Experimental and numerical study of an easily replaceable dissipative system for concrete-steel composite structures when subjected to seismic actions - DRBrC

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Abstract: As time goes by, seismic actions are increasingly taken into consideration in society, particularly in design and dimensioning of structures. With the help of EC8 since 1998, over these years innovative systems capable of mitigating these events, which can lead to tragedies, have been developed and tested.

Thus, this paper describes both experimental and numerical tests of a seismic action dissipative device, designated DRBrC, from the DISSIPABLE project. These devices were subjected to cyclic tests assessing their hysteretic behaviours. In these tests the maximum cyclic alternate forces, the number of cycles to pin failure (ductility) and the accumulated dissipated energy are provided and subsequently studied. The pin ruptures by shear or bending. A parametric analysis is performed between devices in which the configurations are compared, i.e., the steel type of the pin (S235vsStS) and of the housing (S355vsHSS), as well as the distance between internal plates of the housing (70mm vs 90mm). Note that the tests are either ECCS, amplitude increasing gradually, or C, constant amplitude. Finally, 4 reused boxes were tested to understand how they behave in a second use; this time the fitted pins were manufactured in the LERM lab, IST.

Keywords: Repairable dissipative devices; cyclic testing; hysteretic behavior; ductile damage; boxes reuses; braced frames.

1. Introduction

Many years have passed since the 1755 earthquake that shook Lisbon, the south side and Algarve coast, but that cannot be forgotten. It was one of the largest and powerful earthquakes in early modern Europe, it has been estimated to have reached a magnitude of 8 to 9 on the Ritcher scale, just like Tōhoku earthquake, Japan March 11, 2011. Humanity must have the wisdom to realize that in fact there is life under our "feet" (Ferreira, 2021), especially civil engineers when designing and dimensioning structures, where they must be concerned to prevent the structure collapse, prolonging life service and, most importantly, protecting/keeping human life safe (NEHRP, 1997).

In Portugal, successive generations of earthquake-resistant design codes entered into force, namely in 1958, 1983 and, more recently, the Eurocode 8 in 2019 (published as a Portuguese standard in 2010).

Along with EC8, innovative seismic action dissipative systems have been studied and developed, such as the Dissipative Replaceable Bracing Connection (DRBrC), which is part of the DISSIPABLE project (DISSIPAtive plus reparABLE), "Research Fund for Coal and Steel" program organized by the European Community (EC). The DRBrC consists of a housing and a pin, both made of steel. The housing can be divided in two, the male and female, which are connected by a pin that passes through the parts through oval holes. These devices are installed in bracketed frames in beam-column connection areas (fig 1.1).

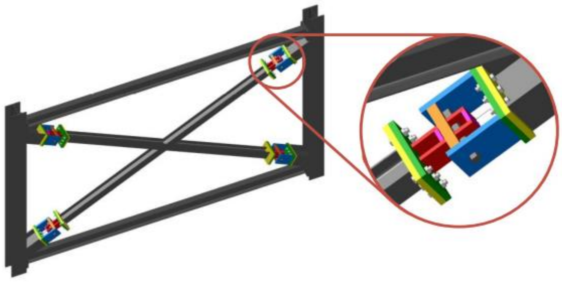


Fig. 1.1: Overall view of DRBrC installed in a frame (DISSIPABLE, 2018).

This device was analyzed through experimental and numerical testing in which a parametric analysis was performed that compares several possible configurations. In these tests, information is collected such as the maximum cycle alternate forces, the number of cycles required for the pin to break, and the accumulated dissipated energy. The DRBrC can be made of S235 or StS steel in the pin and S355 or HSS in the plates that define the case. The inner distance of the plates with 70mm (D1) or 90mm (D2) is also analyzed (RFCS-02-2017, 2017).

2. Literature review

Frames are the trademark of steel structures. It is also very common to have frames in steel-concrete composite structures, but in this case the slab is usually heavy due to the concrete characteristics. With the evolution of construction and the design of structures, bracing was developed, which is the introduction of one or more metal bars, typically two, which serve to support lateral forces (earthquake and wind) and distribute vertical forces (gravity and overloads) by the lower columns. As mentioned above, its main role offers more rigidity to the structure itself, that is, one bar works in compression and the other in tension. They may designate braced frames. The major differences between simple and braced frames are found in the support conditions and connections. While simple frames (MRF's) are embedded in the base and have rigid connections, braced frames (CBF's) are articulated both in the base and in the beam-column connections (Guedes, 2011).

2.1. DISSIPABLE project: DRBrC

Taking advantage of the fact that the use of bracings or trusses, are an effective way to respond to a seismic event, for one bar works in compression while the other works in tension, there are studies of various types of trusses with local devices that have the function of dissipating the energy from an earthquake. Over the last 20 years these devices have been improved fig. 2.1.

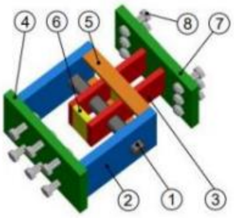


Fig. 2.1: DISSIPABLE device, developed in 2019 (Nascimento, 2020).

With the characteristics:

①-Pin, ability to replace.

②-External plates, welded to ④-Opposite base, bolted in profile (⑧).

③-Internal plates, welded to ⑦-Opposite base, bolted in profile (⑧).

⑤ and ⑥-Spacers, helps concentrate plastic deformation in the pin.

The main goal of developing this device is to create a mechanism capable of dissipating large amounts of energy so that the main structure does not suffer extensive damage throughout a strong earthquake. In addition, the design of the DRBrC was thought so that it would fill the lack of performance reparability, existent in other similar devices. As it is crucial to restore buildings and its functions as quickly as possible, this device was planned, so that it could be easily replaced, resulting in its considerable low weight (100Kg). This device consists of a pin fuse, mounted in the bracing system. The concept of this connection is a pin that is subjected to four-point bending which behaves in a relatively simple and in a predictable way. It is supposed to fail due to low cycle fatigue, by accumulating permanent plastic deformations. In a broad sense the following points summarize the principal objective for the DRBrC (Farinha, 2020):

- Reduced failure probabilities.
- Reduced consequences from failure, in terms loss of lives, structural and non-structural damage, and negative economic and social consequences.
- Reduced time to recovery (restoration of a specific system to its functionality).

To have a more symmetrical behaviour, some plates, called guide plates, were installed. Initially, 2 plates were placed that are welded to the spacer outside, which significantly reduces the lateral clearance (GP1). The problem was not completely solved and to improve it, two more plates were installed on the inside of the box (GP2) (fig. 2.2). The application of these plates reduced 500%(!) the lateral displacement and thus allow the efficient channelling of the movement of the device (Cabrita, 2020).

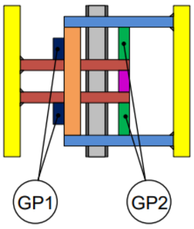


Fig. 2.2: Guiding plates.

In addition to this problem there was still another one to solve in pins with circular section. Due to its geometry, there is a lower degree of recessions and therefore, the pin does not have significant lateral movements it was welded to the external plates. The pins with chamfered section present a failure mode by bending in its middle section, which is assumed, while the other pins their rupture happens in a shear mode curiously where they are welded (until the weld breaks), which prevents greater freedom crane and thus a plastic hinge occurs. At this event it becomes more difficult to replace the pin, which is a performance not intended to happen. It can be concluded that the use of welding is not favourable for the device performance, not only by premature failure but also because it prevents the elongation of the pin, compromising its ductility. Consequently, the use of circular pins is not recommended. Pin elongation plays a key role in the failure mode and cyclic behaviour of specimens (Cabrita, 2020).

To be able to compare in a theoretical level, DRBrC devices were created in the ABAQUS software, to simulate the tests. The device is built with its geometric configurations and the boundary conditions defined, and finally a load history input is made from Excel. To better understand how a numerical model is developed, the following scheme simplifies it (fig. 2.3).

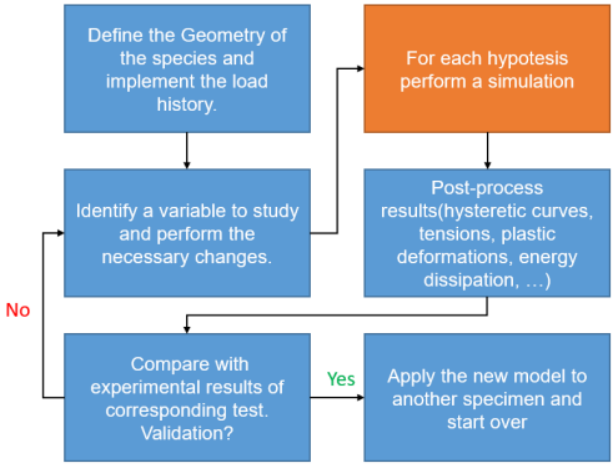


Fig. 2.3: Scheme of the general methodology used (Farinha, 2020).

To run this scheme, one needs to solve 3 core topics to develop the numerical model:

-Finite Element Method: In this simulation a quasi-static resolution was used because as the displacement and velocity are small, the inertial forces and impacts can be neglected. Being a dissipative device with plastic deformation capacity, it takes on a physical nonlinear behaviour, i.e., it is not enough just to define it by Hooke's law. It also necessary to take into account 2nd order effects. Although not so precise, the model had enough elements to avoid discrepancy of values. What was done to have more accurate results was to refine the mesh in the interaction zone between the plates and the pin.

-Material modelling: After the tensile tests carried out at LERM, Initial Hardening Parameter and Kinematic Hardening Parameter, which are arbitrated in an Excel sheet to calibrate with the logarithmic curves originated from the tensile tests, namely with the true stress-strain curve. These arbitrated values are smaller than the theoretical ones since the implemented plastic curve can only have a logarithmic evolution.

-Contact modelling: If there are no contact surfaces modelling throughout the tests, the objects tend to penetrate with each other without any reaction/interaction. This is not realistic and thus the outer limits of each part had to be defined. The main option to use for the contact formulation is master slave. By software default, in ABAQUS there is always some penetration, even in the hard contact formulation, for reasons of numerical stability. Therefore, the type of contact used was surface-to-surface, which is standard in Abaqus. This individually defines the interactions between each pair of elements, and its advantage over the others is that it is more stable than the surface-to-surface node formulation.

3. Experimental Results

The general idea of the loading system is to react against a rigid concrete wall (reaction wall) existing in the LERM. This concept preforms ideally for monotonic unidirectional tests. But, since the tests of the hysteretic pin device are cyclic, another rigid end is needed. Thus, another “rigid” end is built using existing steel elements to erect a rigid frame. The main concept of the test setup is represented in Figure 3.1.

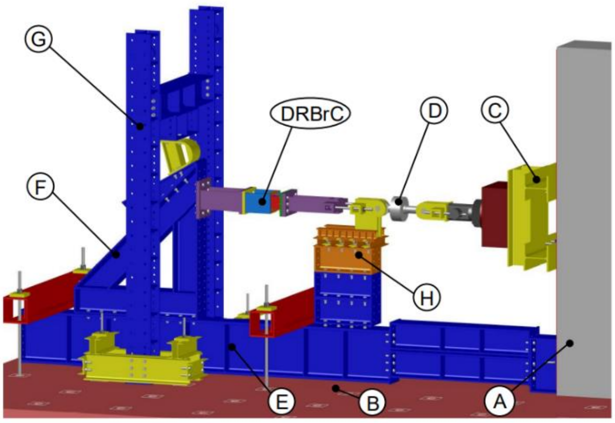


Fig. 3.1: General overview of experimental setup (DISSIPABLE, 2021).

(A)Reaction wall, (B)Reaction floor, (C) Actuator, (D)Load cell, (E) Base, (F) Rigid triangular frame, (G)Frame, (H)Railway base.

The test is performed through the actuator control panel where it moves the rigid bar containing the load cell forward (compression) and backward (tensile). The load cell is one of the sensors that as the name indicates provides the forces. There are 3 more sensors installed around the DRBrC that two of them (in case one fails or when the amplitudes are <50mm) measure the amplitudes and the other one the lateral displacement.

All the experimental results are present in the report 2nd Phase Experimental Full-Scale Tests Behaviour of DRBrC Devices Results by Luís Calado, Diogo Cabrita and Nuno Rosas, 2021. In this document an example device will be demonstrated, it is called Box 26: R_StS_S355_D2_E, "R" for bevel pin, "StS" for steel quality of pin, "S355" for steel type of box, "D2" for distance between inner plates and "E" ECCS cyclic test.

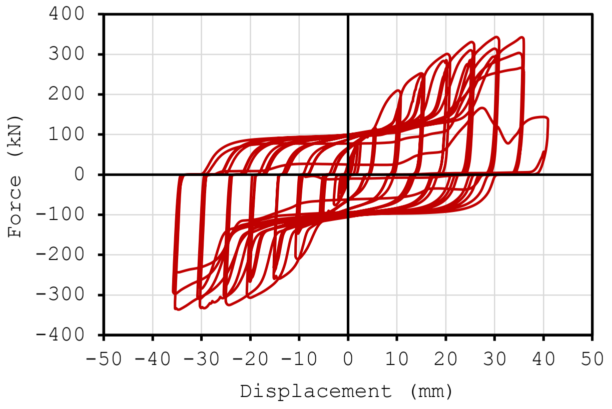


Fig. 3.2: Force-Displacement curve of test number 23.

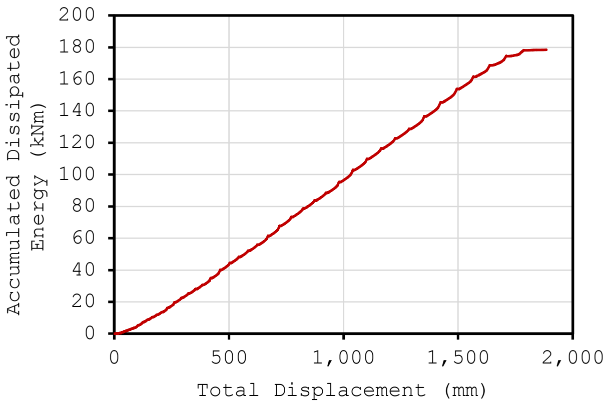


Fig. 3.3: Accumulated Dissipated Energy curve of test number 23.

Tab. 3.1: Results for experimental test 23.

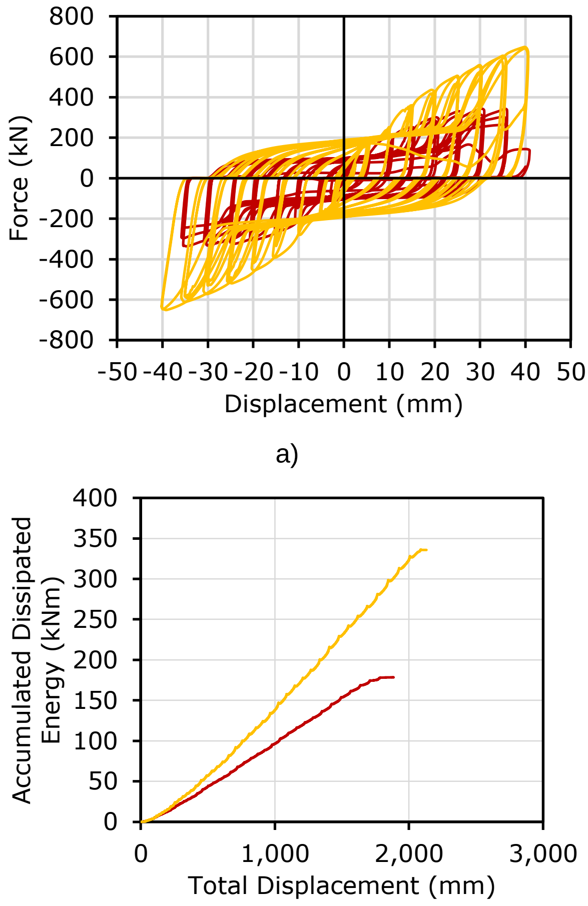
	Positive	Negative
F_{max} (kN)	343.20	-336.36
δ_{max} (mm)	40.92	-35.82
Dissipated Energy (kNm)	178.51	
Nr. of cycles	27	

Note: Reached pin failure.

4. Parametric Analysis

Parametric analysis is used to compare the hysteretic behaviour of the steel types and the plates internal distances. It should be noted that in the following graphs there are no units due to the single fact of visualization. Therefore, the Force-Displacement graphs (first) on the abscissae are the displacements in mm and on the coordinates are the forces in kN, while the Accumulated Dissipated Energy graphs (second) on the abscissae are the total displacement, i.e., the sum of the imposed amplitudes, and the coordinates are then the energy. The variables to evaluate quantitatively are the maximum antigravity forces, number of cycles, and the accumulated dissipated energies. For this example, in box 23 the following graph superimpositions are made:

- Plates: S355vsHSS: The plates of the boxes are made of a type of steel with greater strength to confine much of the earthquake energy in the pin.

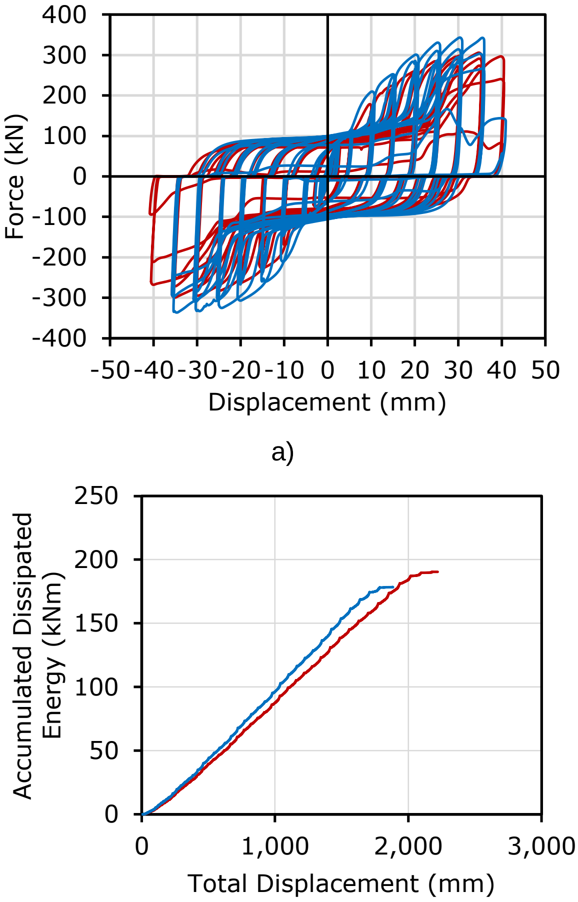


a)

b)

Fig. 4.1: Comparisons between StS_S355_D2 (red-box 23) with StS_HSS_D2 (yellow-box 26): Force-Displacement curve (a), Accumulated energy dissipated curve (b).

- D1vsD2: The distance between plates is central to the study of ovalizations, since the greater this distance, the greater the interior ovalization, and vice versa.



a)

b)

Fig. 4.2: Comparisons between StS_S355_D1 (red-box 9) with StS_S355_D2 (blue-box 23): Force-Displacement curve (a), Accumulated energy dissipated curve (b).

With these tests it is impossible to use box 23 to compare the pin steel type, an R_S235_S355_D2_E configuration would be required.

5. Numerical Analysis

The specimen's simulation is done in ABAQUS software, carrying on the work developed by Diogo Cabrita and Tiago Farinha, with no need to create a new device but to introduce the guide plates even though they are unnecessary for the software. The tests performed in ABAQUS did not detect any lateral displacement. Tensile tests had to be performed on the new materials to calibrate the models. The repeat testing of S235 and S355 steel was to confirm the results of the previous tests.

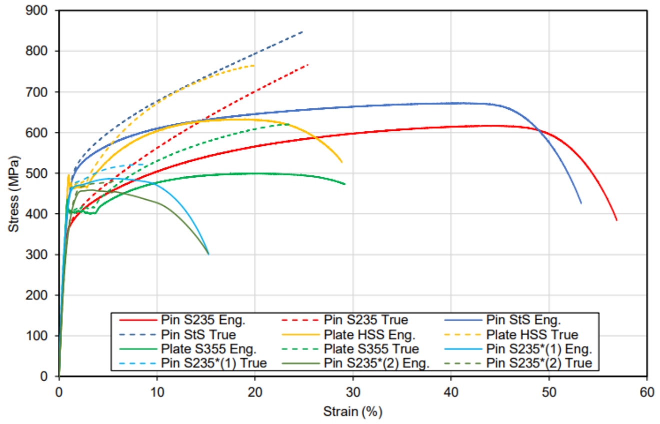


Fig. 5.1: Engineering and true stress-strain curves for all the materials (DISSIPABLE, 2021).

To calculate the true stress (σ_t)-distension (ε_t) curve of the material the logarithmic law is accepted to perform the conversion accurately (equations 5.1 and 5.2) (Faridmehr et al., 2014).

$$\sigma_t = \sigma_e \times (1 + \varepsilon_e) \qquad (5.1)$$

$$\varepsilon_t = \ln(1+\varepsilon_e) \qquad (5.2)$$

It should be noted that these expressions are only valid in the plastic zone, since after this point the stress and strain are no longer distributed by equal cross section because of the neck phenomenon (Soboyevo, 2002). Modeling of plastic hardening for cyclic steel components is done by considering the theoretical combination of hardening present in ABAQUS.

The evolution of the nonlinear kinematic hardening component is derived from the expression:

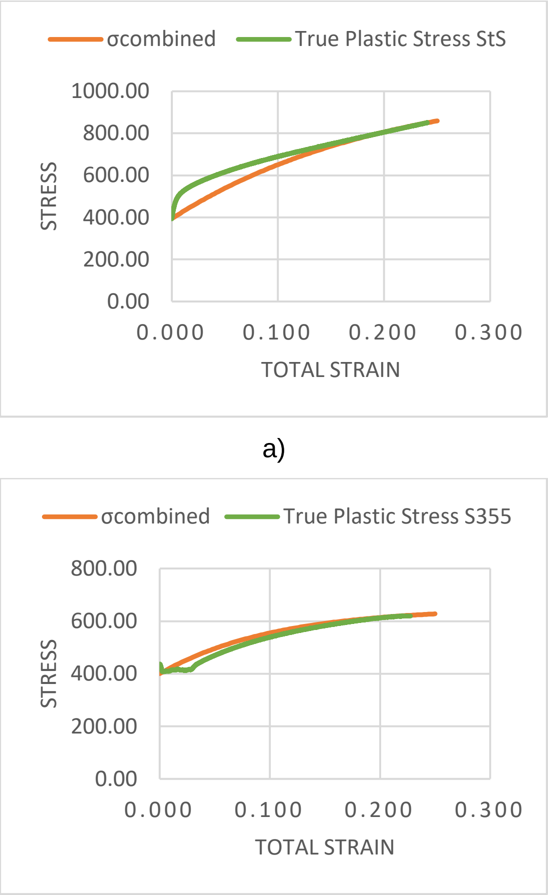
$$\bar{\alpha}_\imath = C \times \overline{\varepsilon^p} \times \frac{1}{f_y} \times (\bar{\sigma} - \bar{\alpha}) - \gamma \times \bar{\alpha} \times \overline{\varepsilon^p} + \overline{\alpha_{\imath-1}} \qquad (5.3)$$

Where, C and γ are kinematic hardening parameters, $\bar{\alpha}$ is equivalent back stress and $\bar{\sigma}$ is equivalent stress or Von Mises stress.

The nonlinear combined isotropic, for this case, and kinematic stress tensor, in the case of a tensile load test, is given by:

$$\bar{\sigma} = f_y + \bar{\alpha} \tag{5.4}$$

Therefore, the values calibrated in Excel for box 23 are as follows:



a)

b)

Fig. 5.2: Plastic range calibration: (a) pin StS, (b) plate S355.

After the device is calibrated, the load history is entered to run the simulation.

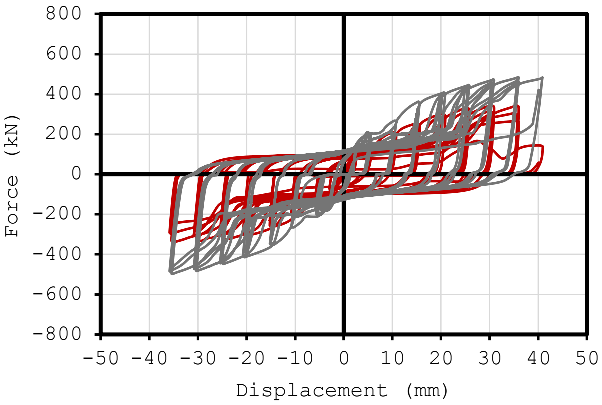


Fig. 5.3: First simulation of box 23 (gray) overlaid on the experimental (red).

In fact, as figure 5.3 shows, the numerical values are higher than the experimental ones because the damage criteria are not set and thus the pin in ABAQUS only plasticizes and does not break.

5.1. Damage Criteria

The most common type of failure in steel is ductile, except under certain conditions, such as low temperatures, that it can be brittle. This failure mechanism is presented itself in yield stress softening and elastic stiffness degradation (Figure 5.4) and is defined using a damage evolution law.

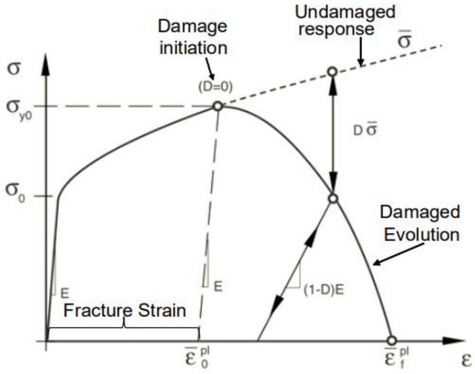


Fig. 5.4: Stress-strain curve with progressive damage degradation (Cabrita, 2020).

When using ABAQUS, the modelling of damage is divided into two steps, the damage initiation criteria (D=0) and the damage evolution (D=1) (DASSAULT, 2014). The damage initiation criteria are defined by the fracture strain value, which corresponds to the plastic strain equivalent to the true plastic strain at damage initiation, $\bar{\varepsilon}_0^{pl}$. The fracture strain is related to the strain at the onset of damage, which corresponds to the ultimate strain, $\sigma_{y0} = \sigma_u$. Once the damage onset criterion is reached, the stress tensor in the material follows the damage evolution law, resulting in an increasing loss of element stiffness and can be adjusted to remove the element from the mesh when the failure point is reached.

$$\sigma = (1 - D) \times \bar{\sigma} \tag{5.5}$$

Where, D is the damage parameter and $\bar{\sigma}$ is the undamaged stress tensor.

The fracture energy is obtained through the expression (5.7) (Hillerborg, 1978).

$$G_f = \int_{\bar{\varepsilon}_0^{pl}}^{\bar{\varepsilon}_f^{pl}} L \times \sigma \, \mathrm{d}\bar{\varepsilon}^{pl} = \int_0^{\bar{u}_f^{pl}} \sigma \, \mathrm{d}\bar{u}^{pl} \tag{5.6}$$

Where, L is the characteristic length of the element determined by the cube root of the volume of the initial geometry.

This variable is introduced in the formulation to reduce the mesh dependence, so the stress-strain relationship no longer accurately represents the behavior of the material, it is defined as an equivalent plastic displacement. (Levanger, 2012). In this case, the energy dissipated during the damage process is specified per area unit, not per volume unit. Since the pin is the only element that breaks it is only to it that this damage criterion applies. So, to perform the box 23 the fracture strain is 0.22 and the fracture energy is 6800 N/mm, these values are based on previous simulations (Al-Khazraji et al., 2017).

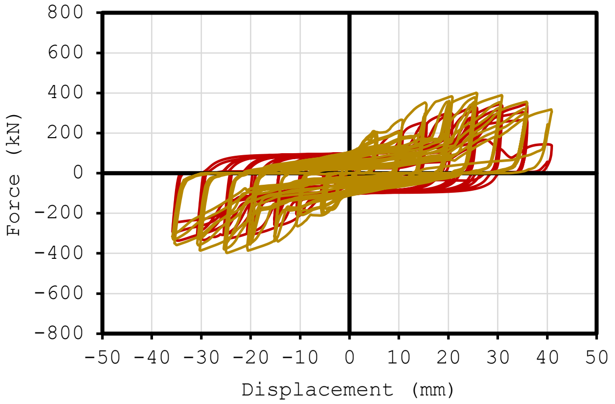
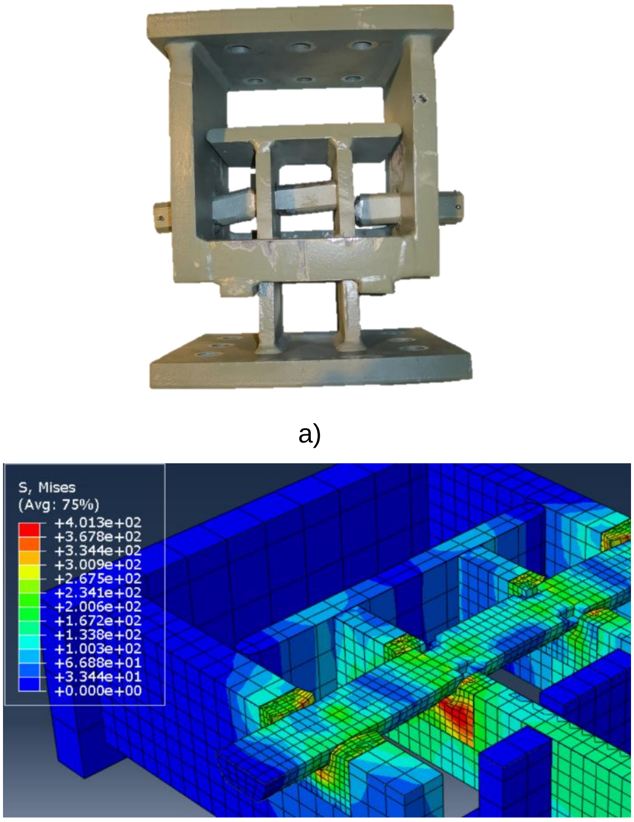


Fig. 5.5: Second simulation of box 23 (golden) overlaid on the experimental (red).

In the following figure both experimental and numerical pin breakages are the same. In both situations the pin reached failure by shear.



a)

b)

Fig. 5.6: Pin breakage: experimental (a) numerical (b).

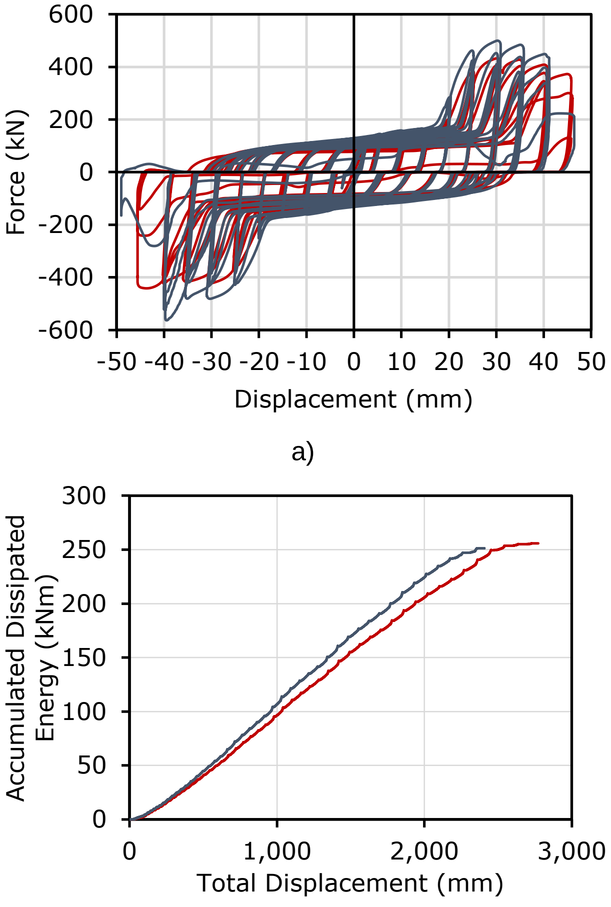
6. Reusable boxes

Not being part of the DISSIPABLE project, 4 boxes were reused to understand the behavior during and after a second test. The choice of the 4 boxes was only due to the final state of the first tests, measuring the ovalizations suffered by the respective pin. This measurement was made using a digital ruler and a ring pliers.

For these tests it was necessary to produce 4 pins. These pins were made at LERM with steel type like S235.

Box 23 was not selected for this analysis but box 25 which is similar. In the following figures parametric analyses of the reused boxes are presented.

- D1vsD2 with reused boxes:

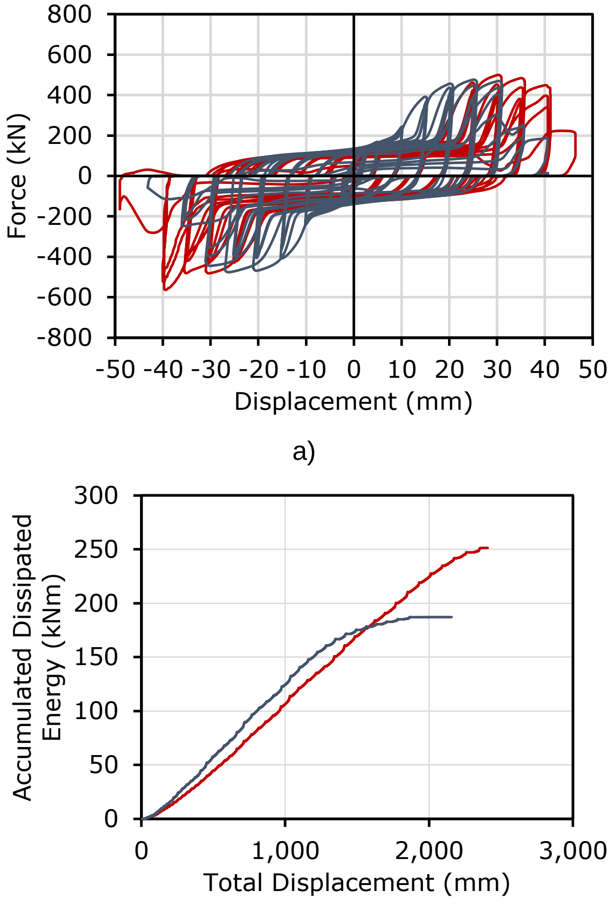


a)

b)

Fig. 6.1: Comparisons between S235*_S355_D1 (red-box 11R) with S235*_S355_D2 (dark blue-box 25R): Force-Displacement curve (a), Accumulated energy dissipated curve (b).

- S355vsHSS with reused boxes:



a)

b)

Fig. 6.2: Comparisons between S235*_S355_D2 (red-box 25R) with S235*_HSS_D2 (dark blue-box 20R): Force-Displacement curve (a), Accumulated energy dissipated curve (b).

7. Conclusions and future developments

7.1. Conclusions

This manuscrit does not conclude which is the perfect combination to dissipate energy from seismic actions, moreover a real earthquake was not simulated since this is characterized by strong and sudden movements, and in the laboratory the movements were the opposite, i.e., smooth and low speed/acceleration to understand in detail the hysteretic behavior of the various DRBrC configurations tested. However, all tests were successfully performed without any measurement problems.

At parametric level having 20 devices in which half have D1 and half D2, there was no distance that stood out the other. Such is the case when comparing the pins steel type, where there are 12 StS and the rest S235, none of them was "better" than the other. Geographically, the countries and areas more prone to eliminar earthquakes are coastal areas, such as Portugal, Japan, Italy, USA, Mexico, Greece, among others and therefore possibly the StS pin is the most recommended, which also has tensile strength to be higher than the S235 pin. Regarding the boxes those show different values, being 14 HSS boxes and 6 S355 that on the parametric analysis, reflects more points in favor of the less resistant box that ovalizes more but makes the pin, the essential element to capture the energy released from the earthquake, more ductile.

Another important result to point out is the fact that 1/3 of the tests had failure mode via shear and not by bending as would have been expected. This failure is not favourable for pin replacement, which is one of the major projects aims on the economic level. That means, to find a device that resists well to a seismic event and is not damaged too much to reuse in a future earthquake, but to be replaced with a new pin. This failure mode did not happen in a specific type of pin, type of box or distance between interior plates in which one could conclude that this event is due to a combination of several characteristics. However, with the same number of devices, more such failures occurred in D2 than in D1.

ABAQUS is not stochastic but deterministic, and so the pins results were always presented with shear failure due to the imposed settings. While in the lab the ruptures happened somewhat randomly, ABAQUS does not give such results, but these are nonetheless coherent. Otherwise, the simulations showed similar values with the real ones. Pinching phenomena were not fully captured by the numerical models. Convergence of the finite element solution was not the focus, so the models presented still have room for improvement regarding their efficiency and material properties can be further improved considering that the isotropic hardening component was not applied. A combined hardening characterization could not be performed accurately because cyclic tensile tests to characterize the cyclic behavior of the steel materials were not possible.

Finally, 4 new tests were performed, in the laboratory, on reused boxes with pins manufactured in LERM's workshops with characteristics similar to an S235. A priori it would be expected that the reused boxes would be HSS because they resist more and therefore deform less. Eventually there were 2 HSS boxes and 2 S355 boxes, which leads to the conclusion that the S355 boxes do not deform much more than the HSS ones, and therefore are also a great final solution. The results of these tests show that the boxes are much less effective the second time they are used.

7.2. Future developments

As said before, the modeling of the devices using ABAQUS can be much improved in terms of the material properties, because in these simulations were used approximate and generalist values, and the meshing, especially at the pin, and in the material damage characterization.

In practice tests are taking place on a seismic table at the National Technical University of Athens (NTUA), tests that more closely simulate a seismic action in such a way that this type of dissipative device solutions can be included in later versions of EC8 to develop design rules and behavior coefficients (*q*).

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