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Experimental and numerical assessment of a steel frame equipped with Dissipative Replaceable Bracing Connections

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Abstract

In the last decades, high priority has been given by the research community to the development of low-damage structures, and reparability has become fundamental for minimizing the environmental and economic impact of reconstruction. In this context, the European Research Fund for Coal and Steel (RFCS) project DISSIPABLE was carried out, with the aim to test large-scale structures where the dissipation is concentrated on replaceable components introduced in the structure. In this paper, the performance of a six-storey braced steel frame with dissipative systems is analysed. The capacity of withstanding seismic actions relies on Dissipative Replaceable Bracing Connections (DRBrC), used for the brace-column joints. The energy dissipation is ensured by wide hysteresis loops experienced by DRBrC, whose configuration enables an easy replacement after a medium-high intensity earthquake. Results of a wide experimental test campaign on full-scale structures and numerical analyses on refined models are presented and compared. In particular, experimental data were used to validate and to calibrate the simplified numerical laws used to represent the cyclic performance of the dissipative components and it was proved the effectiveness of using a simplified formulation from both a theoretical and a practical point of view.

Keywords: Type your keywords here, separated by semicolons ;

1. Introduction

Steel braced frames, such as Concentric Braced Frames (CBF) and Eccentric Braced Frames (EBF) are widely used

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solutions to face horizontal seismic actions. The design of these structures follows the rules of capacity design (EN 1998-1:2005), selecting specific components for concentrating the seismic energy dissipation (e.g. braces and link respectively for CBF and EBF); specific coefficients and structural details are used for oversizing those elements that shall remain in the elastic field, avoiding unexpected brittle failures related to shear actions or buckling phenomena. A good global ductile behaviour is achieved, with excellent hysteretic cycles under seismic loads and limited lateral displacements and interstorey drift thanks to braces stiffness. Recent seismic events otherwise highlighted relevant damages in braced frames, strictly limiting their use and often leading to the need of a whole structural reconstruction, with high economic effort. For these reasons, in the last years, a wide research activity was developed in the field of replaceable dissipative components to be even introduced in braced frames. Just to cite some examples, Sun et al. (2020) proposed special removable links in EBF, Morelli et al. (2019) developed of an asymmetric re-centering dissipative device characterized by a different behaviour in tension and in compression suitable to resist and dissipate the energy generated by asymmetric cyclic loads. The application of a similar re-centering dissipative device was already also demonstrated in past researches (Braconi et al. 2012, Morelli et al. 2017). Bozkurt et al. (2018) proposed a new set of three replaceable EBF links with gusseted brace attachments, different for the position where the beam is spliced. Caprili et al. (2018) studied the design of connections between links and the adjacent non-dissipative elements, considering both horizontal and vertical links with the aim to obtain the full replacement of dissipative links. The high interest in the topic was well evidenced at international level by the European research projects FUSEIS (Vayas et al. 2013) – focusing mainly on Moment Resisting Frame (MRF) structures and, more recently, DISSIPABLE -*"Fully dissipative and easily reparable device for resilient buildings with composite steel-concrete structure"* (Kanyilmaz et al. 2022) – focusing on the development and enhancement of Dissipative Replaceable Devices (DRD), both funded by the Research Fund for Coal and Steel (RFCS) of European Commission. Within the DISSIPABLE framework, the adoption of DRD in steel structures was deeply studied both at local level (i.e. modelling, analysis and experimental tests on single components) and at global level (i.e. modelling, analysis and full-scale tests on steel structures equipped with DRD). Concerning braced frames, the use of a particular Dissipative Replaceable Bracing Connection (DRBrC) was deeply analysed and investigated both numerically and experimentally, evidencing pros and cons of their introduction within the structure, finally providing simplified design guidelines useful to engineers, technicians in the current practice. The present work, developed in the framework of DISSIPABLE project, shows the structural performance of concentrically braced frames with DRBrC components introduced as dissipative connections at the ends of diagonals. Nonlinear dynamic analyses were executed on refined numerical models calibrated using the results of experimental hybrid tests executed at University of Trento laboratory. The effectiveness of the design guidelines proposed within the research project was then proved, confirming benefits for users and simplicity for technicians and designers.

2. DRBrC dissipative components

The DRBrC device is a dissipative element to be used in steel braced structures in correspondence of the connections of the diagonals to the frame. The device consists in a pin with a chamfered rectangular cross section introduced within a rectangular steel box to which is connected through two external and two internal plates (Fig. 1). The connection between the DRBrC and the diagonals is realized through bolted connections, reproducing a hinge. The pin is the only dissipative component of the system, that therefore should achieve the plasticization while the other elements still remain in the elastic range according to a capacity design philosophy (Caprili et al. 2021). When the seismic action occurs, the axial force in diagonals (tension or compression) is adsorbed by the DRBrC and transferred through the internal plates to the pin, in correspondence of specific connection points (Fig. 2). These forces act on the pin as concentrated loads: therefore, the performance can be compared to a beam supported at the ends (external plates) under 4 points bending. In Fig. 2, the three different loading conditions to which the pin is subjected are represented: (a) the first one occurs when the application of the external loads begins, the pin is simply supported since the external plates act as pinned connections and bending action is concentrated in the middle of the dissipative element. The second stage (b) is characterized by the increasing of the bending moment until the achievement of the plastic moment resistance of the pin, with hinges' development in correspondence of the internal plates. The last loading step (c) corresponds to plasticity propagation, leading to the development of plastic hinges even at the ends of the pin.

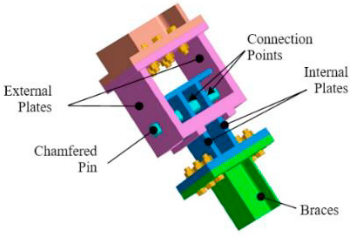
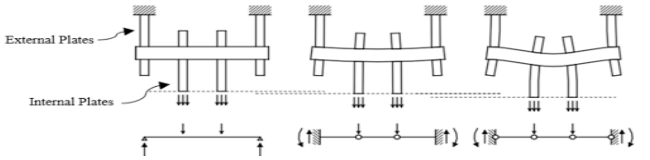


Fig. 1. DRBrC dissipative component



a) 1st loading stage: simply supported beam

b) 2nd loading stage: internal hinges

c) 3rd loading stage: fixed beam, external hinges

Fig. 2. Simplified pin model: stages of loadings.

The static behaviour of the pin can be then schematized through an equivalent beam, where the two external plates are represented through elastic springs with stiffness K_{sup} (Fig. 3a). Through this model, a trilinear axial force/displacement P-δ relationship can be obtained (Fig. 3b), characterized by two cardinal points respectively associated to the achievement of yielding (I) and ultimate (II) conditions (Vayas et al. 2017). The last point (III) is associated to the same ultimate load and to a limit deformation value. Table 1, shows the cardinal equations relative to the points I, II, III as function of the pin plastic modulus W_{pl}, the yielding strength f_y, the clear length between internal and external plates *'a'* and α – ratio a/d_{ext}. The constitutive law reported in Table 1 (with 30% increase to P_{lim}) is generally used for the pre-design of pins within a steel structure according to the rules of the capacity design, being the DRBrC the dissipative components and braces, columns and beams elastic elements (Kanyilmaz et al. 2022).

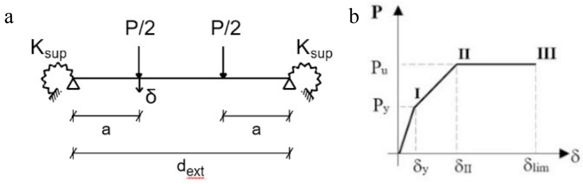


Fig. 3.a) Equivalent beam used for the pin; b) P-δ e pin law.

Table 1. P-δ law of the pin (Kanyilmaz et al. 2022).

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

3. Experimental hybrid tests

The experimental campaign was performed on a two-dimensional steel frame equipped with DRBrC components (Fig. 5) at the University of Trento within the framework of DISSIPABLE project (Kanyilmaz et al., 2022) by exploiting Hybrid Simulation (HS) technique: only a part of the structure was physically used for the laboratory test, simulating the remaining portion through numerical analysis.

3.1. Description of the structure

The case-study, analysed both experimentally in hybrid tests and numerically through nonlinear dynamic analyses, is a two-dimensional six-storey office concentrically braced steel frame, extracted from an entire 3D steel building with rectangular plan, three spans in long direction and two in short, of length equal to 4.30 m, and total lengths equal to 12.90 m and 8.60 m respectively (Fig. 4,Table 2). The interstorey height is up to 3.50 m, resulting in a total height of 21 m. Columns are fully fixed in Y-direction and nominally pinned in X-direction. Steel grade S355 was used for the beams, columns and braces, while for the DRBrC devices, steel grade S460 and S235 were respectively adopted for the box and for the dissipative pin. For the horizontal storey slabs, double-crossed steel structures with 50 mm reinforced concrete C25/30 slab were used. For design seismic action, PGA equal to 0.36g, reference life equal to 50 years, soil category A and topographic class T_1 were selected. A behaviour factor equal to 4.0, aligned with Eurocode 8 (EN1998-1:2005) prescriptions for CBF and with results achieved within DISSIPABLE (Kanyilmaz et al., 2022) was selected. Elements profiles for the 2D case study building are reported in Fig. 4, while DRBrC features are summarized in Table 2, being t_{ext} and t_{int}, the width of the external and internal plates.

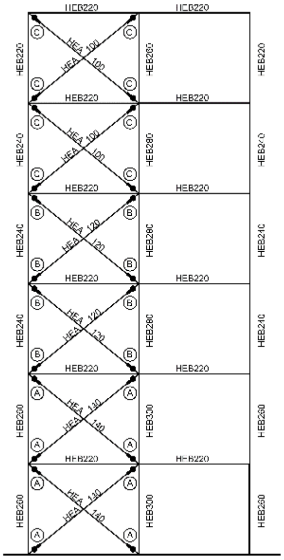


Fig. 4. 2D CBF case study building

Table 2. Dimensions of DRBrC for each floor

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

3.2. Hybrid test: configuration, modelling and selected seismic input

In the spirit of Hybrid Simulation, only the ground floor of the so-described steel frame was physically built, i.e. physical subdomain (PS) in the laboratory, while the remainder of the structure was numerically simulated, i.e. the Numerical Subdomain (NS). The HS tests were performed by means of the partitioned G-α algorithm described by Abbiati et al. (2019), where the continuity between the PS and the NS was restored by means of Lagrange multipliers. More details on the sub-structuring technique can be found in Andreotti et al. (2021). The specimen is presented Fig. 5 and, as previously mentioned, the first floor constitutes the physical substructure, while the remaining floors were only numerically simulated. The physical part is composed of three columns, two beams, and two braces for the left span. The dissipative DRBrC components are located at the braces has been already presented in the previous paragraphs, while geometrical properties are presented in Table 2 (device type A).

Fig. 5. Hybrid Test Configuration of DRBrC frame.

Concerning the top-portion of the frame, numerically modelled through OpenSees software (Mazzoni et al. 2007), beams and columns were provided by an elastic behaviour/material, while the DRBrC components were modelled using the TwoNodeLink elements with Pinching4 materials for the non-linear degree-of-freedom. The backbone monotonic curve of the DRBrC frame, as well as the hysteretic parameters needed for the model, were calibrated by fitting the experimental cyclic curves provided by IST Lisbon, partner of the DISSIPABLE project – framework of the present research work. After performing preliminary tests on the test specimen, a non-negligible gap-clearance between the pin and the plate hole was detected: this introduced a relevant discrepancy with the finite element model. With the aim of considering this difference, a nonlinear elastic model was obtained by putting in series two springs, i.e. a gap material with a gap value of 1.0 mm and the Pinching4 material, where initial elastic stiffness was calibrated from the results of the preliminary tests. In addition, a non-negligible rotational stiffness at the column base joint was observed by the preliminary tests. Therefore, the numerical value of the rotational stiffness was estimated and included by means of a linear link at the base of the columns. For the experimental tests, the pseudo-dynamic method was employed, which allows performing seismic tests with accelerograms by expanding the simulation time by a time-scale factor λ, avoiding the effect of the structural inertia. As consequence, for both the physical and the numerical substructure the mass, as well as the damping contribution, are numerically simulated. The restoring force, on the contrary, is read from the controller for the PS whilst is numerically computed by the algorithm for the NS. Three different limit states with increasing intensity level were considered, namely Damage Limitation (DL), Significant Damage (SD) and Near Collapse (NC) limit states, in accordance with the European standards (EN1998-1:2005). For each of them, an accelerogram was selected with the criteria of spectral compatibility, according to the Eurocode 8 (EN1998-1:2005) provisions. Table 3 summarizes the main characteristics of the accelerograms, where ag is the ground acceleration and T_R the reference period.

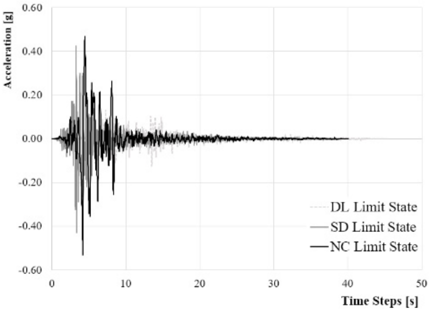


Fig. 6. Selected Ground Motions.

Table 3. Ground motions parameters

Limit State	a_g(g)	T_R(year)
Damage Limitation	0.20	60
Significant Damage	0.36	475
Near Collapse	0.50	1600

4. Structural performance of braced frames with DRBrC devices

The numerical model of the whole six-storey frame presented in §3.1 was realized using OpenSees (Mazzoni et al. 2007). For the modelling of the dissipative DRBrC components, the simplified axial force/displacement law obtained from the static scheme described in Table 1 was used, calibrating parameters on the base of the experimental tests performed on single component by Proenca et al. 2022.

4.1. Numerical modelling of the case study

A distributed plasticity approach was generally used for the elements, including those ones provided, according to the design, by an elastic behaviour; for the nonlinear constitutive law of material, the *Steel02* material model was selected. Models were realized using OpenSees® software (Mazzoni et al. 2007). The shear behaviour, the structure following the capacity design approach, was assumed elastic. To evaluate possible buckling phenomena, an initial imperfection was introduced in braces and columns, according to Eurocodes' prescriptions. With the aim of reproducing the results achieved through HS, *links* in correspondence of the columns' base were introduced, accounting for the non-negligible rotational stiffness at the column base joint. The DRBrC at the ends of diagonal elements were reproduced through the introduction of *TwoNodeLink* elements simulating the behaviour of the pins through the constitutive axial force/displacement law defined in the guidelines for non-linear analysis (Kanyilmaz et al. 2022), assigned using the *Pinching4* material (Table 4,Fig. 7). The constitutive law of the pin was calibrated based on the tests executed by Proenca et al. (2022), on DRBrC that present the same characteristics of the one introduced at the 1st and 2nd floors of the case study, applying a lateral pseudo-static cyclic displacement history. The calibration shown a good agreement between simplified formulation and experimental tests, with a slightly underestimation of the analytical formulation respect the experimental results in terms of forces and of energy dissipated for each cycle.

Table 4: Main equations of $P-\delta$ relationship

Point	Strength	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	$P_{ud}=\frac{4\cdot W_{pl}\cdot f_u}{a}$	$0{,}4\cdot a$
E	$\frac{P_{ud}}{2}=\frac{4\cdot W_{pl}\cdot f_u}{2a}$	$0{,}4\cdot a$
F	$\frac{P_{ud}}{2}=\frac{4\cdot W_{pl}\cdot f_u}{2a}$	$1{,}5\cdot(0{,}4\cdot a\,)$

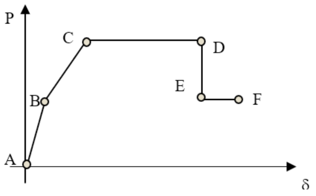
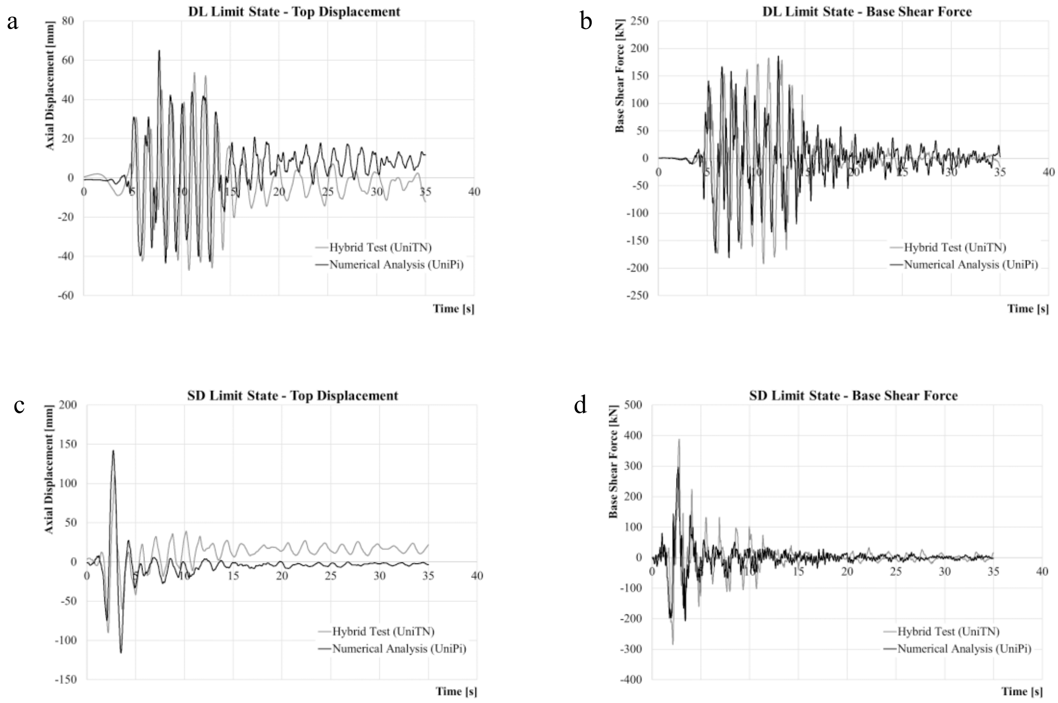


Fig. 7. Cardinal points of Non Linear law

4.2. Nonlinear analyses: results and discussion

Dynamic analyses (DA) were performed on the 2D frame model, using the same the ground motions adopted for the Hybrid Simulation (HS) (Table 3). A comparison in terms of shear forces and top displacements against time is reported:



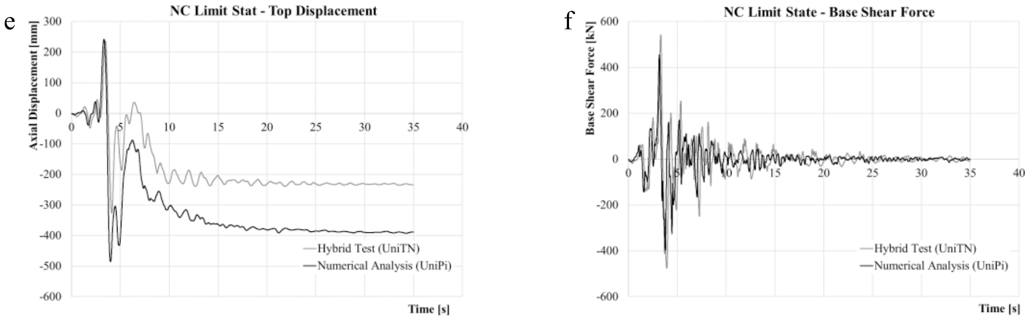


Fig. 8. Comparison of the results between Hybrid Simulation and Dynamic Numerical Analysis, for each Limit State

Comparing numerical results with the same from HS a quite good agreement can be appreciated, with average differences in terms of displacements and forces equal to 15%. In particular, the forces from DA are always lower than the case of HS, which is consistent with the simplified formulation adopted for the pins that leads to values of axial forces slightly lower respect to the experimental results obtained on the dissipative component. At DL limit State, the values of maximum forces are equal to about 186 kN vs 183 kN with corresponding displacements equal to about 45 mm vs 52 mm respectively for DA and HS, and differences of 2% and 10% respectively (Fig. 8 a-b). In case of SD condition, the maximum forces are equal to 300 kN vs 380 kN (with relative displacements equal to 140 mm vs 111 mm) respectively for DA and HS, and differences in the order to 18% (Fig. 8 c-d). At NC limit state, the values of maximum forces are equal to about 460 kN vs 540 kN (with corresponding displacements equal to 180 mm vs 175 mm) respectively for DA and HS, and differences of the order to 14.5% and 2.8% respectively (Fig. 8 e-f). As shown in the graphs, the ground motions at SD and NC limit states presents the maximum value of PGA in correspondence of 3-4 sec, where the maximum values of shear base forces are obtained in the frame. The behaviour of the structure after this point (or 5sec), is governed by nonlinearities of the pins, that result in the post-elastic field and the comparison between HS and DA does not always well agree due to nonlinearities of the systems and last oscillations at the end of the adopted ground motions (Fig. 8 e). At last, the experimental results of the four DRBrC at the 1st floor of the HS and the results on the single component tested by Proenca et al. (2022) are compared with the calibrated curve based on analytical simplified formulation in Fig. 9, showing a good agreement of the results.

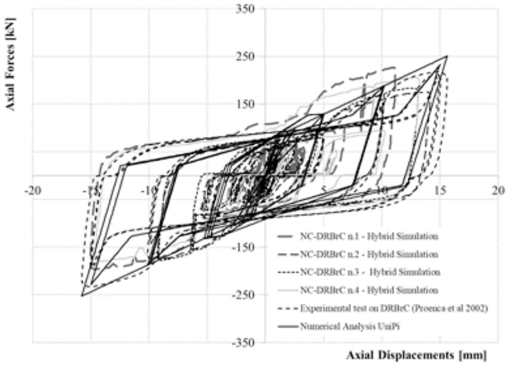


Fig. 9. Comparison of pins constitutive law: HS (UniTN), experimental test on component (Proenca et al. 2022) and numerical analysis (UniPi)

Conclusions

DRBrC are dissipative components introduced at the ends of a steel Concentrically Braced Frame (CBF), with the aim to concentrate the dissipation at the ends of the diagonals, while the rest remains in elastic field after a severe seismic event. This solution leads to replace only the components, avoiding the demolition, and then reconstruction, of the entire structure. During DISSIPABLE European Project (Kanyilmaz et al., 2022) DRBrC were studied through dynamic nonlinear analysis (DA) at global level (CBF equipped with DRBrC), experimental tests such as pseudo static cyclic tests on the single components (Proenca et al., 2002) and Hybrid Simulation on the entire CBF equipped with DRBrC structure (Kanyilmaz et al. 2022). In the present work, a comparison between the structural response of the selected six-storeys CBF equipped with DRBrC, obtained both by HS and by DA is reported. The comparison has been performed considering, for the numerical modelling and for the HS, a simplified formulation, included in recently published design guidelines, to describe the constitutive axial monotonic and cyclic law of the dissipative components. From the comparison, a good agreement between experimental and numerical results in terms of base shear and top displacements emerged, even considering all the uncertainties inherently present of the nonlinear analysis, such as the damping and the nonlinearities of the model. In particular, for each analysed limit state, a slightly underestimation of the forces in numerical results with respect to the experimental ones is observed, due to the fact that simplified law adopted for DRBrC in numerical analysis is lower respect to the real one. Finally, the results of the work validate the effectiveness of the law, that could represent an efficient instrument for the designer and practitioners to predict the behaviour of Concentric Braced Steel Frame equipped with DRBrC.

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