Experimental investigation of composite moment resisting frames equipped with dissipative replaceable beam splices

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Abstract: This work presents the main outcomes of an experimental hybrid test campaign performed by UNITN, in the framework of the European funded Dissipable project. The testing specimen is a composite frame equipped with easily replaceable dissipative seismic components, called DRBeS. Such components are realized by truncating the composite beam close to the beam-column joint and re-establishing the continuity by means of web and flange plates, that constitute the fuse elements. First, the hybrid test procedure is presented, along with the practical issues encountered while performing such tests and the adopted methods for solving them. After this, the experimental results related to the Near Collapse limit state test are presented and discussed. The frame was capable to overcome the NC ground motion and the connections showed a wide hysteretic behaviour. Finally, the algorithmic correction is quantified for the three tests performed on the frame; it revealed to be negligible as the intensity of the input ground motion increases.

Keywords: composite frames, dissipative components, repairability, hybrid simulations, pseudodynamic method

1. Introduction

For decades, capacity design has been the main design strategy in structural engineering, becoming the base of many design codes all over the world. Such technique revealed to be beneficial in avoiding brittle structural failure, but also to lead to consistent structural damage in the case of a seismic event. Because of this, capacity designed buildings can avoid catastrophic collapses, but still need to be demolished and replaced after the occurrence of an earthquake. In this perspective, effort has been made among the structural engineering community in order to develop new design strategies for providing the possibility to repair a structure after a consistent damage introduced by an earthquake, see Kanyilmaz et al. (2019), Valente et al. (2016 and 2017). In the context of repairability, the RFCS-Dissipable project aimed to test real steel structures endowed with ad-hoc components. These are designed to permit a consistent and stable dissipation of energy through hysteresis, and to be replaceable after incurring yielding due to seismic action. Within the Dissipable project, the contribution of UNITN consisted in an experimental campaign, where five full-scale steel and composite frames were tested by means of the hybrid simulation technique. This paper is devoted to i) report the main experimental outcomes of the hybrid tests performed on a composite frame equipped with dissipative replaceable beam splices

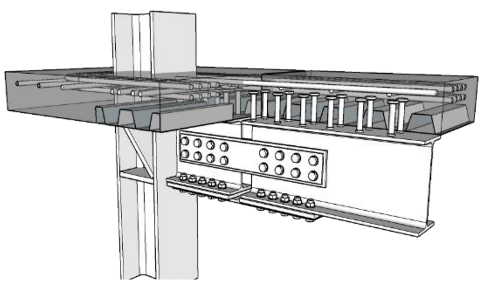


Figure 1 - DRBeS connection

(DRBeS) connection, represented in Figure 1, and ii) underline the main experimental issues faced within the hybrid tests campaign.

2. Hybrid test procedure and practical issues

With the aim to investigate the seismic response of the plane DRBeS frame and in particular of its dissipative components, a series of hybrid tests at different limit states were carried out in increasing order of intensity. Three tests at different levels of seismic intensity were performed, namely Damage Limitation (DL), Significant Damage (SD) and Near Collapse (NC) limit states. The tests were performed in increasing order of intensity, and between SD and NC test, the connections were replaced. The frame specimen was tested by means of heterogeneous (numerical/physical) simulation based on the dynamic sub-structuring technique, which was deeply studied in a previous work (Andreotti et al. (2020)). The physical substructure (PS) was experimentally tested, whilst the numerical substructure (NS) was numerically simulated. The tests were conducted by means of a partitioned G-α algorithm, described by Abbiati et al. (2019), based on the finite element tearing and interconnecting (FETI) method (Fahrat et al. (1991)). The spatial domain is partitioned into two totally disconnected subdomains and Lagrange multipliers are employed to guarantee compatibility at the interface DOFs. The method consists in solving separately the subdomains and imposing the continuity constrain on the interface boundary at each step of the simulation. The tests performed were hybrid pseudo-dynamic tests, therefore, to avoid the effect of the structure inertia, a testing time scale λ is introduced to expand the test duration. The restoring force is algorithmically calculated for the numerical subdomain and obtained as feedback from the actuators for the physical one. The latter was initially corrected as described by Bursi and Shing (1996), in order to mitigate the effects of displacement control errors in pseudo-dynamic tests, as:

$$R_{n+1}^{P} = R_{n+1}^{FBK} + K_P \cdot (Y_{n+1}^{P} - Y_{FBK}^{P}) \quad (1)$$

in which R_{n+1}^{P} is the algorithmic force acting on the physical subdomain, R_{n+1}^{FBK} is the actuator force feedback, K_P is the stiffness matrix, Y_{n+1}^{P} denotes the displacement computed by the algorithm, and Y_{FBK}^{P} represent experimental feedback displacement from the actuators. After preliminary testing the frame, considerable discrepancies were found between the actuators feedback and the algorithmic solution. Hence deeper analyses on the algorithmic correction, herein briefly exposed, were required. Since the floor is considered as a rigid diaphragm in the reference FEM model, lateral beams were placed at the floor level to impose the same displacement at each column and to avoid the application of a significant axial force to the beams and the connections. In addition, two beams with high axial stiffness were placed at the level of the higher actuator to impose the same displacement at the top of each column, see Figure 2. At both levels, the connection between the axially rigid beams and the structural elements was realized by means of hinges consisting of three plates, through which a pin is inserted. Such hinges were employed, rather than a fixed joint, to avoid any residual bending moment that would increase the real stiffness of the original frame. Nevertheless, due to the absence of clearance between the pin and the hole, it was necessary to lathe all the pins in order to assemble the hinges, causing the formation


Figure 2 - Experimental frame specimen

of a gap between the pin and the plate. With the intention of decreasing such gap, the pins were welded to the external plates. To consider the source of error introduced by the gap, auxiliary displacement transducers were installed on the opposite frame side to the actuators on an external ground-fixed frame (visible on the right side in Figure 3), in order to measure the absolute displacements of the right column. Hence, a correction of the physical feedback force was introduced for accounting the discrepancies between the displacement imposed by the actuators and the displacement on the opposite side of the frame. The overall correction of the physical feedback force reads

$$R_{n+1}^{P} = R_{n+1}^{FBK} + K_P \cdot \left(Y_{n+1}^{P} - \frac{Y_{FBK}^{P} + Y_{AUX}^{P}}{2} \right) \tag{2}$$

where Y_{AUX}^{P} is the displacement feedback of the auxiliary transducers. The second term in Eq. (2) is the algorithmic force correction, which is proportional to the difference between the algorithmic displacement and the mean displacement of the columns.

3. Test configuration and setup

A schematic representation of the hybrid test simulation is depicted in Figure 3. The 1st floor of the frame constitutes the physical substructure, while the remaining floors are included in the numerical substructure. The physical part, built in the laboratory, is composed of three columns and two composite beams, at the ends of which the dissipative DRBeS components are located. Moreover, half of the second floor was also included in the physical substructure in order to control the translational degree of freedom able to impose bending moment at the floor level of the column. These horizontal displacements were imposed by means of a lower and upper actuator, namely MOOG1 and MOOG3.

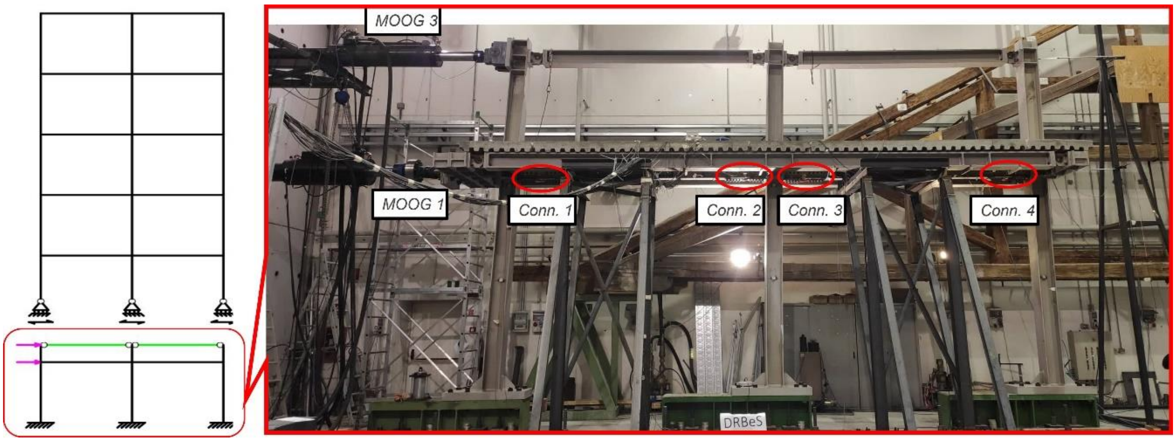


Figure 3 - DRBeS Hybrid Test Configuration

Three dissipative components were instrumented with strain gauges applied to the reinforcement bars for detecting any possible yielding. Moreover, as illustrated in Figure 4, three sections of each composite beam were instrumented with strain gauges for measuring the strain of the concrete slab upper edge and the lower part of the steel beam and estimate then the related curvature. For the steel beam, the strain gauge was located on the web rather than the flange to avoid the influence of shear-lag effects. The bending moment on each instrumented section could then be estimated. Such bending moment values, in the elastic region of the beam, were then linearly interpolated for evaluating the bending moment at the DRBeS cross sections. In order to measure the rotation of the connections, two displacement transducers were placed at the level of the concrete slab upper edge and of the lower steel flange.

a)

b)

c)

d)

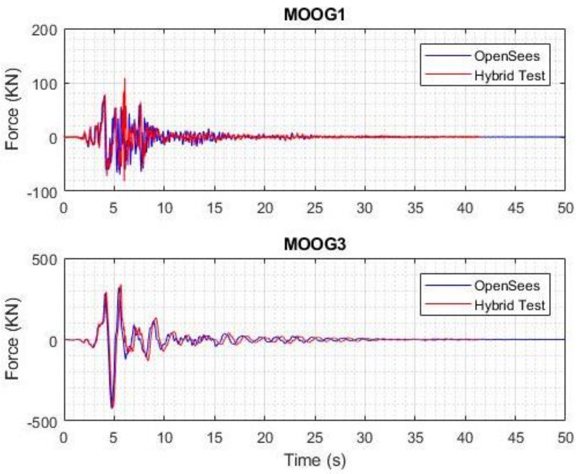
Figure 4 - Strain gauges employed for concrete a) and for steel b), displacement transducers employed for concrete c) and for steel d)

Nonetheless, an important point to investigate is whether the column base undergoes plastic deformations under the seismic load. With this aim, inclinometers were placed at different levels of the columns, as depicted in Figure 5. By measuring the rotations in two different sections of the column, the moment at the base of the columns could be estimated using the elastic beam theory.

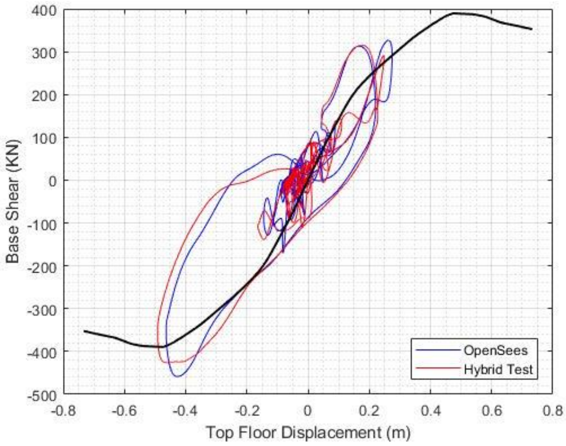
Figure 5 - Inclinometers employed for steel columns

4. Hybrid test results

In this paragraph, the results of the NC limit state test are presented. Figure 6a shows the test results as comparison between the hybrid test and the reference model, in terms of actuators algorithmic forces.



a)



b)

Figure 6 – Actuators forces as output from the hybrid test algorithm (a) , Base Shear vs. Top Floor Displacement (b)

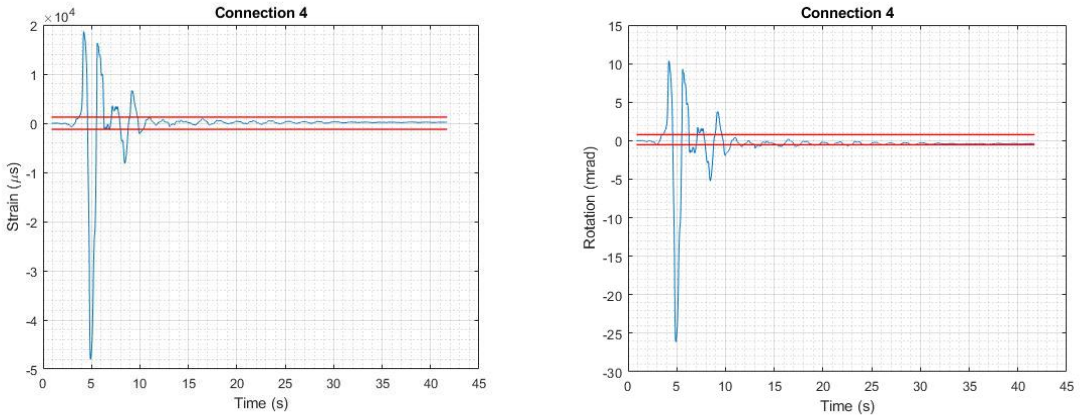
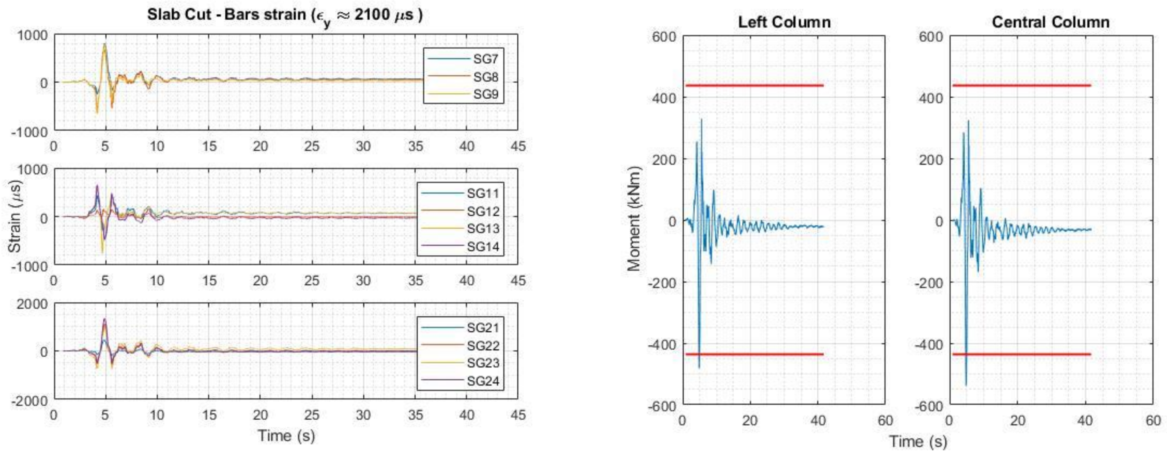


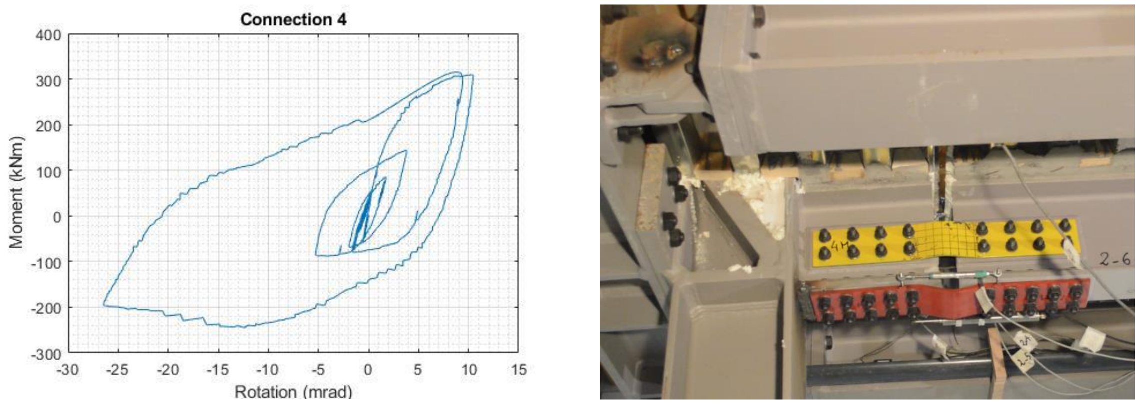
Figure 7 – Experimental flange strain (a) and rotation (b) of the DRBeS connection 4 (ε_y = 1234.3 µs

φ_y^+= 0.78 mrad – φ_y^-= 0.54 mrad)



a) b)

Figure 8 – Reinforcement bars strain for, in order, connection n. 2, 3 and 4 (a); columns bases moment histories (b)



a) b)

Figure 9 – Experimental Moment-Rotation diagram of the DRBeS connections (a) and picture of the connection during the test peak response

Figure 6b shows the comparison, in terms of Base Shear vs. Top Floor Displacement graph, between the hybrid test and the reference model. The graphs are superimposed with the reference model pushover curve too. Clearly, the structure exhibited significant inelastic behaviour; this is also confirmed by the results in terms of flange plate strain and connection rotation depicted in Figure 7, which shows how the connection deforms beyond the yielding limits both in sagging and hogging. It is worth noting that in compression the flange plate strain measurement is affected by the buckling behaviour of the plate. Figure 8a shows that the strain of the steel reinforcement bars does not exceed the yielding limit, while Figure 8b shows the bending moment at the base of the left and central column. Here, the yielding limit is only slightly exceeded for both the columns. Figure 9a shows the experimental moment-rotation diagram for connection number 4, estimated by means of instrumentation system. A wide and stable hysteretic behaviour was detected, and the connection was able to reach a total rotation of about 25 mrad. Figure 9b shows connection number 4 at the peak response, whose plates are clearly bent and plasticised.

5. Algorithm correction

As described in the previous paragraphs, the actuator force feedback was corrected to consider the effect of the gap between the pin and the supporting plates of the truss members placed at both the actuators levels. The most significant part of the response, both in terms of displacement and force, is given by actuator MOOG3, for which the force feedback correction is quantified in Figure 10, together with the difference in terms of displacements between the left and right columns of the frame. It is worth observing such quantities for each of the three tests performed, namely DL, SD and NC limit states. As shown, the displacement difference is significant with respect to the total displacement for DL test, where the gap, heavily affects the frame response, given its low magnitude. Such displacement difference becomes less important for SD test and almost negligible for NC test, which means that the gap influence is lower as the response amplitude increases. Consistently, the force feedback correction is less important for increasing magnitudes of the seismic input, meaning that, for the most severe limit state tests, a good estimation of the peak response force can be obtained even without the algorithmic correction.

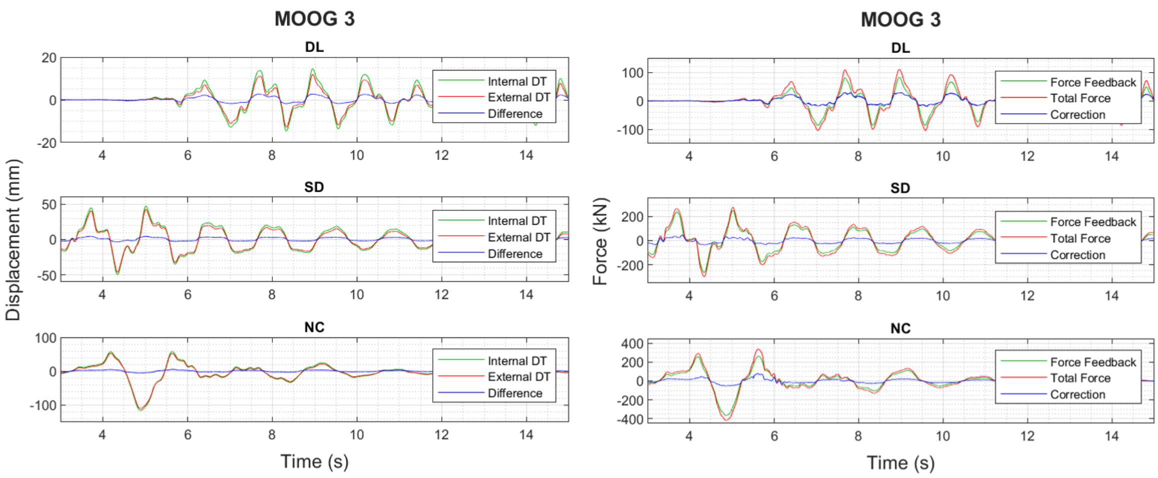


Figure 10 - Algorithm correction quantification

6. Conclusions

The hybrid tests performed on the frame endowed with the DRBeS provided a comprehensive information about its seismic behaviour. Indeed, it was possible to analyse the whole frame with a high degree of accuracy by keeping a full-scale test. The specimen was subjected to natural accelerograms and the response of the physical substructure was influenced by the presence of the five floors above, that were numerically simulated. Moreover, by dividing the frame into a physical and a numerical substructure it was possible to perform the test in the laboratory by consequently cutting the costs. At the NC limit state, the DRBeS connections experienced significant inelastic behaviour, exhibiting a wide and stable hysteretic behaviour. Despite the fact that the structure was not designed for the NC limit state, it survived the strong motion, which is a favourable outcome in terms of the structural response.

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