

ORIGINAL ARTICLE



Experimental Investigation of Steel Frames Equipped with Easily Replaceable Components

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Abstract

Modern techniques of structural design are effective in preventing structural collapse due to earthquake actions. Nevertheless, repairability has become an important issue to deal with in order to minimise the economic and environmental impact of structural damage. In this respect, this paper presents the design of experimental tests on full-scale specimens of steel frames to be tested according to hybrid simulation. This work is conducted within the ongoing European research project DISSIPABLE that seeks to test easy to replace structural components installed in steel buildings. In fact, by including these Dissipative Replaceable Devices (DRD) into the building, it is possible to provide full post-earthquake functionality after damage. Three are the devices that will be tested, namely DRD1, DRD2 and DRD3, which are going to be briefly presented in the paper. Five hybrid tests will be performed and major details will be given to the numerical modelling of the components and the identification of the substructures to be employed in the tests. Finally, the design of the physical substructure and the test setup will be briefly described.

Keywords

Hybrid simulation, Replaceable Seismic Devices, Full-Scale Tests, Steel Structures

1 Introduction

Due to the high risk associated with the earthquake, efforts were done by the scientific community in order to increase the resilience of structures with the aim to achieve sustainable design, that means the reduction of resource consumption and environmental loads in the post-disaster situation.

Nowadays, the design of structures in seismic areas is based on the classical approach of the capacity design that implies the localisation of the energy dissipation through inelastic deformation in specific members. However, this point of view does not consider the post-earthquake situation, that has to face the structural damage by possibly fixing and replacing every damaged part of the structure. This process is not always feasible or it is too expensive and it may determine a long interruption of functionality, with consequent economic losses.

On these premises, the European Research Fund of Coal and Steel (RFCS) DISSIPABLE pilot project was funded to provide experimental evidence on both the high degree of energy dissipation and the easily replaceability after a major seismic event of full-scale steel structural specimens endowed with dissipative seismic components. In this respect, 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 the work done to prepare the experimental campaign.

The paper is organised as follows: a brief description of the three Dissipative Replaceable Devices (DRDs), namely the DRD1 (INERD pin connection), the DRD2 system (FUSEIS beam links) and DRD3 (FUSEIS bolted beam splices)[1], and their numerical models are described in Section 2; in Section 3 the building prototypes are reported; whilst the substructuring of the case studies is presented in Section 4; 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

In this section a brief description of the DRDs and their numerical modelling is provided. Indeed, an accurate numerical representation of the cyclic behaviour of the DRDs is paramount to perform meaningful hybrid simulation tests, that imply to divide the structure into a physical and a numerical substructure.

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

Considering braced frame systems, the DRD1 was conceived to be used as connection between the column and the bracing as shown in Figure 1. The advantage of using these devices lies on the replaceability guaranteed by bolted plates connected to the column. This

prevents the bracing to yield in tension and to buckle in compression. The dissipation is only localised in the pin, which behaves in bending and shear. The final device capacity is reached when the plastic hinges are fully developed in both the external and the internal plates.

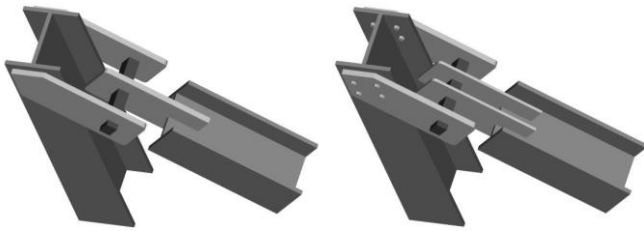


Figure 1 DRD1 configurations [1]

As it is possible to observe in Figure 2, the device undergoes significant pinching effect due to the ovalization of the holes of the pin. This phenomenon could be avoided by using high strength steel for the external plates. Other modifications to the geometry shown in Figure 1 are under investigation to avoid the different response under tension and compression by adding reinforcements between the external plates to prevent later bending. Moreover, an improved detailing is being investigated to enhance reparability. Nonetheless, the device highlights wide cycles with excellent dissipative properties.

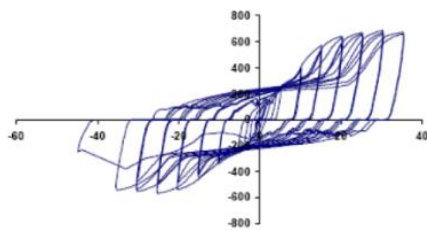


Figure 2 DRD1 cyclic behaviour [1]

A numerical model of the device was developed in the finite element software *OpenSees* [6] by means of the material model *Pinching4* [6] as it allows for considering the pinching effect. The monotonic numerical curve was identified in accordance with [1] whilst the hysteretic parameters were derived from a previous numerical model and then checked to be in accordance with the experimental behaviour reported in Figure 2. In Figure 3 the dimensionless hysteretic curve for a 50 mm x 30 mm device is shown.

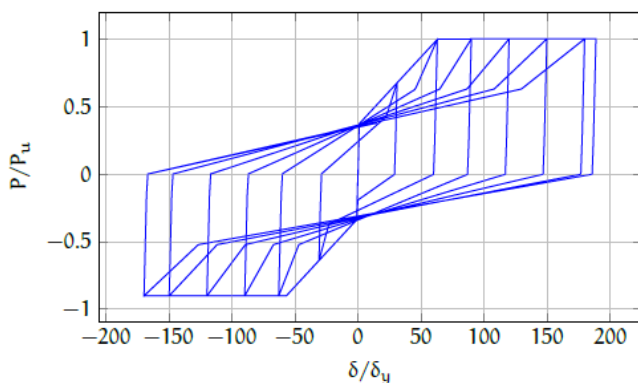


Figure 3 DRD1 numerical modelling

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

The DRD2 system is made up of two parallel columns connected by reduced section beams. 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. The behaviour of the system could be represented as a Vierendeel beam, where the columns are subjected to a strong axial force component while the beam links work mainly in bending or in shear, depending on their length. The beam is typically weakened at the ends to force the formation of the plastic hinges at those locations.

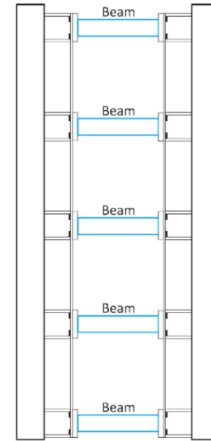


Figure 4 DRD2 configuration [1]

The cyclic behaviour of the device was investigated in previous projects, reaching satisfactory dissipative behaviour, as shown in Figure 5. The DRD2 device was numerically modelled in the software *OpenSees*. The steel profile realizing the DRD2 was modelled subdividing the whole beam in five different parts, where non-linear springs were considered for the reduced beam section (RBS) while the remaining parts were elastic beam elements with stiffness properties of the gross section. The constitutive law chosen to represent the hysteretic behaviour of the device was the Bouc-Wen model implemented in *OpenSees* [6], whose parameters were determined fitting the numerical curves obtained by finite element model developed in the software ABAQUS [7]. Figure 6 shows the numerical modelling of the DRD2 that is going to be used in the laboratory tests.

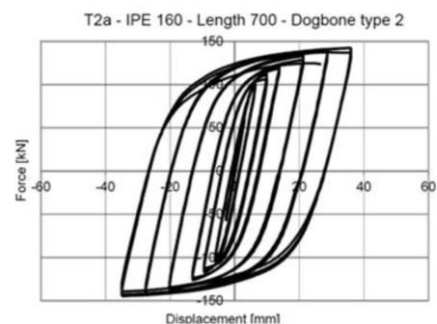


Figure 5 DRD2 cyclic behaviour [1]

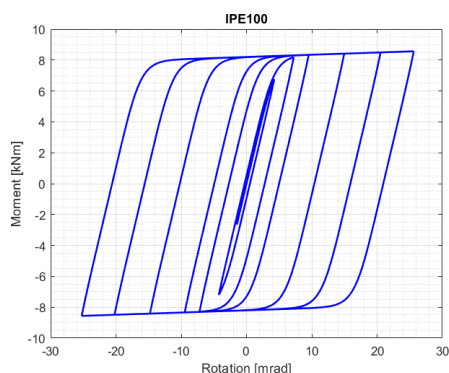


Figure 6 DRD2 numerical modelling

2.3 DRD3 – FUSEIS bolted beam splices

The DRD3 was intended to be used in moment resisting frame, weakening the composite beam in order to localise the plastic hinges close to the beam column joint. This was achieved by interrupting the steel profile and the concrete slab, as shown in Figure 7, and restoring the continuity with fuse plates on the web and the flange of the steel profile, which were designed to dissipate energy. The reinforcement bars of the concrete slab were continuous through the gap and they were over designed as they have not to remain in the elastic field. The purpose of the gap was to avoid concrete cracking as well as allow the plate deformation connected to the steel profile. For preventing the beam from damage, some additional plates were welded to the steel profile, aiming to the local enhancement of the non-dissipative component resistance. Moreover, to ensure a flexural mode of collapse and to avoid shear collapse, also the shear resistance of the web plate was designed with overstrength with respect to the flange plate.

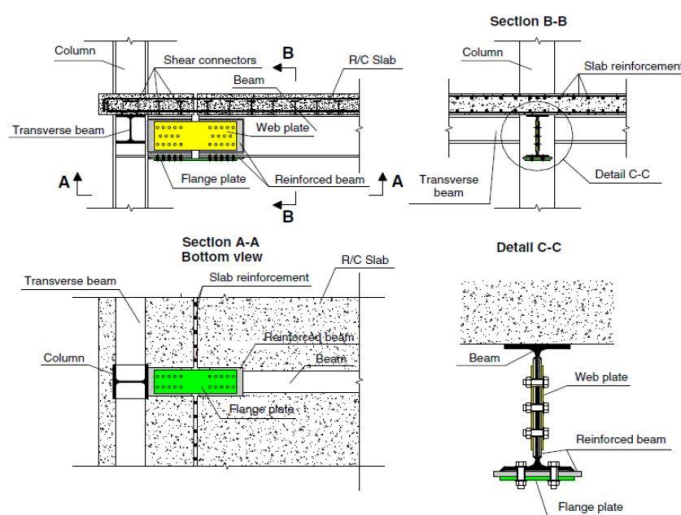


Figure 7 Front, lateral and plan view of DRD3

The replaceability was ensured as the web and flange plates were bolted to the beam profile. Because of the geometric configuration and different material properties, the monotonic behaviour of the device is characterised by strong non-symmetry [2][3]. A numerical model was developed in *OpenSees* by means of the material model *Pinching4* as it allows for considering both the non-symmetric constitutive relationship and pinching effect of the device. The numerical model was fitted on the experimental curves obtained by previous experimental campaigns [2][3]. In those tests, the devices were different from those employed in DISSIPABLE, therefore the experimental curves were normalized to the actual bending resistance

and yielding rotation of the DISSIPABLE devices. The fitting was performed by means of the applicative software Multical [4], and the results are illustrated in Figure 8, which show good agreement.

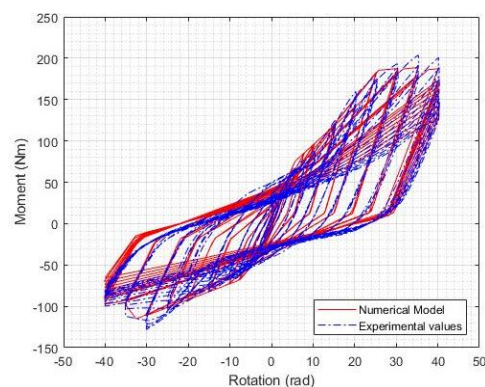


Figure 8 Fitting of DRD3 experimental behaviour

3 Building prototypes

The experimental campaign purpose is to test five different buildings, equipped with such devices and 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. The case studies were composed by two spans in the transversal X direction, three spans in the longitudinal Y direction and six-storeys. The span length was chosen in conformity with laboratory constraints and restricted to 4.275 m, while the inter-storey height was equal to 3.5 m. The initial modelling of the 3D building was developed in SAP2000 [9]. The design was carried out by means of the EN 1998-1 design spectrum, with peak ground acceleration equal to 0.36 g and soil type A. The nonlinear model of each building was developed in *OpenSees*. Modal, push-over and time-history analyses were employed to investigate the buildings response. Accelerograms at Damage Limitation (DL), Significant Damage (SD) and Near Collapse (NC) limit states were used to perform time-history analyses. For brevity, the DRD2 mild steel building used to extract the relative specimens is illustrated in Figure 9.

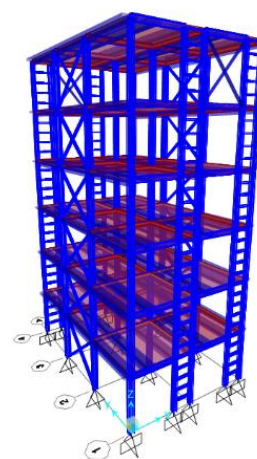


Figure 9 DRD2 mild steel

Two parallel shear walls made of DRD2 of sections IPE 100, IPE 140 and IPE 160 of steel grade S235 were considered in order to reduce the building deformability in the X direction, whereas DRD1 were used in the Y direction. The hysteretic behaviour of DRD2s mild steel building subjected to a SD accelerogram is reported in Figure 10. As it is possible to notice, uniform dissipative behaviour was achieved, except for the top floor because of the presence of the bracing system.

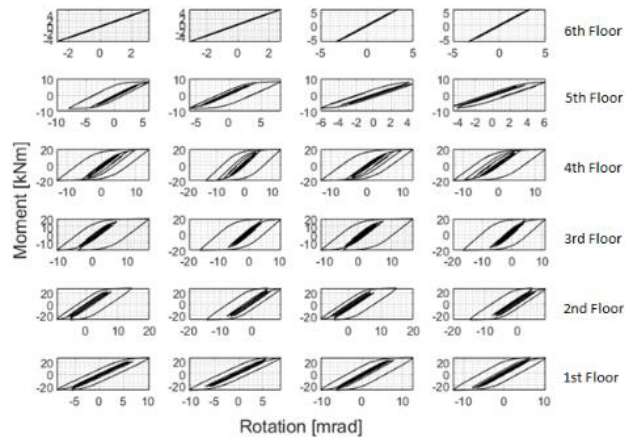


Figure 10 Hysteretic behaviour of: a) DRD2 mild steel and b) DRD2 with HSS coupling beams

4 Reduction to substructured frames

The RFCS project goal is to test full-scale structures in order to demonstrate the effectiveness and the replaceability of the devices. Since the whole specimen cannot fit in the laboratory, substructuring technique was employed to divide the structure into a numerical subdomain and a physical subdomain. 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. The procedure that was followed was divided into two steps: i) development of 2D nonlinear FE models in *Opensees* that are as representative as possible with the 3D models; ii) development of meaningful 2D nonlinear FE models of substructures that are representative of the actual partition between physical and numerical substructures hybrid tests.

4.1 From 3D buildings to 2D frames

The laboratory tests will be performed on a 2D structure. Under the hypothesis that the mass and base shear distribution are proportional, linear dynamic analyses were performed to calculate the percentage of base shear of each frame. In the DRD3 building all the frames are equipped with the device and a slight difference in terms of stiffness was highlighted between the internal and external frames by these analyses, thus the mass is not equally distributed between the four frames, but is more concentrated in the two internal frames. For symmetry, the 25% of the total mass was assigned at each frame. Concerning the other prototype buildings with the other DRDs, only the two external frames mainly withstood the lateral load in the X direction, therefore the first frame of the building was considered, for the study of the two-dimensional frame. In order to take into account the effect of the gravity frames, 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. The comparison of the fundamental period between the 3D and 2D prototype buildings is reported Table 1. Good agreement can be noticed.

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

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

4.2 Substructured frames

The hybrid tests, which are going to be performed, consist in modeling the structure as a numerical domain and an experimental domain where the inertia and viscous forces are numerically simulated, whilst the internal force and the hysteretic damping are directly measured. The partition is conducted by using the substructuring technique which consists in the identification of the constraint position between the two different parts, in such a way to well reproduce the behaviour the entire structure. The experimental substructure should include the parts of the structure that experience the highest plasticisation. In this respect, the first storey of the frame was selected as physical substructure. Moreover, it is not a floating domain and it can be connected to the reaction floor with its actual connections. During the test, the physical part is also numerically modelled 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. Due to laboratory constraints, only the horizontal degree of freedom was kept by means a maximum of two actuators. For the DRD1 building, as the reader might see in Figure 11a, one actuator at the floor level is sufficient, whilst for the other prototype buildings, another actuator is necessary to better represent the dynamic behaviour of the entire frame. In particular, the second actuator is to be placed at the point of contraflexure of the column which is located with good approximation at the column mid-height. The validation of the substructures shown in Figure 11 was achieved by means of modal, push-over and time-history analyses, confirming that no significant discrepancies are occurring between the 2D model and the substructure. The comparison results in terms of the fundamental periods is illustrated in Table 1, whereas in terms of push-over analysis in Figure 12.

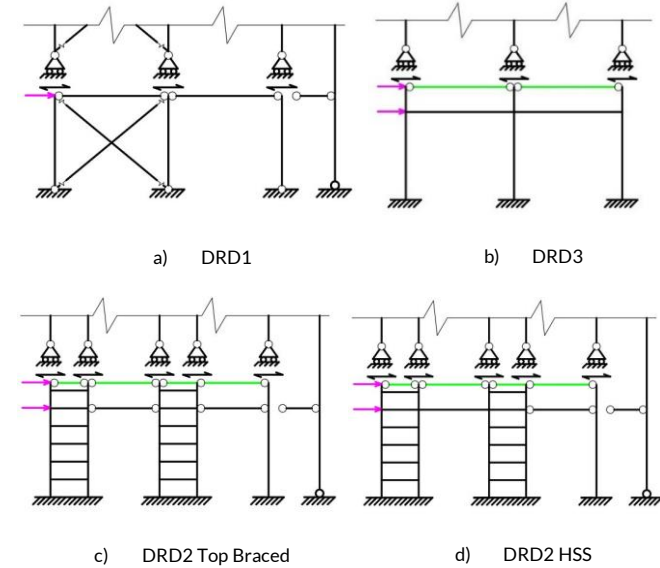
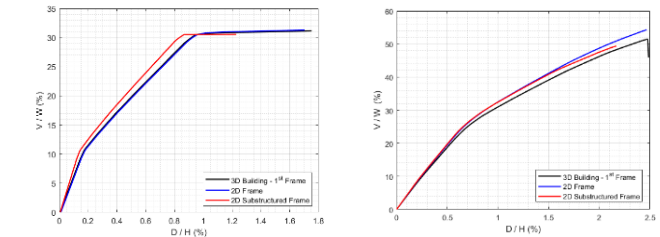


Figure 11 Substructuring configurations



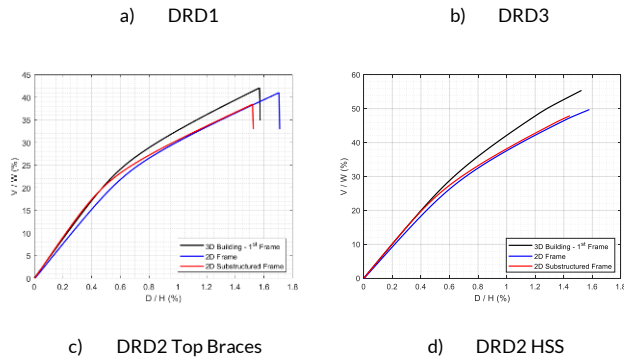


Figure 12 DRD2 Top Braced push-over comparison

Moreover, also accelerograms were used to evaluate the non-linear behaviour by means of the same suite employed for the 3D building. The comparison between the model results was carried out in terms of global dissipated energy in the whole building, by calculating percentage error, and of force developed by the devices. 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 2D substructure.

$$\text{NENERR} = \frac{\|x_i\|_2 - \|x_j\|_2}{\|x_j\|_2} \quad (1)$$

$$\text{NRMSE} = \frac{\|x_i - x_j\|_2 / \sqrt{N}}{x_{j,\max} - x_{j,\min}} \quad (2)$$

Eq. (1) provides indications on the amplitude error, while Eq. (2) gives information on the frequency error between the two data sets. The results in terms of global energy dissipated for the DRD2 mild steel model are shown in Figure 13 and Figure 14. As can be seen, the mean error stays below 10% for all cases. The record employed for hybrid test will be selected based on these analyses.

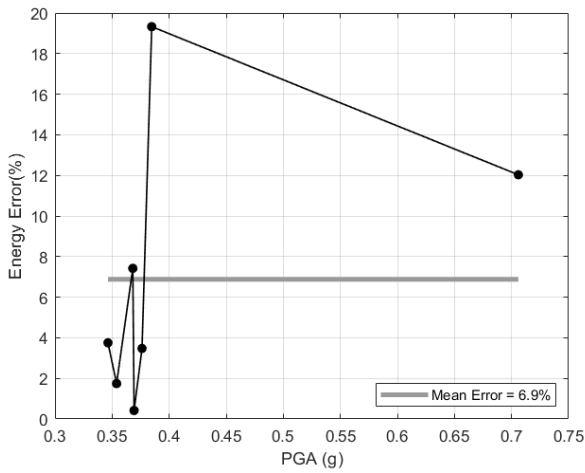


Figure 13 DRD2 Global Energy Error

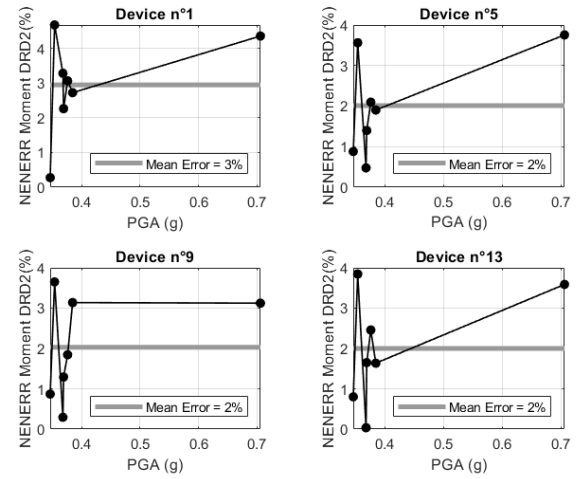


Figure 14 NENERR on Moment for the 1st Floor devices

5 Laboratory layout

Concerning the laboratory layout, a truss system is adopted to laterally brace the frame so as to prevent any out-of-plane instability, as depicted in Figure 15. For the hybrid simulation test on the DRD2 specimen, two actuators will be employed: one at the floor level the other at mid-height of the second floor. Moreover, for the DRD2 and DRd3 test set-up, two beams with high axial stiffness will be placed at the level of the higher actuator to impose the same displacement at the top of each of the columns. Furthermore, as the floor is considered a rigid diaphragm, external beam elements at the floor level are used to impose the same displacement at each column, see Figure 16. The connection of the columns is realized through a 110 mm thick plate connected to a heavy welded 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.

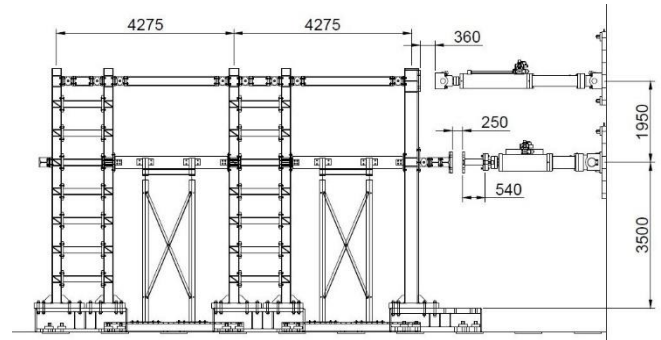


Figure 15 Experimental test set-up for test on DRD2 frame - Front view

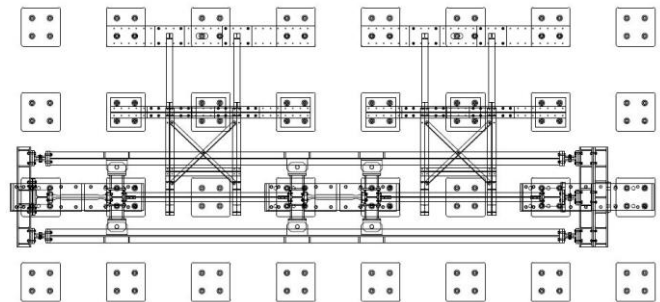


Figure 16 Experimental test set-up for test on DRD2 frame - Plan view

6 Conclusion

This paper focused on the identification of most representative substructure and the design of the experimental tests to be conducted on steel frames equipped with different DRD through dynamic hybrid simulation. The modelling and calibration results of the single devices were shown. Moreover, the procedure conducted demonstrated that the 2D substructure well represented the global behaviour of the 3D building in terms of global dissipated energy and force developed by the devices. Controlling one actuator, in case of DRD1, and two actuators, in case of DRD2 and DRD3, is sufficient to well represent the seismic behaviour of the specimen.

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