB260 (int)	HEB220	HEA100	

3.2 Nonlinear modelling and analysis

Nonlinear modelling and analyses were performed using OpenSees® [23]. A distributed plasticity approach (fiber section) was adopted and a calibrated Menegotto-Pinto law was used for steel elements [24]. For the behaviour of the DRBrC devices, the simplified P-δ law of Table 5 was used: the *Pinching4* material law was attributed to specific *TwoNodeLink* elements, calibrating the relationship through the results of experimental tests executed on DRBrC components in the framework of DISSIPABLE Project [25]. Figure 4 shows non linear P-δ laws used for each pin typology adopted in the case study building.

Table 5: Main points of the constitutive relationship describing the pins' behaviour.

Point	Force	Displacement	
A	0	0	
B	$P_{yd} = \frac{2 \cdot W_{pl} \cdot f_y}{a}$	$\delta_y = 1{,}5 \cdot \frac{W_{pl} \cdot f_y}{EJ} \cdot l^2 \cdot \frac{\alpha}{6} \cdot (3 - 4\alpha)$	
C	$P_{ud} = \frac{4 \cdot W_{pl} \cdot f_u}{a}$	$0{,}2 \cdot a$	
D		$0{,}4 \cdot a$	
E	$\frac{P_{ud}}{2} = \frac{4 \cdot W_{pl} \cdot f_u}{2a}$	$0{,}4 \cdot a$	
F		$1{,}5 \cdot (0{,}4 \cdot a)$	

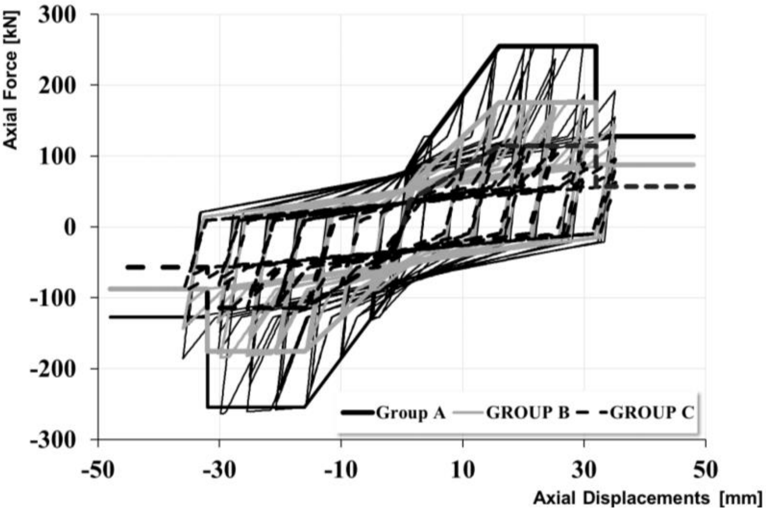


Figure 4: Nonlinear laws of the DRBrC components.

To analyse the structural performance of the case study, crossing the demand from the analysis with the capacity of elements, specific criteria for relevant limit states (Immediate Occupancy – IO, Damage Limitation - DL, Severe Damage – SD, Near Collapse – NC) were considered. For the DRBrC frame, the Engineering Demand Parameter (EDP) is represented by the axial displacements reached in the pin at selected limit states, whose limits coming from the indications achieved in [20] (Table 6). The value of the capacity of the elements at IO was obtained considering 2/3 of correspondent values at DL condition [1].

Table 6: Collapse criteria for different limit states for DRBrC.

Limit State	Axial displacement of the pin(mm)
IO	0.25 h
SD	0.60 h
NC	0.40 a

4 STRUCTURAL PERFORMANCE OF THE DRBrC FRAME

For the execution of IDA ten Ground Motions (GM) [26]-[27] were used, selected to provide relevant results in relation to building location, structural features, etc. Figure 5 shows the elastic response spectra of selected GMs considering a 2% damping factor [28].

Results of nonlinear analyses are presented in terms of capacity curve (i.e. base shear action vs top displacement of the considered frame) and Peak Interstorey Drift (PID) vs selected Intensity Measure (IM) parameter, i.e. the spectral acceleration associated to the first modal period of the frame (Figure 6). Besides, the trend of the axial displacement in the dissipative component is presented in relation to IM (Figure 7). Structural collapse was achieved when the first DRBrC device reached the plasticization at NC limit state, in correspondence of the ultimate displacement capacity equal to $0.40 \cdot a = 32\ mm$ (being ‘a’ the distance between external and internal plate, Table 6).

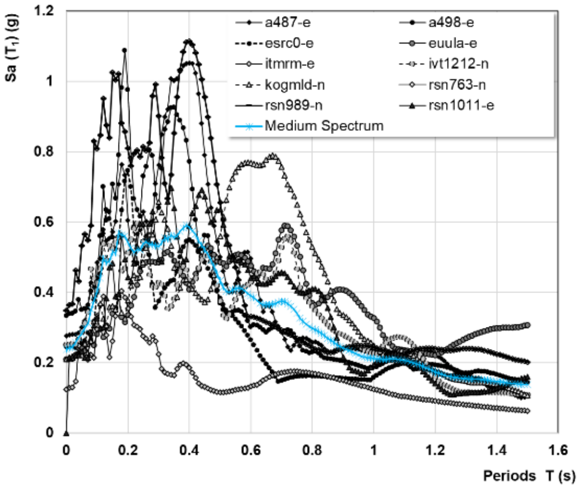


Figure 5: Elastic response spectra for the selected GMs used in IDA.

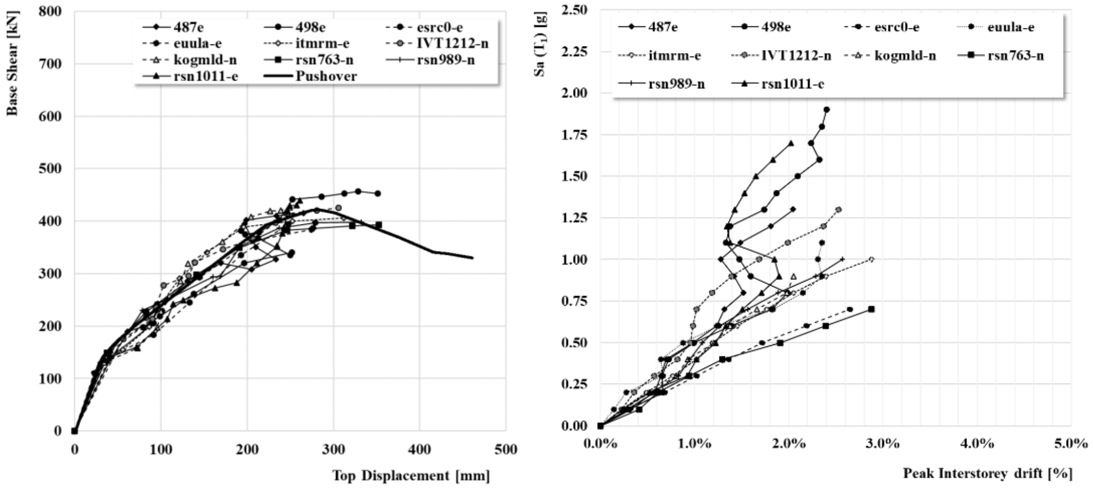


Figure 6: a) Base shear vs top displacement curve and b) PID vs IM parameter for the different GMs.

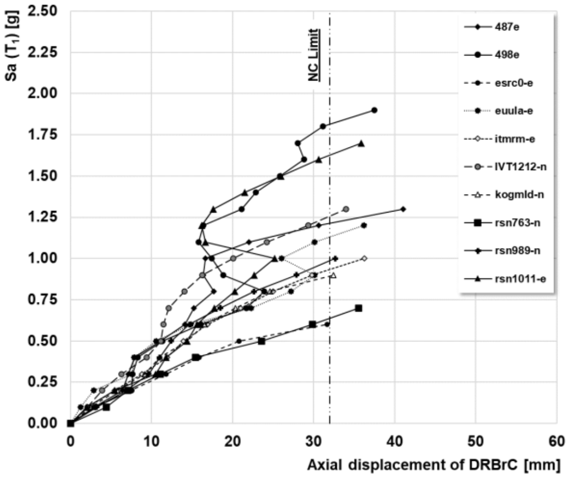


Figure 7: Axial displacement of the DRBrC device vs IM parameter.

What is visible from achieved results is that braces, beams and columns are able to remain in the elastic field, confirming that DRBrC are the only dissipative component and therefore the efficacy of the capacity design approach for the sizing of elements even in presence of non-standardized components such as the proposed dissipative devices. This is a good input for the adoption of DRBrC components in steel braced frames, simplifying design operations by using consolidated methodologies.

The frame shows a good ductile global behaviour, being therefore aligned with what suggested by current standards. Relevant Limit States for increasing higher values of the IM parameter $S_a(T_1)$: for example, IO was achieved for average values of $Sa(T_1)$ equal to 0.40g, while SD and NC for values equal to 0.90g and 1.18g respectively. To the aforementioned achieved values of IM correspond high values of top displacements and PID, and this is due to fact that the presence of the dissipative components leads to a high global deformability of the entire frame. In particular, at NC, the relevant values of the top displacement are equal to – at least – 300 mm in correspondence of base shear of about 400 kN, with PID values equal to 2.4%. Finally, the results of the analysis highlight a comparable performance to traditional steel braced frames (concentrically braced frames with X diagonal tension braces), for which otherwise the global stiffness is generally slightly higher, resulting in lower values of the modal properties. Table 7 summarizes IDA results (at NC limit state), showing three selected percentile levels.

Table 7: Resume of structural response results for NC Limit State, for CBF and for DRBrC frame.

GM ID	**$Sa(T_1)$ [g]**	**PID [%]**	**Max Top Disp. [mm]**	**Base Shear [kN]**
487.e	1.21	2.1%	265	415
498.e	1.81	2.3%	352	453
esrc0-e	0.62	2.6%	247	394
euula-e	1.15	2.3%	296	402
itmrm-e	0.93	2.9%	312	406
ivt1212-n	1.25	2.5%	306	425
kogmld-n	1.21	2.1%	249	426
rsn763-n	0.70	2.4%	337	392
rsn989-n	1.05	2.6%	371	400
rsn1011-e	1.62	2.0%	261	440
Percentile (%)				
16% $_{\text{value}}$	0.80	2.1%	254	396
50% $_{\text{value}}$	1.18	2.4%	301	411
84% $_{\text{value}}$	1.46	2.6%	345	434
Max value	1.81	2.9%	371	453

5 CONCLUSIONS

The seismic performance of a steel building equipped – in one direction - with a new typology of Dissipative Replaceable Devices used in X braced frame (DRBrC) is presented. The DRBrC components were developed in the framework of the European research project DISSIPABLE

[18] with the main aim to be easily and quickly replaced after the emergency phase, avoiding the demolition and reconstruction of the entire structure, therefore optimizing economic and time restoration effort. A six-floor case study building was designed according to a capacity design philosophy, specifically optimized considering DRBrC components as the only dissipative elements. Besides, an ‘internal’ capacity design approach was even used for the design of the DRBrC device, where the dissipation is devoted to the single pin element (being therefore elastic the external and internal plates, etc.). The structural performance was assessed through the execution of IDA [21] and expressed in terms of capacity curves and PID trends. The results of the analysis show a good performance of the case study building with DRBrC components, with values of PID, top displacements and base shear forces comparable to what obtained for similar steel X braced structures of the category. The resulting ductile global behaviour, fully satisfying the capacity design rules even if slightly different from what actually standardized according to Eurocodes, where plastic deformations only occur in correspondence of the DRBrC components, strongly encourages the adoption of DRBrC devices in X-braced steel frame, thanks to the possibility of easily replace the damaged elements after the earthquake without compromising the functionality of the whole building.

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