Assessment of hysteretic dissipative devices to improve the seismic behaviour of steel-concrete composite structures

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ABSTRACT

Composite steel-concrete structures subjected to strong earthquakes should be able to dissipate large amounts of energy. Conventional energy dissipation systems rely on the inelastic deformation of the main structural elements. This leads to long interruption of functionality of the building, assuming that the repair work is feasible and not too expensive. The project DISSIPABLE is currently developing an innovative, low-cost and easily-replaceable dissipative device, to absorb the seismic energy, leaving the main structure undamaged. In this work, a numerical model is developed that accurately simulates the behaviour of such devices. Based on experimental tests, a numerical methodology is developed and calibrated, by optimizing the simulation approach, the material model, the contact model, the geometry definition and the damage criteria. Using the Abaqus/Implicit software, finite element quasi-static simulations were performed to evaluate the hysteretic response of several devices and compare them with the corresponding experimental results. For validation of the numerical model, INERD devices are used. To enhance the plastic response of the constituent materials, a methodology was also developed to calculate approximate parameters of a cyclic combined hardening type of material. A damage criteria was implemented in the model, successfully simulating material degradation through the opening of a crack. To circumvent the complexity of this strategy, a simplified criteria was studied that is able to predict the failure cycle through the accumulation of plastic strains, with an error lower than 2 cycles. Finally, parametric analysis of the model suggests an improved behaviour using high strength steel on the plates, and a higher distance between the internal plates.

Keywords: Finite elements analysis; Hysteretic damper; Damage criteria; Material modelling; Replaceable devices; Pin fuse

1 INTRODUCTION

In the event of a strong earthquake, large amounts of energy are transmitted to structures. Depending on the capacity of the structure to dissipate this energy, the damage can range from mild to the total destruction of the structure. To reduce the loss of life and the ruin of structures due to seismic events, new and improved methods have been studied, especially in the last decades. Depending on the type of building, different design strategies can be used, with careful attention in the development of the structural project [1,2]. Although these strategies and methods increase the seismic resistance behaviour of a structure, these are not usually enough to prevent extensive damage during strong earthquakes. This damage may be so severe that post-earthquake serviceability cannot be maintained and replacement of the structure is necessary. Even if the damage is modest, the structure may be required to be taken out of service while inspection and repairs are undertaken. In the end, for structures where the inactive time should be minimum, structural control systems should be employed. These are an alternative seismic energy dissipation approach that can be achieved using separate non-load bearing supplementary damping systems [3]. This ensures continued post-earthquake serviceability by keeping the primary gravity load-bearing structure behaving elastically.

The European project “DISSIPABLE” (“Fully Dissipative and Easily Repairable devices for resilient buildings with composite steel-concrete structures”) has the objective to develop innovative low-cost, dissipative and easily replaceable structural control devices. Thereby, promoting buildings with an improved economy and feasibility resiliency, in a post-disaster situation. One of those devices is a metallic yield damper called DRD1 “Dissipative Replaceable Device no 1”, composed by a chamfered pin fuse that is introduced in the ends of the diagonal braces (Figure 1) of a composite steel-concrete building. In order to meet the specified objectives of the DRD1 study proposal, several parametric studies of this device are necessary. To effectively perform this task, a numerical finite element model was developed, which was calibrated using information from devices tested in a laboratory. An experimental program was performed in eight different physical models and the respective material coupons tensile tests [4]. This solution is an evolution of a previous research project that developed the INERD device between 2001 and 2004 [5]. This device was constituted only by the four lateral plates and the pin (rectangular and chamfered).

The aim of this work is, therefore, to understand the behaviour of the DRD1 and create a numerical model capable of reproducing it, using the software *Abaqus*. To achieve this task, the experimental data available will be used to calibrate and validate such model.

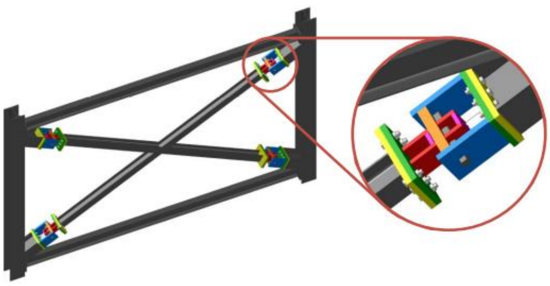

Figure 1 - Location of implementation of the device in a frame [6].

2 METHODS

The methodology will follow a cyclic type of analysis due to the extensive number of parameters needed to calibrate such numerical model. Using the force-displacement curves from the experimental tests, each parameter was calibrated so that it would achieve close results for several DRD1. The only values that are intrinsic to each test, are the geometry of each device (Figure 2) and the load history to which each device was subjected. Besides, it was necessary to choose the simulation method to evaluate hysteretic behaviour, develop a material modulation, define the contact definition and implement a damage criteria to the model. A numerical model has already been developed within the scope of the INERD project [7] and then extended to some of the DRD1 [8]. However, these methods did not have a damage criteria and the material model lead to significant errors.

With the purpose of developing a robust model that could be easily applied to different devices, quasi-static finite element analyses are used [9]. The software *Abaqus/Implicit* is used to define the model and to solve it through an implicit process. After implementing the geometry of the correspondent device it was discretised using 3-dimensional C3D8R elements with 8 integration points and reduced integration. As most of the stresses will be generated in the contact between the pin and the plates, those regions are meshed more tightly (around 5 mm) than the rest of the devices (Figure 3). In the boundary conditions definition, the base plate connected to the external plates was fixed and the other end was allowed the movement perpendicularly to the pin, alongside the lateral plates.

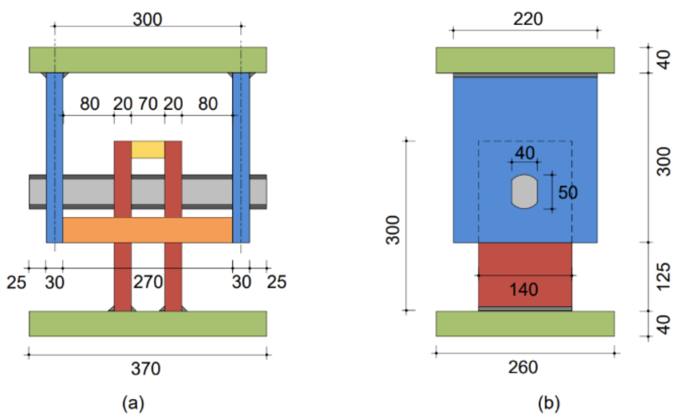

Figure 2 - DRD1 first campaign geometry: (a) top view and (b) side view, dimensions in mm.

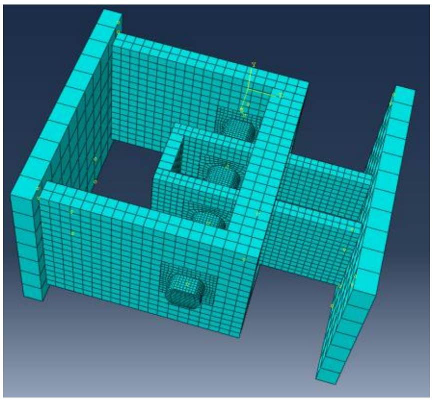

Figure 3 - Mesh dimensions of a generic example that achieve accurate results.

To correctly replicate the experimental tests, it was necessary to use the exact load history applied experimentally, so using the cyclic displacement applied in each experimental test, an array was created for each test. The maximum and the minimum displacements of each cycle was implemented with a linear development between them. This load history was then applied to the movable end of the device. Each cycle was represented in one step on the simulation, with four notorious positions: X.0 is the start of the cycle; X.25 is where the maximum displacement is applied in one direction; X.5 when it returns to the initial position; X.75 the maximum displacement to the other direction.

The type of contact used in these simulations was the *surface-to-surface contact* [9]. All the surfaces that might come into contact were defined individually using finite sliding. The friction coefficient was calibrated to 0.05. Regarding the pressure-overclosure, the *hard contact* formulation was used to minimize the penetration between two surfaces, otherwise, large amounts of energy were mitigated from these models.

In order to achieve accurate results, a methodology was created to assess the true material parameters of the stress-strain relationship that constitute the hysteretic devices. The material modulation includes an initial elastic range (Poisson's Modulus = 0.3 and Young Modulus = 210 GPa), followed by a plastic hardening phase. Although there is an extensive research on the conversion of engineering tensile curves to true tensile curves, none takes into account a combined hardening in the material definition, following the equations from Lemaitre and Chaboche [10]. These define the plastic range through 2 variables: C_1 and γ_1. Using *Abaqus/Implicit* the geometry and boundary conditions of the tensile tests were implemented (Figure 4), then the variables that defined the plasticity of the material were change until the stress-strain relationship from the numerical tensile tests were similar to the experimental results. After calibrating the necessary types of material, these were used in the material model of the DRD1 simulations.

Figure 4 - Photo of the 15PIN235 pin before the test (left); geometry and boundary conditions of the corresponding numerical model in *Abaqus*.

With the objective of implementing a damage criteria in the model, two approaches were studied, the *Maxpe damage* and the *Ductile damage* [9]. The first simulates the opening of a crack in the material and was defined with damage initiation and a damage evolution to control the opening and the propagation, respectively. The second was implemented only with damage initiation, which does not add degradation in the material but was found to generally assess, with low error, the failure cycle of these types of devices.

3 RESULTS

In the DRD1 devices, there are two different types of material: the plate material and the pin material. The main concern to assess a close approximation to the real stress-strain relationship was to accurately capture the necking effect. Using the tensile tests information and the correspondent numerical model, it was observed that better behaviours were obtained when the plastic definition followed the initial logarithmic conversion [11] (up until the experimental maximum stress) and reach a higher ultimate stresses (Figure 5). Using such a material model applied in the numerical tensile test, the result stress-strain relationship is close to the curve of the experimental test (Figure 6). This methodology yielded good results for different types of steel material, using their correspondent tensile test. It is important to refer that this initial study does not take into account failure, only the elastic and plastic response of the materials. The calibrated material values were then applied to the correspondent DRD1 constituent materials.

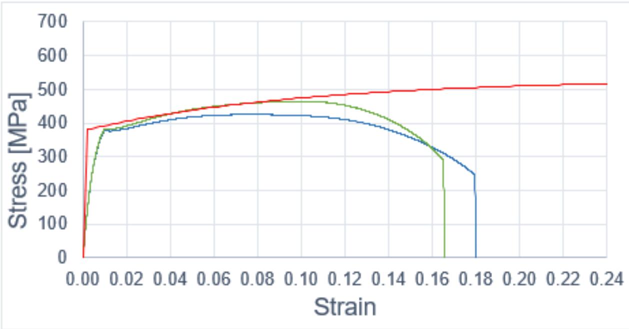

Figure 5 – Calibrates true stress-strain relationship of the pin material (orange), the engineering curve (blue) and the logarithmic curve (green) of the experimental test.

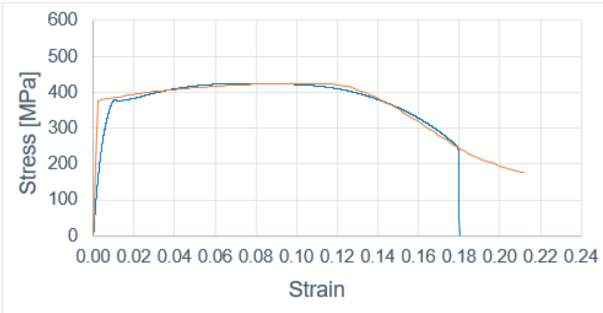

Figure 6 - Numerical response of the pin material with the stress-strain relationship of figure 5 (orange) compared with the respective engineering curve (blue).

In the calibration of the DRD1 model, three experimental tests were used. These have the same dimensions but were subjected to different cyclic loads, without the implementation of any type of damage criteria. The average time that the solver takes to reach a solution is around 7 hours per simulation. The first was tested using the ECCS load standards [12] and the comparison between the experimental force-displacement curves with the numerical curves are shown in Figure 7a. The second and third test were subjected to constant displacements and the comparison is represented in Figure 7b and 7c, respectively. The three numerical results are the product of the same model subjected to different load cases. In other words, the devices had similar geometries and were tested with different cyclic loads, as in the simulations.

Assessing the results, a close behaviour to the real curves was captured, using the developed numerical model. Some phenomenons were not captured by this model, such as the stiffness degradation in the unloading of each cycle. However, most of the other numerical evaluation parameters were quite positive, such as the maximum stress reached in each cycle, the stiffness in the loading range and the overall similarity between curves. The dissipated energy of both numerical and experimental tests and their correspondent percentual difference are shown in Table 1. Although the error is considerable, especially in the third device, it was observed that the inability to accurately predict the unloading range is responsible for around 5% of the total error. It is worth noticing that the higher error was obtained in the third device, mainly due to a more spaced influence, throughout the cycles, that material degradation has on this test. The same numerical model was applied to three experimental tests on three different devices of the INERD project (first - c50_eccs, second - c70_eccs and third - r70_eccs) [5]. These tests were subjected to similar ECCS standard loads but had different geometric properties(1 - chamfered pin and 50 mm between internal plates; 2 - chamfered pin and 70 mm between internal plates; 3 - rectangular pin and 70 mm between internal plates;). The results achieved identical agreement between curves as the DRD1 simulations.

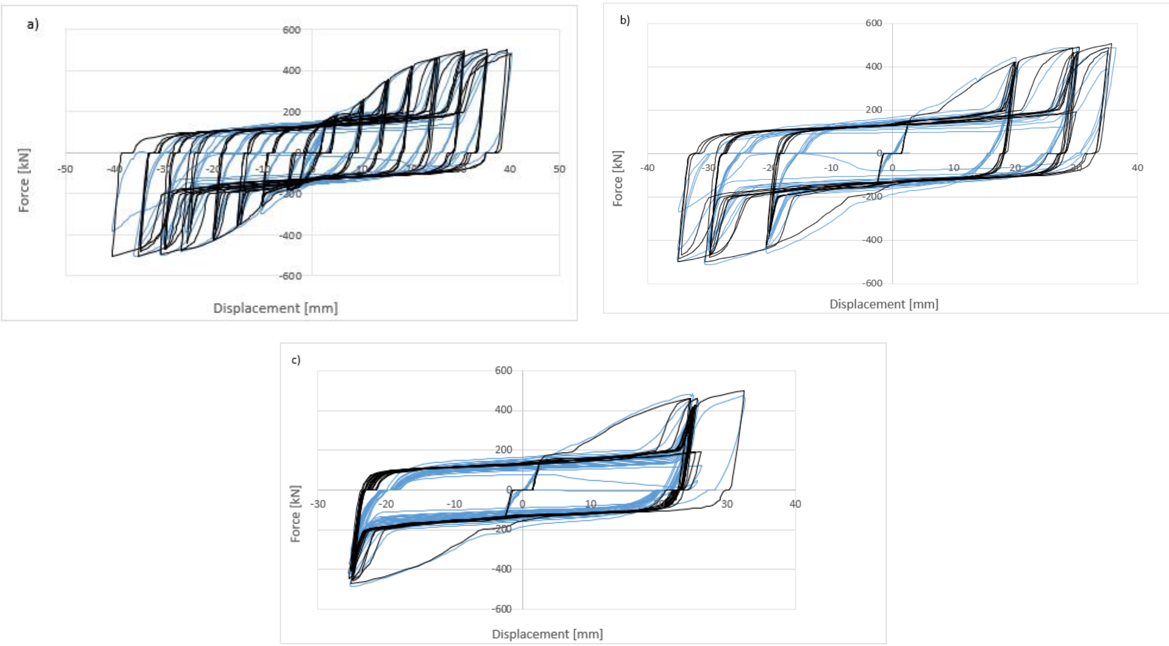

Figure 7 - Comparison of hysteretic curves between experimental test (blue) and numerical model (black), of the first (a), second (b) and third (c) DRD1.

Table 1 - Energy dissipated and percentual difference of each numerical simulation with its corresponding experimental test.

	First Device [kNm] | [%]		Second Device [kNm] | [%]		Third Device [kNm] | [%]	
Numerical model (Energy dissipated | Percentual difference)	241.1	9.8	210.5	10.6	243.0	16.4
Experimental test (Energy dissipated)	218.5		189.2		206.1	

With the objective of implementing damage criteria, the *Maxpe damage* was introduced in the numerical pin material definition, of the first device model. This was achieved using information from the pin tensile test, such as the strain at maximum stress and the area from that strain until failure (fracture energy). Figure 8 (left) represents the influence of this definition in the hysteretic curves and the right side of the same figure, the crack that is created in the pin is displayed. This definition proved to be accurate since the total failure of the simulation happened in the exact cycle as the experimental test. Unfortunately, the complex definition of this damage criteria and the longer solving time (more than 3 times the normal), made the calibration of such criteria difficult to execute. So, in order to develop a lighter and simpler model for use in the screening of future devices, the *ductile damage* function was explored.

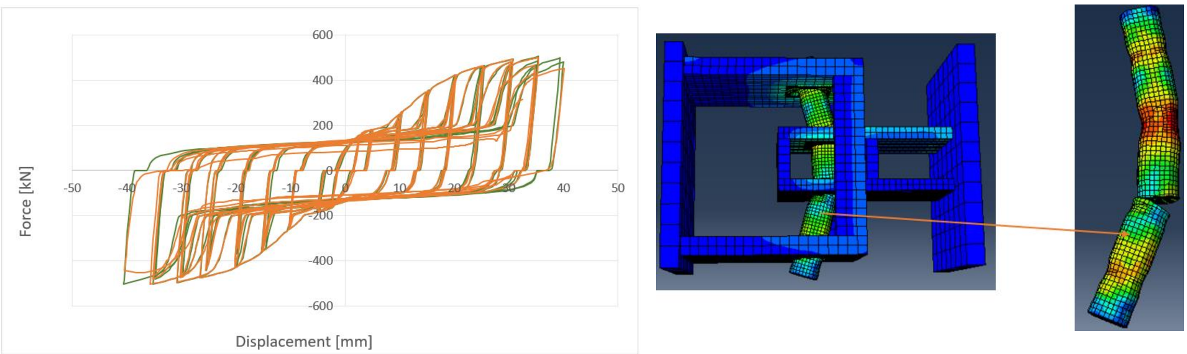

Figure 8 – Left: Comparison between the numerical results of the first device with (orange) and without the damage implemented (green); Right: State of the device at the end of the simulation upon total fracture of the pin.

Using *ductile damage,* the implementation of damage degradation was not possible due to the characteristics of the solver. Nevertheless, it allowed the assessment of the number of cycles that could be performed before failure. So using only the equivalent plastic strain (PEEQ) as the parameter that indicates the end of the simulation, it was calibrated to a value of 5.833. Then, applied to the six devices studied, the accuracy of this method was evaluated, comparing the difference of cycles achieved between the simulation and the experimental test.

Table 2 – The number of cycles performed in the experimental test, the number of cycles achieved in the simulation using the calibrated value of PEEQ, the difference between them and the error percentage

Number of cycles achieved	DRD1 – first device	DRD1 – second device	DRD1 – third device	INERD 1	INERD 2	INERD 3
Experimental	25.25	18.75	22.25	24.50	25.00	20.50
Numerical	25.43	19.62	20.65	23.60	24.40	24,00
Difference	0.18 (0.7%)	0.87 (4.6%)	1.60 (7.2%)	0.90 (3.6%)	0.60 (2.4%)	3.50 (17%)

Regarding the simulations of the devices from DISSIPABLE, this simplified method proved to be very efficient, although the third device had a larger discrepancy (due to its sparse degradation through a larger number of cycles). Considering the results for the devices from INERD, two preliminary conclusions can be drawn. Firstly, as this function uses a strain variable, it can be applied directly to devices with different types of material. Secondly, the shape of the pin influences the precision of this method (the INERD 3 test was the only that had a significative error - this device has a rectangular pin while the other five were constituted by chamfered pins).

4 CONCLUSIONS AND FUTURE WORK

The objective of this work was to develop a numerical model that could simulate the hysteretic behaviour of the innovative low-cost, dissipative and easily replaceable structural control devices developed by the DISSIPABLE project.

The material calibration methodology proved to be quite efficient to define the true variables required on a *combined hardening* formulation when only the engineering curve is available. With the first step of numerically simulating the experimental tensile tests, the parameters calculated could be directly implemented in other simulations such as the DRD1 and the INERD.

Using experimental tests with a wide variety of load cases, different boundary conditions and geometries, it was concluded that the numerical model could obtain accurate hysteretic curves regardless of those conditions.

For the implementation of a damage criterion, it was identified a possible way to implement such behaviour. The *Maxpe* formulation proved to be capable of achieving such a task but, unfortunately, this method was difficult to calibrate. Not being able to reach a unique set of values that could attain satisfactory results for different devices with different conditions, another method was developed. This method, that relies on the concentration of plastic strains was capable of achieving an acceptable prediction on the number of cycles that each device could withstand, even though it does not implement degradation on the material. This technique was successful for every device with a chamfered pin. However, it had poorer performance in a specimen with a rectangular pin, indicating that it probably depends on the geometry of the pin.

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