Experimental investigation of braced steel frames equipped with dissipative replaceable connections

Roberto Andreotti – University of Trento, Trento, Italy, roberto.andreotti@unitn.it

Giulia Giuliani – University of Trento, Trento, Italy, giulia.giuliani-1@unitn.it

Nicola Tondini – University of Trento, Trento, Italy, nicola.tondini@unitn.it

Oreste Salvatore Bursi – University of Trento, Trento, Italy, oreste.bursi@unitn.it

Abstract: This paper reports the main experimental results of a series of experimental tests performed at University of Trento by means of the hybrid simulation technique. The testing specimen is a single storey braced frame, part of a six-floors structure, endowed with DRBrC components. Such components are designed in order to protect the remaining parts of the frame, i.e. columns, beams and braces. After a brief introduction on the dissipative component, the hybrid simulation framework employed for carrying out the tests is presented. The main results of the hybrid tests are then shown for the near collapse limit state test performed on the frame endowed with mild steel components. The favourable performance of the frame and the connection are highlighted. Finally, the mild steel components and the HSS components are compared in terms axial force-displacement diagrams. The hysteretic behaviour of the connections reveals that no actual benefit could be achieved by employing HSS in fabricating DRBrC boxes.

Keywords: structural resilience, steel frames, dissipative connection, replaceability, hybrid tests

1. Introduction

Braced frames are a popular structural solution for steel buildings, especially when these rise in seismic areas. According to capacity design, such frames shall be designed to concentrate damage in the braces, which are non-necessary elements for withstanding vertical gravity loads. Thanks to this strategy, it is possible to avoid structural collapses that would be triggered from the damage of other elements, e.g. the columns. Nevertheless, it is still considerably expensive and operatively cumbersome to replace the whole bracing elements after undergoing severe damages due to earthquake events. Because of this, wide research activity has been carried out in order to provide repairability to steel buildings, by means of easily replaceable dissipative components (Kanyilmaz et al. (2019), Valente et al. (2016 and 2017)). RFCS-Dissipable, is a European funded research project, that aimed to test real steel structures equipped with such components, under the earthquake load. With respect to braced frames, a particular dissipative replaceable brace connection (DRBrC), depicted in Figure 1, was conceived for locating damage into a pin supported by plates forming a box. This element is designed to protect the remaining parts of the frame and to be replaced after the occurrence of a seismic event causing the yielding of the pin. Moreover, in order to investigate the possible benefits of composing the supporting boxes with high strength steel (HSS) plates, the same tests

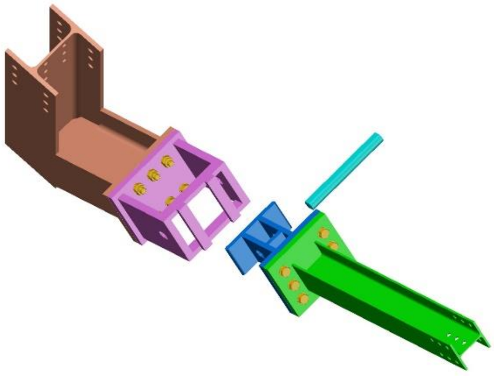


Figure 1 - DRBrC connection

were conducted both for mild steel (S355) and HSS (S460) supporting boxes, while the pin, being the fuse element, was made in steel S235 for both cases. The objective of this work is to present the main results of an experimental campaign performed by UNITN on full scale braced frames endowed with DRBrC components both with mild steel and HSS components.

2. Hybrid test framework

Within the Dissipable project, a series of experimental hybrid tests were carried out at LPMS-Trento on a steel frame endowed with DRBrC components, aiming to investigate the behaviour of both the frame and the components under the seismic loading. In particular, three tests for each steel grade of supporting boxes were performed in increasing order of intensity, according to European standards, namely Damage Limitation (DL), Significant Damage (SD) and Near Collapse (NC) limit states. The components were replaced between SD and NC tests. Given that no damage was detected in the remaining parts of the frame even after NC test, such parts were employed both for mild steel and the HSS specimens. With respect to the hybrid test methodology, the tests were conducted by means of a partitioned algorithm based on the finite element tearing and interconnecting (FETI) method (Farhat et al. (1991)). The spatial domain is partitioned into totally disconnected subdomains and Lagrange multipliers are introduced to enforce compatibility at the interface nodes. The method consists in solving separately the subdomains getting the free solutions and then imposing the continuity constrain on the interface boundary. A particular FETI algorithm, the G-α algorithm described by Abbiati et al. (2019), was employed for the tests. The pilot buildings were tested by means of heterogeneous (numerical/physical) simulation based on dynamic sub-structuring. The issues related to the sub-structuring technique were widely studied in a previous work (Giuliani et al. 2020). The physical substructure (PS) was experimentally tested by means of a hydraulic actuator, whose displacement was numerically controlled by a target PC, on which the numerical substructure (NS) was simulated. The tests performed were hybrid pseudo-dynamic tests, in which the mass contributions are numerically simulated for both PS and NS. Therefore, to avoid the effect of the structural mass inertia, a large testing time scaling factor λ was used to decrease physical velocities and accelerations.

3. Test configuration and experimental setup

A schematic representation of the hybrid test simulation is depicted in Figure 2. As shown, the testing specimen, which constituted the physical substructure (PS), was the first floor of the frame, while the remaining floors were included in the numerical substructure (NS).

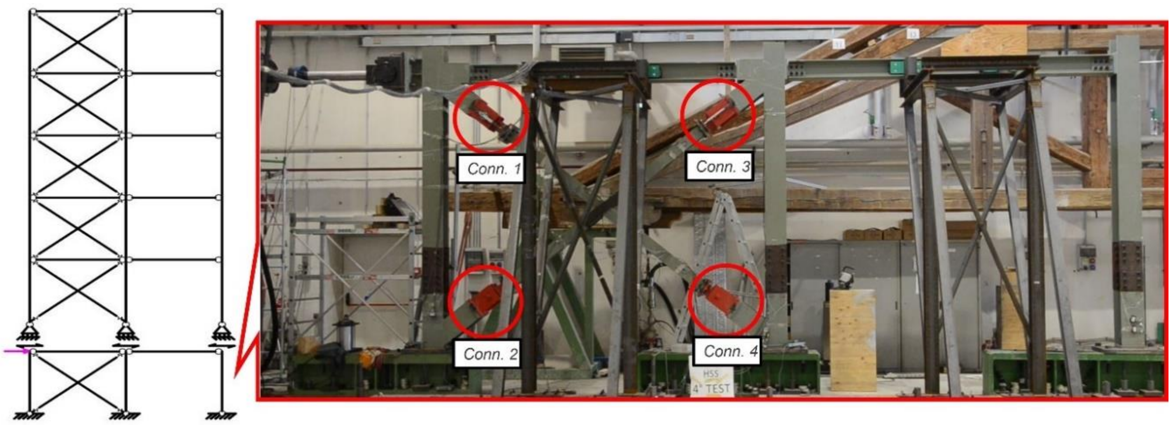
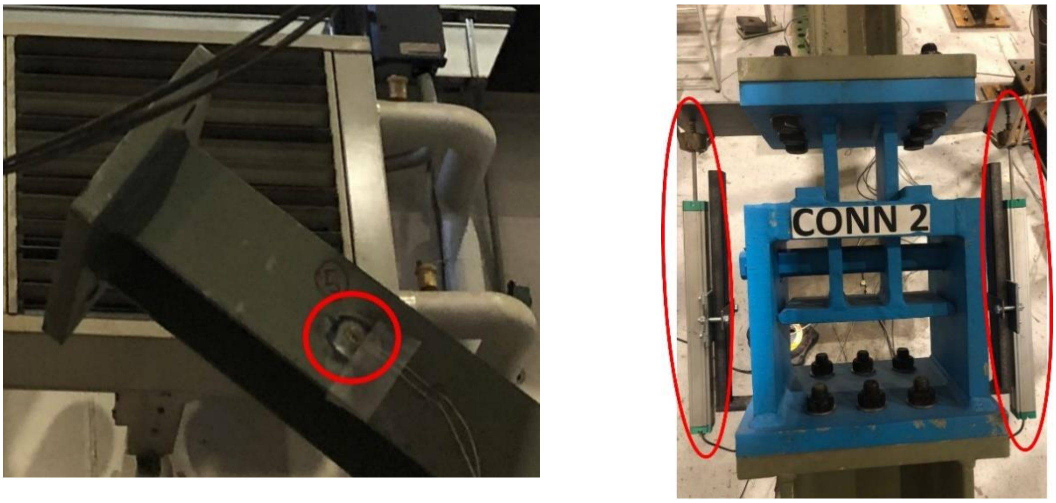


Figure 2 - Hybrid Test Configuration of DRBrC frame

The physical part is composed of three columns, two beams and two braces for the left span. The dissipative DRBrC components are located at the braces ends, as illustrated in Figure 2. The hydraulic actuator was attached to the braced span rather than the unconstrained span, for avoiding any gap in the transmission of forces to the fuses. As shown in Figure 3a, in order to measure axial forces, strain gauges were applied at the end of braces in couples, for then averaging the measurements and account for any out-of-plane deformations that could introduce non-symmetries in the strain field of the instrumented sections. Moreover, displacement transducers were also installed on both the sides of DRBrC connections, as depicted in Figure 3b.



a) b)

Figure 3 - Connections instrumentation: a) strain gauge, b) displacement transducers

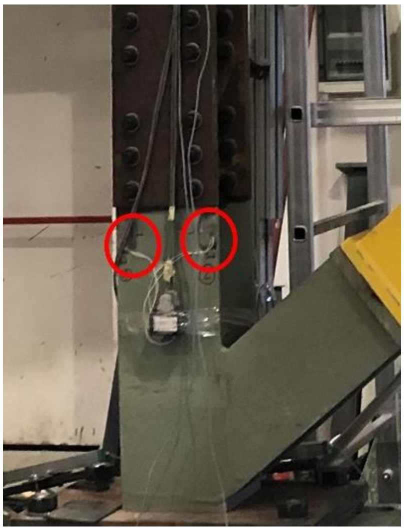


Figure 4 - Base column instrumentation: strain gauges

As for all the other connections, also the columns bases were considered as hinges in the computational model built for performing hybrid tests. Clearly, such connections have a certain degree of rotational stiffness, introduced by the bolts working in tension and the width of the column base section supported by the base plate. Here, for measuring residual bending components, two couples of strain gauges were adopted to instrument the base column sections, see Figure 4. The chord rotation was estimated as the ratio between the horizontal storey displacement and the column height, in order to evaluate the bending stiffness of the column bases. After some preliminary cyclic tests performed on the frame, the base columns bending stiffness was estimated to be 14836 kNm/rad. This stiffness value was included in both the reference model and the algorithm stiffness matrix necessary for running the hybrid tests. Furthermore, the same preliminary cyclic tests, highlighted the presence of a gap tolerance between the pin and the plates of the DRBrC components. For a consistent behaviour between the PS and NS, a gap-like constitutive law was implemented and introduced in series to the Pinching4 constitutive law (see Giuliani et al. (2020)) of all the NS connections and adopted throughout all the hybrid tests.

4. Hybrid test results

This paragraph reports the results of the NC limit state test, performed on the frame endowed with mild steel components, highlighting the comparison with the reference model built in Opensees. The suitability of the testing technique to reproduce reliable results is therefore underlined. Figure 5 show the test results in terms of force of the actuators compared with the Opensees reference model, denoting a satisfactory comparison between the two time history responses.

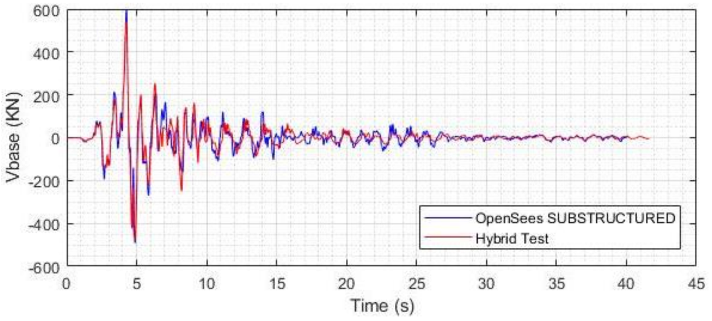
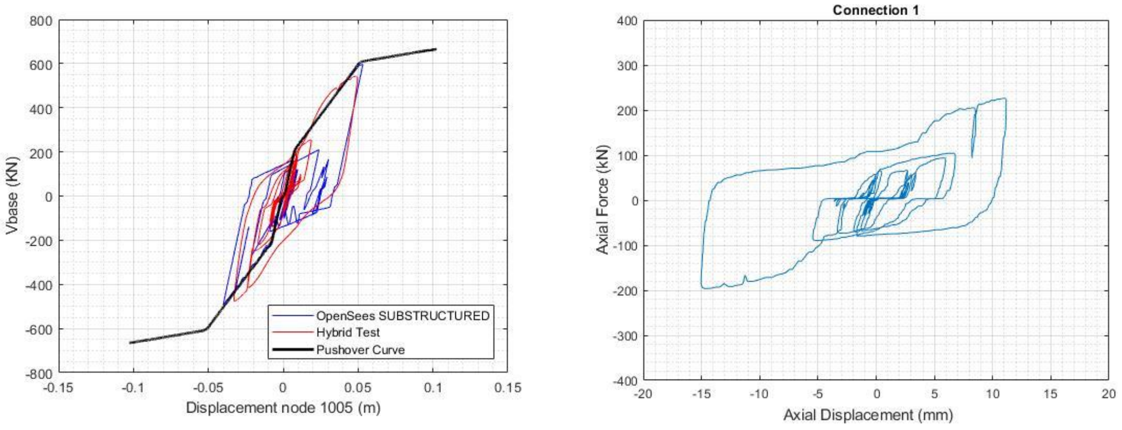


Figure 5 - Actuator displacement and force as output from the algorithm



a) b)

Figure 6 - Base shear vs. 1st floor displacement (a) and experimental axial force-displacement diagrams (b)

Figure 6a shows instead the comparison in terms of Base Shear vs. 1st Floor Displacement between the hybrid test and the OpenSees reference model. The graphs are superimposed with the pushover curve of the structure obtained from the reference model. Clearly, the yield limit is widely exceeded, approaching the third branch of the pushover curve, which highlights that the structure was subjected to large plastic deformations. Figure 6b depicts the axial force-displacement diagram of connection number 1 in the test specimen, highlighting a remarkable nonlinear behaviour and a significant dissipation capability of the DRBrC component. A significant pinching effect was detected in the hysteretic cycle of the physical DRBrC component, which is due to the ovalization of the holes and the gap clearance. Figure 7 reports the pictures of connection

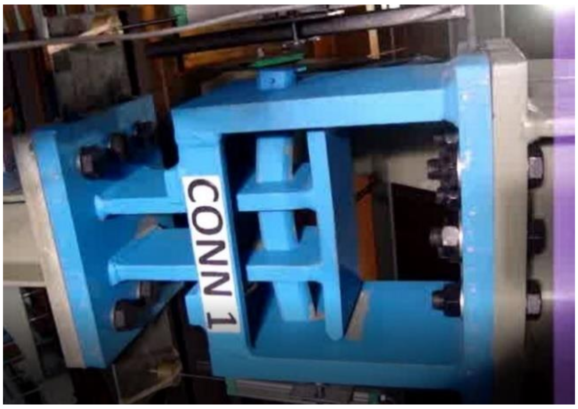


Figure 7 – Connection 1 during frame peak response

number 1 during the NC peak response of the frame. As described in the previous paragraphs, the column bases were instrumented in order to estimate the column bending moments. The related moment-rotation diagram is depicted in Figure 8, which shows a linear behaviour, highlighting that the irreplaceable parts were efficiently protected by the DRBrC fuses.

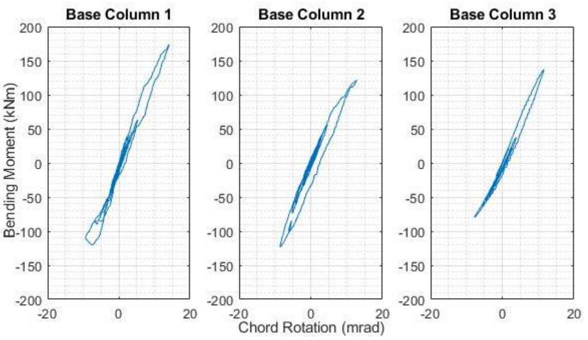


Figure 8 - Base columns Moment-Rotation diagrams (a) and node equilibrium

5. HSS Components

Within the Dissipable project, the potential benefits of employing High Strength Steel in the components fabrication was investigated. In particular, numerical analyses proved that no actual benefit can be given by realizing the pin with a high tensile strength, since it constitutes the dissipative element. Therefore, the box plates are chosen to be composed of HSS, to evaluate the possible benefits obtained from the reduction of the hole bearing and ovalization, as the reduction of the pinching effect in the hysteretic behavior of the DRBrC components. Nevertheless, such benefits were not observed in the hybrid tests performed by UNITN. For the test campaign, a steel grade S460 was employed for the box plates. Same accelerograms of the DRBrC mild steel tests were adopted in order to obtain a consistent comparison of the experimental tests outcomes. Note that the same numerical model was used for both the mild and HSS cases and the same periods were obtained for the two structures. Moreover, the same test configuration of the mild steel frame tests was employed for the HSS frame tests. Figure 9 shows the comparison between mild steel and HSS DRBrC connection number 1 in terms of axial force-displacement diagrams, obtained from the NC tests. Note that, each component had a different gap value owing to the tolerance between the hole and the pin, which is considered to be the main reason for the difference in the axial force-displacement diagrams between the two types of connection. As a conclusion, at least for the ground motion intensities examined in this experimental campaign, no significant improvements or differences are found in the behaviour of DRBrC HSS components with respect to DRBrC mild steel components.

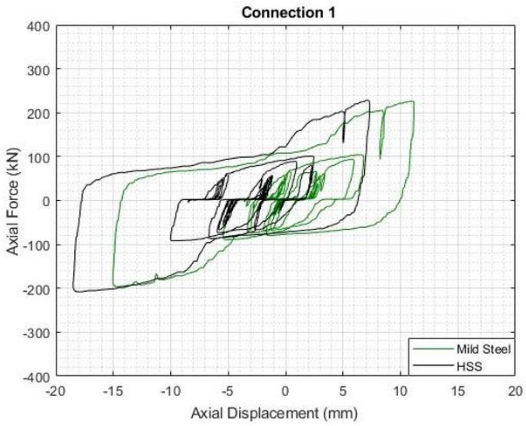


Figure 9 - Superposition of Mild Steel and HSS DRBrC axial Force-Displacement diagrams

6. Conclusions

The pseudodynamic hybrid tests performed on the frame equipped with DRBrC components provided a comprehensive and detailed information on its nonlinear behaviour under earthquake loads. The nonlinear behaviour under natural earthquake accelerograms was tested and it was possible to analyse the entire frame including the five floors above in the numerical substructure, while keeping the physical substructure in full-scale. Preliminary cyclic tests highlighted the existence of a gap between the hole and the pin in the DRBrC component, that increased the pinching effect in the hysteretic behaviour. Nevertheless, a large and stable hysteretic capability of the DRBrC component was noticed for the NC tests.

The irreplaceable members of the frame did not experience damage and this was an important outcome of the tests. Indeed, damage was instead confined into the dissipative replaceable connections. Particular attention was given to the column bases that did not exhibit plastic deformation even at NC limit state test. Finally, at least for the ground motion intensities examined in this experimental campaign, no significant improvements or differences were found in the structural performance of HSS DRBrC components with respect to DRBrC mild steel components.

Acknowledgements

This project has received funding from the Research Fund for Coal and Steel under grant agreement No 800699 - DISSIPABLE. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or Research Fund for Coal and Steel. Neither the European Union nor the Research Fund for Coal and Steel can be held responsible for them.

References

- Kanyilmaz A, Muhaxheri M, Castiglioni C A, (2019). Influence of repairable bolted dissipative beam splices (structural fuses) on reducing the seismic vulnerability of steel-concrete composite frames. Soil Dynamics and Earthquake Engineering, Volume 119, 2019, Pages 281-298, ISSN 0267-7261, https://doi.org/10.1016/j.soildyn.2019.01.007
- Valente M, Castiglioni C A, Kanylmaz A, (2016). Dissipative devices for earthquake resistant composite steel structures: bolted versus welded solution, Bull Earthq Eng, 14 (12) (2016), pp. 3613-3639, doi: https://doi.org/10.1007/s10518-016-0002-9
- Valente M, Castiglioni C A, Kanyilmaz A (2017). Numerical investigations of repairable dissipative bolted fuses for earthquake resistant composite steel frames, Eng Struct, 131 (2017), pp. 275-292, DOI: https://doi.org/10.1016/j.engstruct.2016.11.004
- Abbiati G, Lanese I, Cazzador E, Bursi O S, Pavese A (2019). A computational framework for fast-time hybrid simulation based on partitioned time integration and state-space modelling. Structural Control and Health Monitorning. DOI: 10.1002/stc.2419.
- Farhat C, Roux F X (1991). A method of finite element tearing and interconnecting and its parallel solution algorithm. Numerical Methods in Engineering, 32(6):1205-1227.
- Oreste S. Bursi, Pui-Shum B. Shing (1996). Evaluation of some implicit time-stepping algorithms for pseudodynamic tests. Earthquake Engineering and Structural Dynamics, 25(1): 333-355.
- Giuliani G, Andreotti R, Tondini N, Bursi O S (2020). Experimental Analysis of steel frames protected with easily repairable dissipative seismic devices. XI International Conference on Structural Dynamics (EURODYN 2020).