DYNAMIC SUBSTRUCTURING TESTS OF STEEL FRAMES EQUIPPED WITH EASILY REPAIRABLE DISSIPATIVE SEISMIC DEVICES

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Abstract

Civil structures have always been important and strategic resources for the community and, nowadays, it is clear that how to build and maintain such structures is a relevant aspect from the economical and environmental point of view. In this perspective, the protection from earthquakes that might bring to catastrophic disasters actually represents a critical point and an important challenge. In this respect, the aim for building structures to be resilient has become a crucial purpose for civil engineers, but while fragile collapse is easily avoidable through the capacity design, the post disaster restoration is still far from being economic and environmentally sustainable. Therefore, the strategy of avoiding fragile structural collapse has to be enlarged to reduce or totally avoid structural damage. This is the purpose of DISSIPABLE, an ongoing European research project, that, in the context of steel structures, aims to test structural components that can be easily replaced, Dissipative Replaceable Devices (DRD), after getting damaged by strong earthquakes so as to give full post-earthquake functionality to the structure. Within DISSIPABLE, buildings equipped with such devices are studied and experimentally tested. In particular, this paper focuses on the design of the experimental tests to be conducted at the University of Trento through dynamic substructing technique. Thus, the features of the dissipative devices and their numerical modelling will be thoroughly described. Then, the procedure to achieve meaningful substructures to be selected as experimental specimens starting from building prototypes will be presented.

Keywords: dynamic substructuring tests; low damage structures; full-scale experimental tests; steel structures

1. Introduction

After the occurrence of main seismic events in the last century, engineers started to develop new design methods for avoiding fragile structural collapse. With the purpose to activate a global dissipation mechanism, the application of the capacity design method implies to concentrate damage and plasticization in few and very confined parts of the structure. In this way, structures are able to dissipate energy by exhibiting highly nonlinear behavior. However, this way of designing seismic-resistant structures entails lots of damage, which may result in social issues and economic losses since the building is no longer functional.
In this context, the European Research Fund of Coal and Steel (RFCS) DISSIPABLE pilot project aims to provide experimental evidence about the ability of special Dissipative Replaceable Devices (DRD), conceived in previous projects, to provide a high degree of energy dissipation by being easily replaceable after a major seismic event. In particular, steel-concrete composite structures will be tested to achieve this objective. In fact, whilst the behavior of the individual devices has already been widely investigated before DISSIPABLE [1] not much had been done to identify the global seismic response of entire buildings equipped with these DRDs. For this purpose, experimental tests will be carried out by means of shaking table tests and hybrid simulation tests. The latter will be discussed in greater detail in this article, which describes all the work done in preparation to the experimental campaign for investigating the behavior of full-scale frames equipped with DRDs through dynamic substructuring.
The paper is organized as follows: the description of the three selected DRDs, namely the INERD pin connection (DRD1), the FUSEIS 1 shear wall (DRD2) and FUSEIS 2 (DRD3) [1], and their model numerical calibration are described in Section 2; the building prototypes are reported in Section 3; whilst in Section 4 the substructuring of the case studies is thoroughly presented; in Section 5 the laboratory test set-up is illustrated and finally in Section 6 conclusive remarks are drawn.

2. DRD description and numerical modelling

2.1 DRD1 – INERD pin connection made of mild steel and high-strength steel

The DRD1 was conceived to be used in bracing systems. In particular, it is located at the end of the bracings and connected with bolted plates to the column and the bracing member (see Fig.1) in order to ensure the replaceability of the device.

Fig. 1 – DRD1 configurations [1]

The only dissipative part is the pin that plasticizes in bending and shear under an earthquake load. In this way the bracing remains elastic in tension and does not buckle in compression. The pin can be modeled as a beam loaded in one or two points depending on the number of internal plates. Under a serviceability load, the pin behaves as a simply supported beam. After the yielding moment is reached in correspondence to the internal plate support, the large deformations activate rotational stiffness at the external plate supports. Therefore, the beam is considered as fixed until its final capacity is reached, or rather when the plastic hinges at the external plate supports are also formed. The aforesaid mechanical behavior leads to a trilinear curve, as illustrated in Fig.2, in which three different phases can be identified. During the first phase the pin is in the elastic field. In second phase the plastic hinge forms at the middle, the supports become fixed constraints and the stiffness decreases. Finally, the third state is characterized by a plastic sliding.

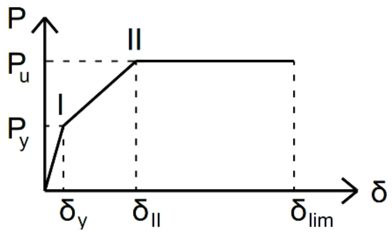

Fig. 2 – Trilinear behavior [1]

The cyclic behavior shows excellent dissipative properties and highlights a different response under tension and compression, as well as a significant pinching due to the ovalization of the holes of the pin, as shown in Fig. 3. In order to avoid the first issue, the geometry of the device was modified by adding a reinforcing bar between the external plates to avoid the lateral bending of the plates, see Fig.4. Regarding the pinching problem a different solution is under investigation, using high-strength steel for the plates. Two different tests with DRD1 made of mild steel and high-strength steel plates will be carried out. Nevertheless, there is no difference in the structural scheme of the two solution, therefore the same frame will be studied for the two cases.

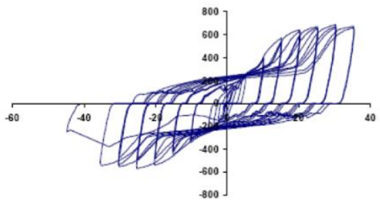

Fig. 3 – ECCS test result [1]

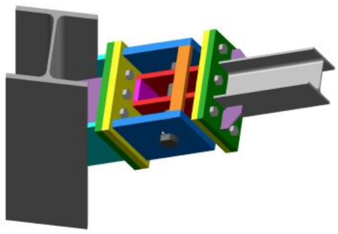

Fig. 4 – DRD1 new configuration

The behavior of DRD1 has been numerically modeled with the finite element software *OpenSees* [6] using the *Pinching4* Material command, which allows to consider the pinching phenomenon in addition to the material degradation under cyclic load. The model parameters were identified according to [1] and then checked to be in accordance with the experimental behavior reported in Fig.3. The dimensionless hysteretic curve obtained, for a generic device is shown in Fig.5, which well represents the behavior of the device.

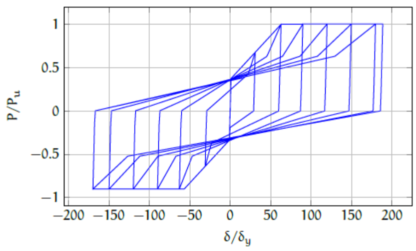

Fig. 5 – DRD1 numerical modelling

2.2 DRD2 – FUSEIS beam link (mild steel and HSS)

The DRD2 device is made up of two very rigid neighboring columns connected by multiple beams, so that the whole system works as a Vierendeel beam (Fig.6), in which the beam links work mainly in bending or in shear, depending on their length, and the columns are subjected to a strong axial force component. The beam can be realized with different sections weakened at the ends to guide the formation of the plastic hinges, as shown in Fig.7. The main advantage of this solution is the ease of replaceability of the beam links since they are connected to the columns through bolts and they are not part of the gravity load carrying system. Different types of tests were performed [1] in order to understand the behavior under monotonic and cyclic loads. Most of the beam links tested reached a maximum drift around 16% before collapsing under a monotonic load and showed a very ductile behavior under cyclic load eventhough cracks and buckling occurred quite early (Fig. 8).

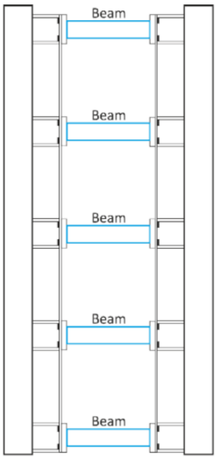

Fig. 6 – DRD2 configuration [1]

Fig. 7 – Section types for DRD2 [1]

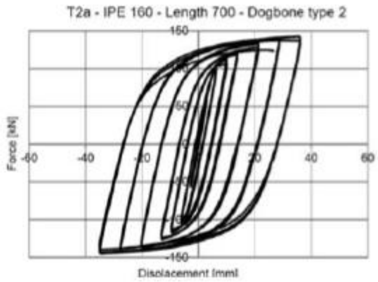

Fig. 8 – DRD2 cyclic behavior [1]

The DRD2 device was numerically modeled in the software *OpenSees* [6]. The steel profile realizing the DRD2 was modeled with elastic beam elements apart from the reduced sections that were modeled with a Bouc – Wen hysteretic model. The Bouc-Wen parameters were determined by using the software Multical [4], fitting the curvesobtained from the model of the entire device developed with the finite element software ABAQUS [7]. In this respect, the numerical modelling of the DRD2 that will be used in the tests is shown in Fig. 9.

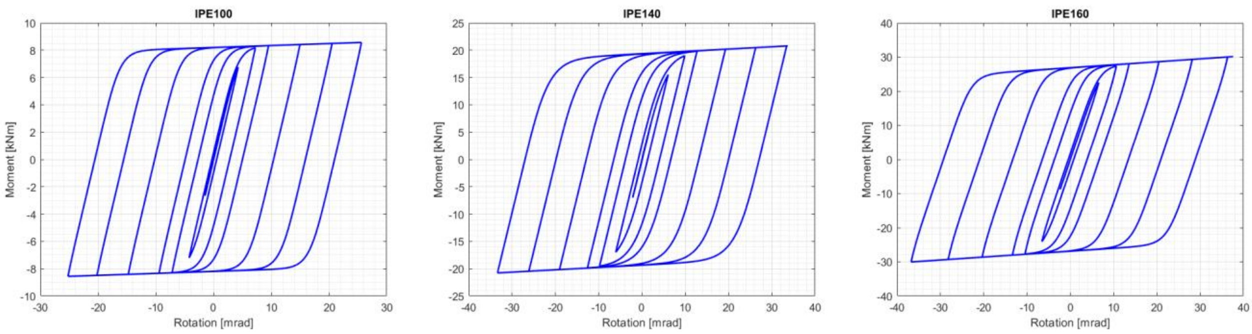

Fig. 9 – DRD2 numerical modelling

2.3 DRD3 – FUSEIS bolted beam splices

The DRD3 is based on the localization of plastic hinges in bolted beam splices located at a certain distance from the beam-to-column joint, which are part of a moment resisting frame. The main purpose is to locally weaken the beam, realizing a fuse that interrupts the steel profile as well as the concrete slab, leaving a gap between two cross sections, as shown in Fig. 10. These sections are connected by means of the reinforcement bars, that are continuous through the gap, and steel plates situated on the web and the flange of the steel profile. While the gap in the steel profile is left to allow for the plate deformation, the slab gap is included to avoid concrete cracking or damage of the floor finishes that might occur due to large rotation demand. From a design point of view, the weakening is realized by designing the web and flange plates to be less resistant than the composite beam. For preventing the beam from damage, some additional plates are welded to the steel profile, aiming at the local enhancement of the non-dissipative component resistance. Since the reinforcement bars are not replaceable, they also have to be considered non-dissipative elements, and therefore additional reinforcement is included in the weakened zone. Moreover, to ensure a flexural mode of collapse and to avoid shear collapse, also the shear resistance of the web plate is designed with overstrength with respect to the flange plate. In this way the plastic hinge is forced to develop at the fuse and damage is concentrated in the flange plate. Experimental tests conducted during the FUSEIS project showed how the web plate also includes plastic deformations due to wide rotations that might occur during earthquakes. Therefore, in addition to the flange plate, also the web plate is to be replaced after the seismic event to create a new fully performing connection. The ease of repair is guaranteed by connecting the plates by means of bolts rather than welds.

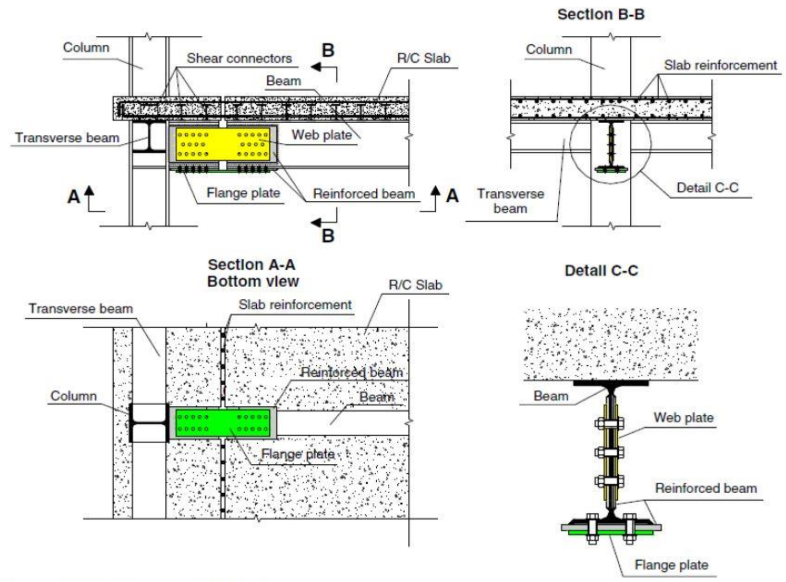

Fig. 10 – Front, lateral and plan view of DRD3

Because of their unsymmetrical geometry, composite beams exhibit different sagging and hogging moments. This lack of symmetry is even more evident in the case of DRD3, in which the fuse plates and the over-resistant reinforcement bars confer to the device heavily non-symmetrical behavior. Indeed, for sagging moment the flange plate yields whilst for hogging moment it buckles. Moreover, from hogging to sagging moment, the flange plate buckling also entails a delay in reloading, resulting in a pronounced pinching effect. Furthermore, also the clearance between the hole and the bolt contributes to emphasize pinching effects. Therefore, the device under cyclic loading exhibits highly pinched cycles in the moment-rotation diagram, that results in a reduction of its hysteretic dissipative capacity.

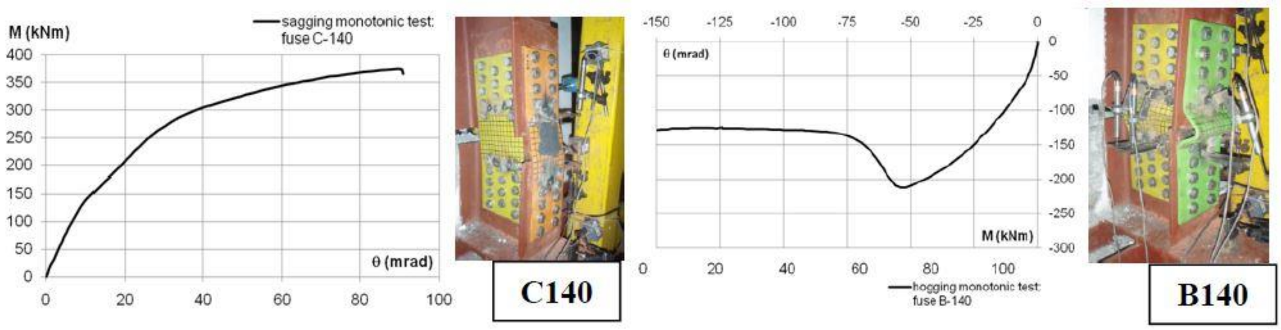

Fig. 11 – FUSEIS: Monotonic sagging and hogging test [1]

The connection was modelled by means of *OpenSees*. Due to the asymmetric behavior in the moment-rotation relation and the strong pinching effect, the material model *Pinching4* was employed. Experimental curves obtained by previous experimental campaigns [2,3] representing the cyclic loading on a real device were employed to catch the actual hysteretic rotational behavior. Since not the same devices employed in FUSEIS were employed in DISSIPABLE, these curves were normalized to the proper values of moment strength and rotation of the DISSIPABLE devices. The behavior of each of the three devices was then fitted on the corresponding curve. The calibration of the *Pinching4* material parameters was performed through the *OpenSees* applicative software Multical [4].

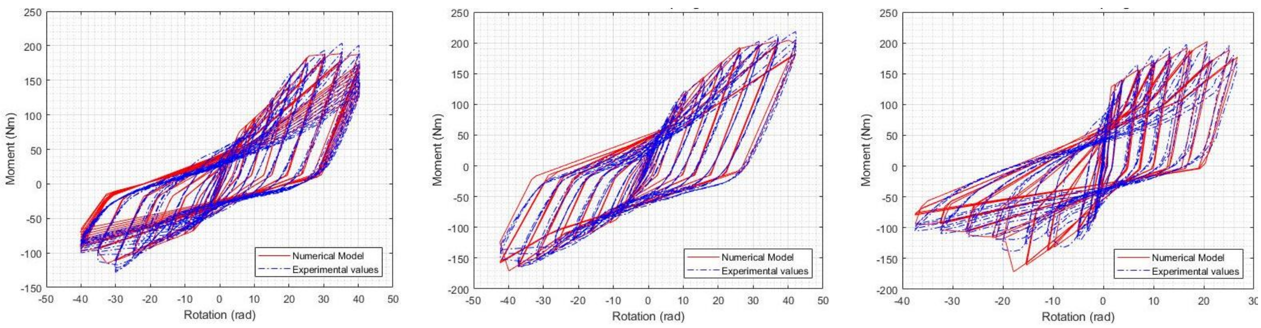

Fig. 12 – Fitting of DRD3 experimental behavior

3. Buildings prototype

For the hybrid simulation experimental campaign, five buildings were designed according to EN 1998-1 [8]: i) DRD1 mild steel; ii) DRD2 mild steel; iii) DRD3 mild steel; iv) DRD1 high-strength steel and v) DRD2 high-strength steel. All buildings have two spans in the transversal X direction, three spans in the longitudinal Y direction and six-storeys. In particular, the frame that will be tested in laboratory at the University of Trento is the one in the X direction owing to laboratory constraints. In fact, the span length was restricted to 4.275 m, while the interstorey height was equal to 3.5 m. 3D models were developed in SAP2000 for design purposes. The EN 1998-1 design spectrum, with peak ground acceleration equal to 0.36 g and soil type A. Then, for each building a 3D nonlinear model was developed in *Opensees* with DRD numerical models calibrated in Section 2.. Accelerograms at Damage Limitation (DL), Significant Damage (SD) and Near Collapse (NC) limit states were used to perform time-history analyses. The design accelerograms were obtained by scaling natural ground motion records and checking their compatibility with the design spectrum between 0.2 and 1.5 times the fundamental period of the structure. Fig. 13 shows the hysteretic behavior of DRD3 installed in a building subjected to a SD accelerogram. For sake of simplicity only the moment-rotation diagrams of DRD3s of one frame are here presented. As the reader might notice, the structure experienced large and uniformly distributed, apart from the top floor, hysteretic behavior. Moreover, the frame equipped with DRD3 is base fixed, therefore some damage might potentially be expected in the columns. Nevertheless, time history analyses showed that no significant plasticization affects the column base at both SD and NC limit states, which is an important result for allowing the structure to be still functional after a major earthquake.

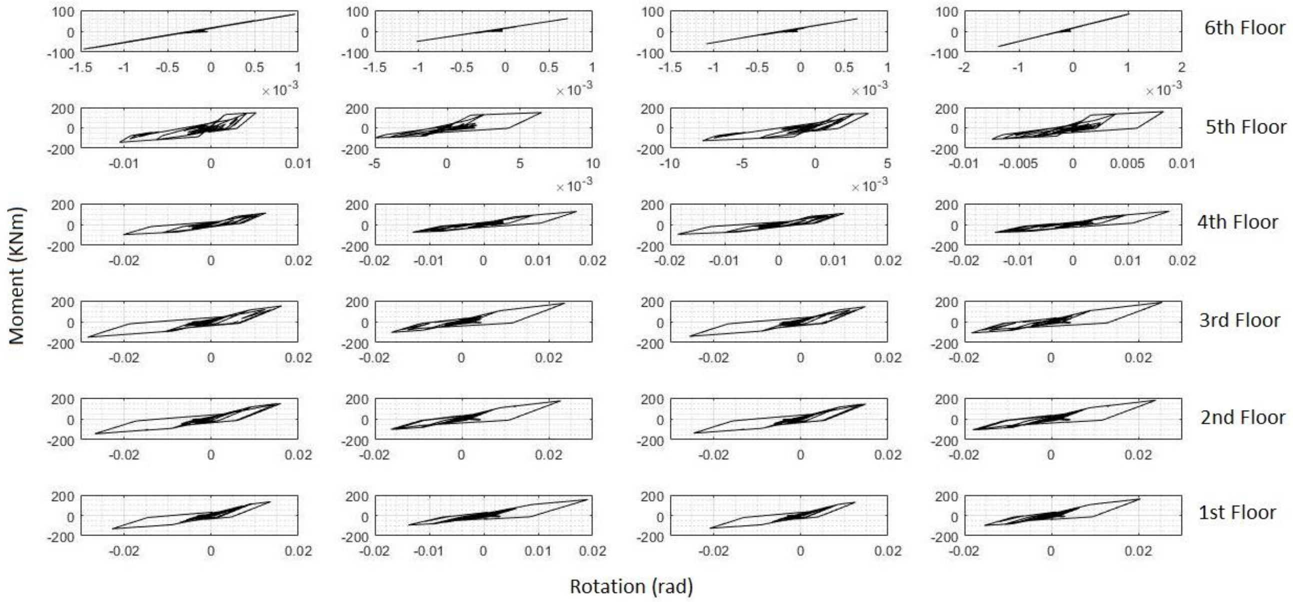

Fig. 13 – Hysteretic behavior of DRD3 devices - Record: itacc-eSD

4. Reduction to substructured frames

The aim of the experimental campaign is to test five different two-dimensional frames each of which is a representative part of a three-dimensional building. The tests will be conducted by employing the pseudo-dynamic method, which allows to run seismic records on a structure not in real time but by expanding the simulation time by a time-scale factor. Since the tests will be performed in full scale and the frame considered was extracted from a 3D six-story building, the whole specimen cannot fit in the laboratory and therefore dynamic substructuring was employed. This method consists in dividing the structural domain into a physical subdomain and a numerical subdomain, where the former includes just the ground floor of the frame and the latter includes the remainder part of the structure. In order the specimen to be representative of the actual building, two reduction steps in terms of substructures were analyzed: i) from the 3D building to the 2D frame and ii) from the entire 2D frame to the substructure to be actually tested based on the degrees of freedom that will be controlled in the laboratory.

4.1 From 3D buildings to 2D frames

Since the experiments are going to be run on a two-dimensional frame, linear dynamic analyses were performed in order to understand what fraction of the global mass refers to the single frame to be tested. Therefore, for each building, three accelerograms were used to evaluate the distribution of the base shear among the four frames, given the assumption that mass and base shear distributions are proportional. Building n.3 is composed of four DRD3 frames in the X direction, therefore around 25% percent of the base shear is carried by each frame, apart from a variation of few percentage points due to a small difference of cross-section between the internal and external columns. For all the other buildings, only the two external frames mainly withstand the lateral load in the X direction. Therefore, they have tributary mass around 50%. In particular, for DRD1 and DRD2 building prototypes the gravity frames are composed with columns that are continuous along their height. Thus, in order to well reproduce the dynamic response in a 2D modelling, a leaning column and a lumped gravity column were included in the model to incorporate P-Δ effects and the flexural continuity of the columns belonging to the gravity frames

4.2 Substructured frames

As mentioned before, the substructuring technique entails to divide the structure into a physical substructure and a numerical substructure. The physical substructure should include the components and members that are likely to experience nonlinear behavior. In this respect, the ground floor was selected as physical substructure, also because it is attached to the base and does not represent a floating domain [5]. During the test, the physical part is also numerically modeled to evaluate the inertial effects. The mass of the substructure has to be condensed at the points where the actuators are applied according to the degrees of freedom that can be controlled in the laboratory. In our case, a maximum of two degrees of freedom can be controlled with two actuators. In particular, for the DRD1 frame just one horizontal actuator at the level of the beam suffices, whereas for the DRD2 and the DRD3 frames a second actuator located at midheight of the second floor was included to control the bending moment in the columns. Fig. 14 shows the substructuring configurations for the four structures. Essentially, the position of the second actuator was chosen to be located at the point of contreflexure of the column that in practice represents a hinge because the rotational degrees of freedom are highly complex to control with hydraulic actuators. After a series of tries the best position to avoid significant discrepancies in the structural behavior between the entire 2D frame and substructures one was found to be at midheight of the second floor. The comparison between the 2D frame and the substructured one was performed in terms of modal, pushover and time-history analysis. Table 1 reports the periods of the first mode of vibration along the X direction of the four case studies for the 3D building, 2D frame and 2D substructured frame. In Fig.15 the same comparison is done in terms of pushover analysis. Therefore, the applied substructuring procedure led to substructures which are representative of the prototype building both for linear and nonlinear behavior.

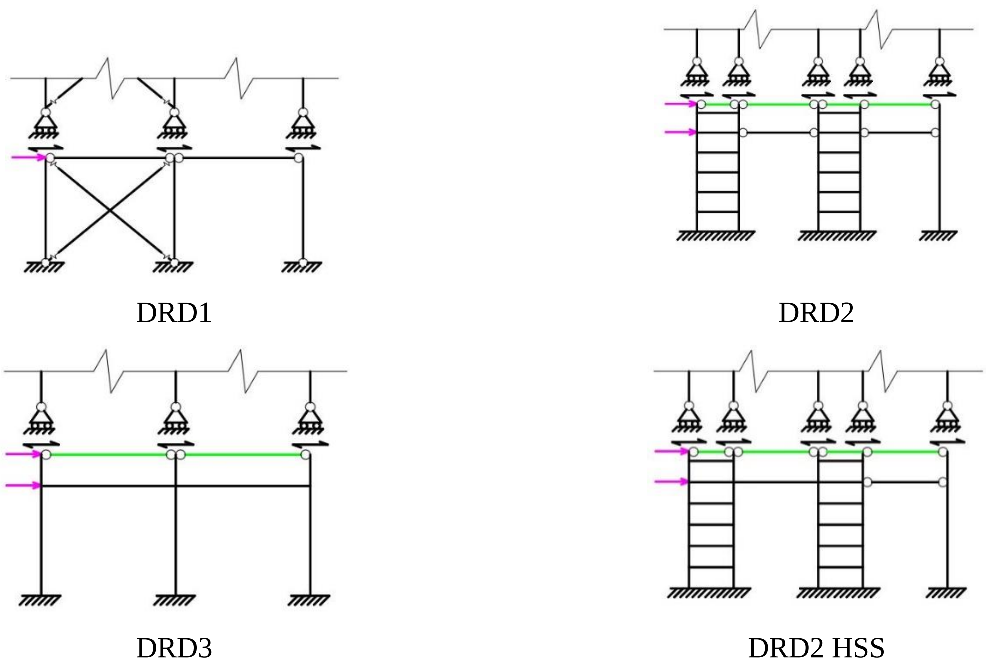

Fig. 14 – Substructuring configurations for the 4 different structures

Table 1 – First period along the X direction. Dimensions in sec.

Model	DRD1	DRD2	DRD2 HSS	DRD3
3D	0.99	1.52	1.31	1.40
2D	0.99	1.55	1.29	1.38
2D - Substruct	0.90	1.39	1.24	1.37

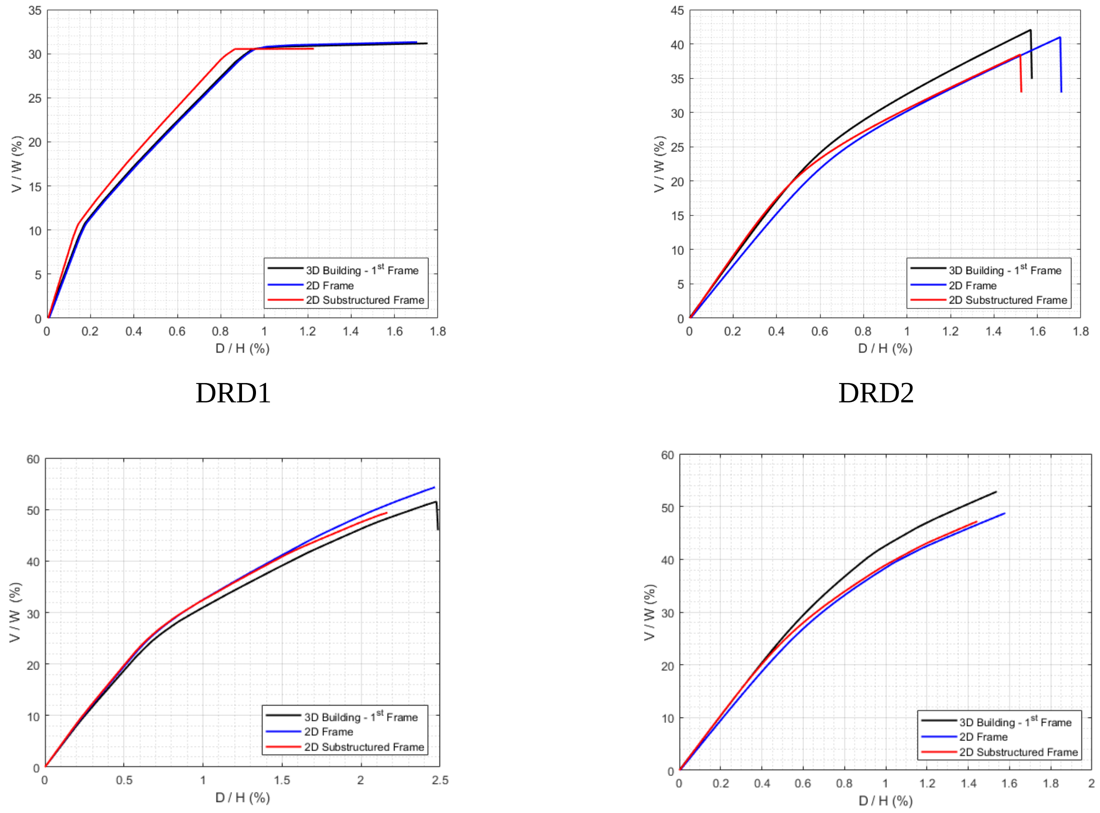

Fig. 15 – Pushover curves comparison

Concerning time-history analyses, the same suite of records adopted for 3D building analyses was adopted in this case. The three levels of modelling seen above were compared in terms of global dissipated energy, base shear and of force developed by the devices. The former comparison was done in terms of percentage error, while for the latter, the two indicators employed are reported in Eq. (1) and Eq. (2). In the two equations, the subscript *j* refers to the 2D building while *i* indicates the substructure.

$$\text{NRMSE} = \frac{\|x_i - x_j\|_2 / \sqrt{N}}{x_{j,max} - x_{j,min}} \quad (1)$$

$$\text{NENERR}=\left|\frac{\|x_i\|_2-\|x_j\|_2}{\|x_j\|_2}\right| \tag{2}$$

Eq. (1) gives information on the frequency error between the two data sets, while Eq. (2) provides indications on the amplitude error. For brevity, only the results for the 2D-Substructure comparison obtained for DRD3 are presented. The results are in terms of global energy error, NRMSE of base shear and bending moment on the 1st floor devices, as shown in Fig.16 and Fig.17. The results show that the mean error stays below 10% for all case besides the global energy error, for which the mean value results of 13.1%. The record employed for hybrid test will be selected based on these analyses.

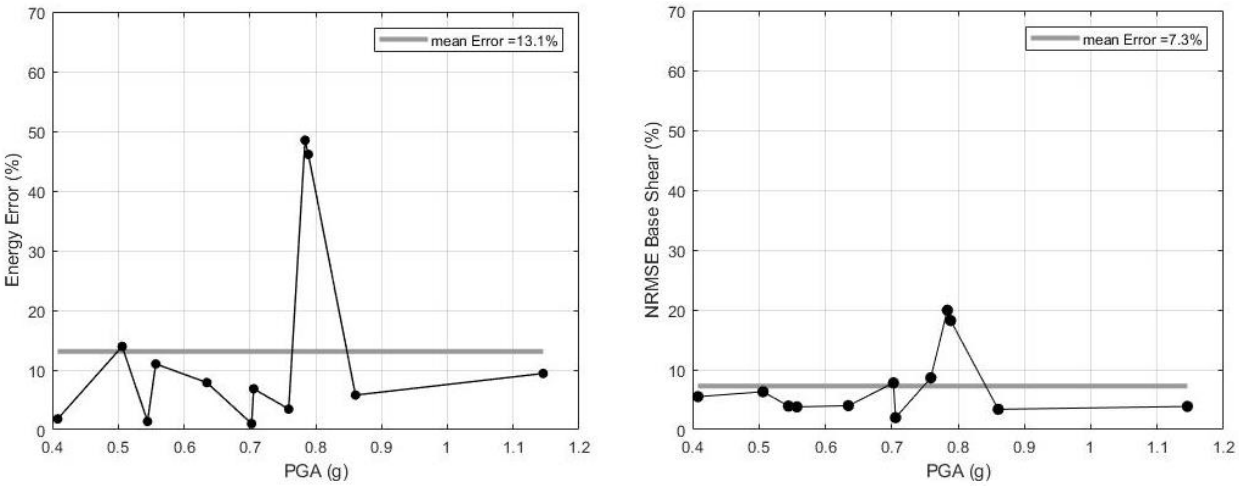

Fig. 16 – DRD3: Global Energy Error and NRMSE on Base Shear

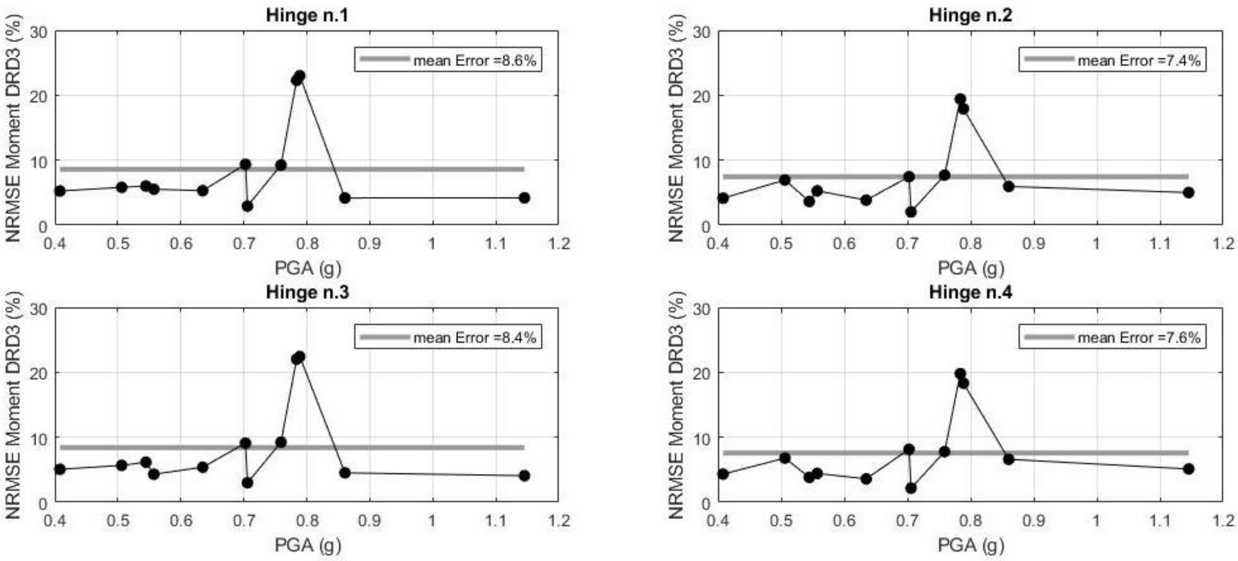

Fig. 17 – DRD3: NRMSE on Moment for the 1st Floor devices

5. Laboratory layout

For brevity, the test set-up conceived for the DRD3 test will be described. Fig. 18 and 19 show the two actuators: one at the floor level the other at mid-height of the second floor. A truss system is adopted to laterally brace the frame to prevent any out-of-plane instability. Two beams (Fig. 18) with high axial stiffness are also placed at the level of the higher actuator to impose the same displacement at each of the three columns. Moreover, as the floor is considered a rigid diaphragm, in order to apply a load representative of such behavior external beam elements at the floor level are used to impose the same displacement at the each column, see Fig. 19, without applying a significant axial force to the beams that would affect the response of the DRD3. Since in the actual building the devices also carry the gravity loads, masses reproducing the total floor weight will be positioned at the quarters of the span. The connection of the columns is composed by a 110 mm thick plate connected to an HD profile fixed to the floor at both ends. This to ensure a full strength rigid joint at the base of the columns, as assumed in the numerical models.

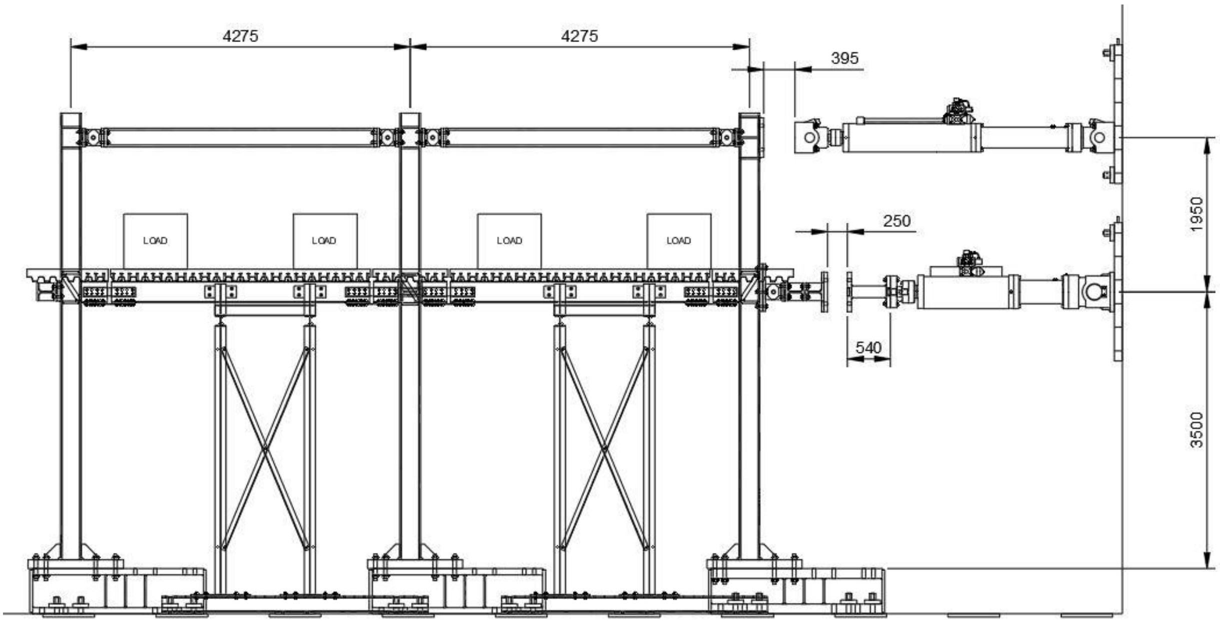

Fig. 18 – Experimental test set-up for test on DRD3 frame – Front view

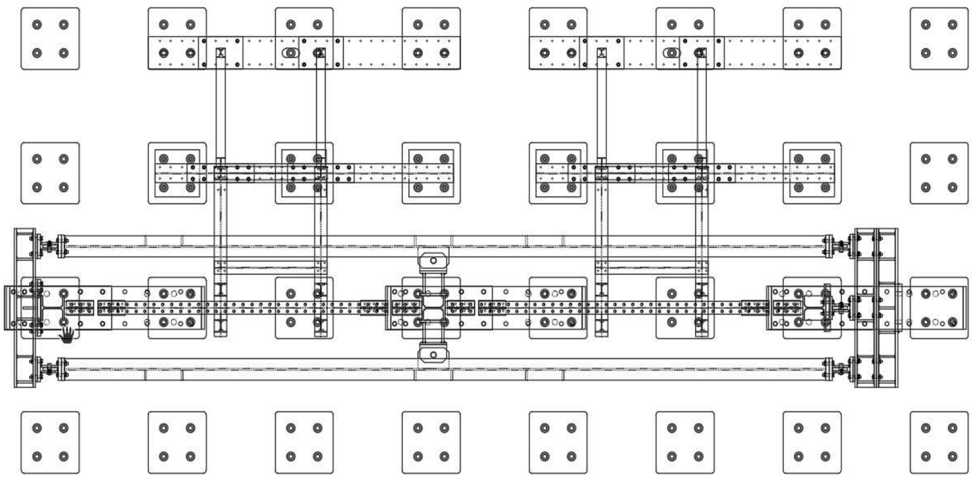

Fig. 19 – Experimental test set-up for test on DRD3 frame – Plan view

6. Conclusion

The paper focused on the design of experimental tests to be conducted on steel frames equipped with different DRD at the University of Trento through dynamic substructuring technique. The features of the single DRDs and their cyclic experimental response were described. Numerical calibration of the DRD hysteretic behavior conducted with the finite element software *OpenSees* showed that good agreement with experimental data was achieved. Moreover, from the design of the prototype 3D buildings, the representative physical substructures of the 2D frames to be tested were derived. Good agreement in terms of global dissipated energy, base shear and of force developed by the devices was obtained, meaning that by controlling one, in case of DRD1 or two actuators, in case of DRD2 and DRD3, the seismic response of the frames is well represented. Finally, the test set-up was presented, that highlighted the complexity to reproduce the structural dynamic behavior of the specimens.

7. Acknowledgements

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