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REPARABILITY ASSESSMENT OF A LARGE-SCALE STEEL STRUCTURE EQUIPPED WITH FRICTION-BASED DISSIPATIVE BRACES AND SELF-CENTRING COLUMN BASES

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Abstract

Over the last few decades, increasing research efforts have been devoted to the development of innovative seismic resilient design strategies to reduce both direct and indirect seismic losses. Among others, the use of dissipative braces in steel Concentrically Braced Frames (CBFs) has proven to be an effective solution for achieving high stiffness, strength, and energy dissipation capacity. These braces typically consist of an elastic brace paired with a dissipative device, which can be either displacement- or velocity-dependent. Friction Devices (FDs) represent a common type of displacement-dependent device, characterised by an almost perfectly plastic behaviour and minimal structural damage. However, while their energy dissipation capabilities are valuable, their low hardening response can impair the structure's ability to self-centre after a seismic event, potentially leaving residual drifts that complicate repair and affect seismic resilience. To address these challenges, recent research has demonstrated how the use of such devices, combined with Self-Centring Column Bases (SC-CBs), can be beneficial for reducing residual drift and enhancing reparability. Despite their potential benefits, the application of these systems in steel CBFs has received limited attention. To address this gap, an experimental campaign was conducted on a large-scale, two-story steel structure integrating dissipative braces with FDs and SC-CBs. A series of pseudo-dynamic tests were performed at varying intensity levels, and after each test, repairs were carried out by simply loosening the bolts of the FDs in the braces. This paper presents the design of the test specimen, the experimental programme, and preliminary findings, which highlight the effectiveness of SC-CB connections in minimizing residual drifts, protecting first-story columns from damage, and improving the system's reparability.

Keywords: Experimental tests, Concentrically Braced Steel Frames, Friction Devices, Self-Centring Column bases, Reparability.

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1 INTRODUCTION

Steel Concentrically Braced Frames (CBFs) are among the most widely used seismic-resistant systems in building structures, thanks to their high strength, stiffness, and effectiveness in withstanding the seismic actions. Compared to Moment Resisting Frames (MRFs), CBFs generally allow more rigid configurations, resulting in structures that are less prone to second-order effects and more easily compliant with damage limitation requirements. However, CBFs also present some challenges, primarily due to their limited ductility and energy dissipation capacity, which can be compromised by brace buckling under cyclic loading. For these structures, the traditional 'capacity design' philosophy implemented in modern seismic codes (*e.g.,* [1]-[2]) ensures the achievement of the target ductility through the controlled damage of braces and their connections [3]-[7]. However, although this strategy ensures meeting the life safety requirements, it may entail the occurrence of irreparable damage to specific structural components (*e.g.,* diagonal in tension/compression [8]). Indeed, recent destructive seismic events [9] have highlighted significant damage in braced frames, which consequently led to widespread structural demolitions/reconstructions with high direct (*e.g.,* repairs) and indirect (*e.g.,* business interruption) losses, thus posing significant economic and social challenges.

To address these challenges, in the last decades, several research works have been developed in the field of replaceable dissipative components to be introduced in braced frames such as Friction Devices (FDs) (*e.g.,* [10]-[13]), metallic dampers (*e.g.,* [14]-[16]), and viscous dampers (*e.g.,* [17]-[18]). Within these systems, dampers absorb seismic energy, preventing or mitigating damage while also enhancing the ductility of the structural system [19]. However, despite their valuable energy dissipation capabilities, these devices can impair a structure's ability to self-centre after a seismic event, potentially resulting in residual drifts that complicate repairs and reduce long-term resilience. To overcome this drawback, extensive research has been devoted to combine energy-dissipative devices with high-strength Post-Tensioned (PT) steel bars or strands, promoting the self-centring capability of the structural system (*e.g.,* [20]-[25]).

In this direction, the authors have recently highlighted the significant advantages of implementing innovative structural solutions for Self-Centring Column Bases (SC-CBs) ([26]-[31]) to minimize post-earthquake residual drifts in steel MRFs and, more importantly, to improve their reparability. In this context, experimental studies have demonstrated that the use of SC-CBs facilitates the restoration of a damaged structure's original seismic performance ([32]) through quick and effective repair methods. However, despite the potential benefits of SC-CBs, their application in steel CBFs has still received limited attention. Furthermore, while progress has been made in the field of reparability, there remains a gap in comprehensive research on system-level performance recovery for repaired structures, mainly due to the limited availability of suitable repair techniques and the uncertainty regarding the long-term performance of repaired systems.

To further advance research in this area, an experimental campaign was conducted on a large-scale, two-story steel structure equipped with CBFs integrating braces with FDs and SC-CBs. The experimental programme was carried out at the University of Salerno using the Pseudo-Dynamic (PsD) procedure [33]. Several PsD tests were performed at different intensity levels, and, at the end of each test, the structure was 'repaired' by loosening and retightening the bolts of the FDs. The present paper shows the specimen's design, the test programme, the set-up and instrumentation, and two of the tests performed with and without the contribution of the PT bars of the SC-CBs, to assess their influence on the overall structure's resilience and reparability. The results confirmed the crucial role of PT bars in facilitating self-centring behaviour and the effectiveness of the repair methodology in successfully minimizing or eliminating residual drifts.

2 DESIGN OF THE TEST SPECIMEN

The specimen for the PsD tests is illustrated in Figure 1(a). It consists of a two-storey steel structure equipped with two longitudinal CBFs conceived to withstand the seismic actions and two transversal bracing that prevent undesired accidental torsional and/or out-of-plane effects. The interstorey height is 2.40 m at both storeys, and the longitudinal and transversal bays have spans equal to 4 m and 2 m, respectively. The specimen has been extracted from a prototype structure scaled based on the material and acceleration scaling identity, with a scaling factor equal to $\lambda = 0.6$. The design is performed following the Eurocode 8 provisions [1]. The design earthquake at the Ultimate Limit State (ULS) is defined considering the Type 1 elastic response spectrum with a PGA = 0.35g and soil type B. The behaviour factor is assumed equal to q = 4, following the requirements of the Eurocode 8 [1] for frames with diagonal concentric bracings. The inter-storey drift limit for the Damage Limit State (DLS) is assumed to be 1% [1]. The floor system is a HI BOND A55/P600 steel-concrete composite floor with a total height of 110 mm. The diagonal brace consists of a steel Square Hollow Section (SHS) profile with cross-sectional dimensions of 140×140×12.5 mm. The brace is equipped with a FD whose geometry and connection detailing are illustrated in Figure 1(b). The FD comprises a central slotted plate made of AISI 304 steel, welded to the SHS, and two cover plates which are bolted to the central plate with four HV M16 bolts of Class 10.9. The friction pads, consisting of steel plates coated with a thermally welded material, are between the central slotted plate and the cover plates. The friction coefficient μ is assumed equal to 0.45 and according to the design, the slippage forces of the FDs at the first and second stories are 123 kN and 78.5 kN, respectively. It is highlighted that the elastic brace is properly overdesigned with respect to these forces to avoid yielding and/or buckling. Successively, beams and columns are designed to meet the requirements defined by Eurocode 8 provisions [1]. The selected profiles are IPE 270 for beams and HE 200B for columns with 355JR nominal steel grade. The column base connection considered in this work is the SC-CB experimentally tested in previous experimental works [28][31], and it is shown in Figure 1(c). It consists of a rocking column splice joint where the FDs are realised including friction pads with the same material used for the braces' FDs, pre-stressed with high-strength pre-loadable bolts on both web and flanges. High-strength PT bars with disk springs are symmetrically placed and connected to anchorage plates welded to the column to increase the axial force and control the rocking behaviour. The design methodology of the SC-CB is based on a step-by-step procedure, and the moment-rotation behaviour can be easily obtained by simple analytical equations.

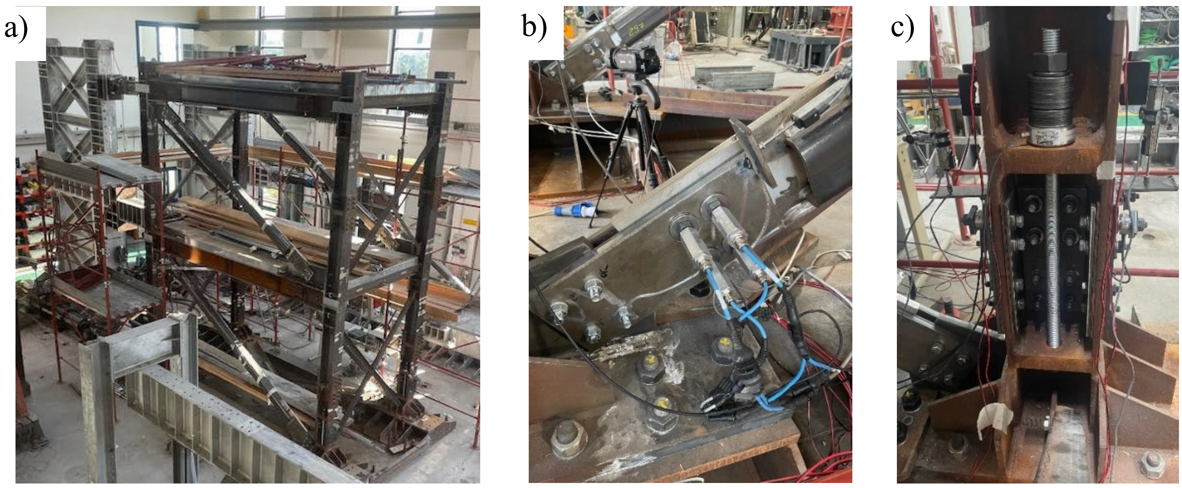

Figure 1: Large-Scale Test Specimen: a) Test Specimen; b) Brace with FDs; (b) SC-CB connection.

3 TEST SET-UP, INSTRUMENTATION AND TEST MATRIX

The test set-up and instrumentation are illustrated in Figure 2. To apply the horizontal loads, two actuators were connected at the structure's first and second levels. Wire transducers were used to measure the floor displacements and to control the floors' translations in the two main directions and were used to check for possible deck rotations. The local response of the FDs of the braces was monitored using LVDT to assess the displacements. Strain gauges were applied to the columns' top and bottom sections to check the bending moments at the columns' ends and to define the bending moments at the connection level using the nodal equilibrium. The local response of the SC-CB connections was monitored using LVDTs to measure the vertical displacements in both column sides to assess the rotations. Load cells were installed in the SC-CB connection to monitor the forces in the PT bars. Additionally, advanced sensors (*i.e.,* https://tokbo.it) were used to monitor the force variation throughout the test in all bolts belonging to the FDs of the braces.

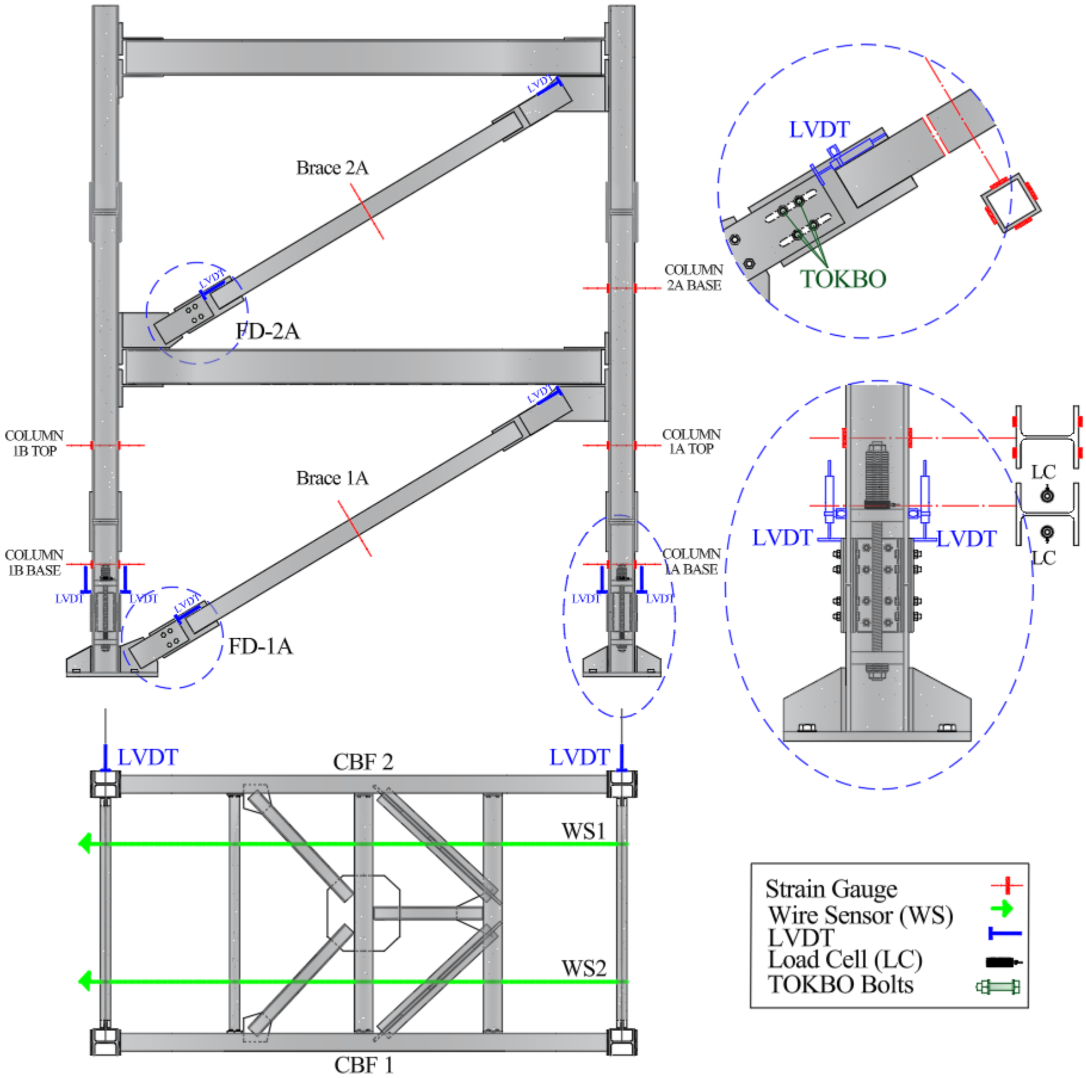

Figure 2: Set-up and instrumentation of the test

The test matrix consisted of several PsD [33] tests, using an algorithm based on the central difference method. Three different seismic inputs were selected from a set of 30 natural ground motion records based on spectrum compatibility with the Eurocode 8 [1] design spectrum. The sequence of ground motions was then scaled at different seismic intensities corresponding to the design spectrum [1] including DLS, ULS, 1.4ULS and 1.6ULS. Several zero acceleration points were added to the end of each record to allow the free vibrations to stop and correctly capture the residual displacements. In this paper, results are reported for a single ground motion (*i.e.,* Test 5, Imperial Valley accelerogram scaled at 1.4ULS).

4 RESULTS

The structure has been subjected to the entire test sequence and ground motion intensities without significant residual drifts after each test. For the sake of brevity, in this paper, global and local results are reported in detail for a single ground motion record (*i.e.,* Test 5, Imperial Valley accelerogram scaled at 1.4DBE). Figure 3(a) and (b) illustrate the global response of the tested structure in terms of displacement time history and Interstorey Drifts (IDR). The residual IDRs are compared with the limit of 0.5% [34], which is conventionally assumed as a permissible residual drift to ensure the building's repairability. In addition, the limit of 0.2% is also considered, which is the FEMA P58-1 [35] limit value, to ensure that no structural realignment is necessary. For the ground motion record considered, the residual displacements were approximately 8.67 mm at the first storey and 14.21 mm at the second storey, corresponding to residual IDRs of 0.36% and 0.23%, respectively. These values are below the 0.5% reparability threshold; however, additional repair operations were performed to further reduce the residual drifts and restore the structure to its original state. In addition, Figure 3(c) and (d) show the interstorey drifts and the base shear histories for the same ground motion. It is possible to observe that the peak floor displacements and the peak actuator forces occurred at the same instants, in agreement with the expected response, for the regularity of the structure and the predominance of the first vibration mode. Regarding the local results, the FDs of the braces experienced stable and wide moment-rotation curves, while the SC-CB exhibited a flag-shaped hysteretic curve.

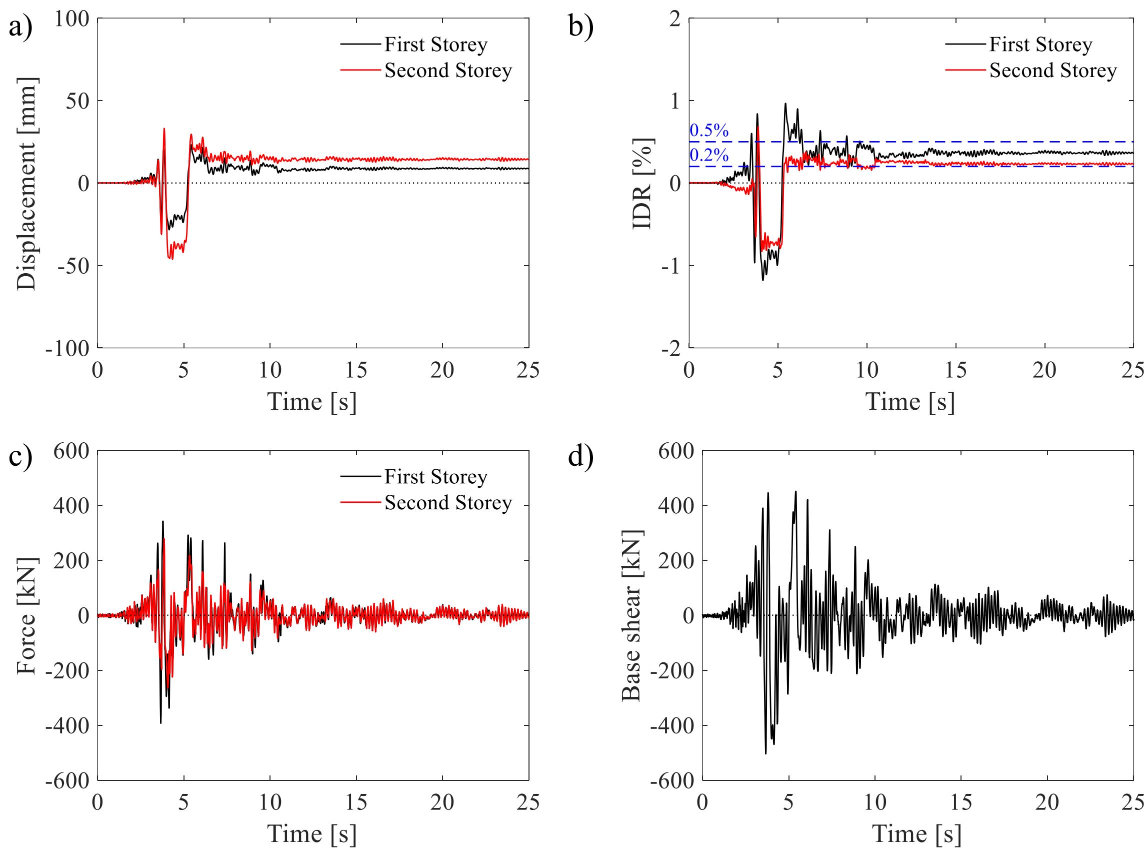

Figure 3: Global results for Test 5 (*i.e.,* Imperial Valley scaled at 1.4DBE)

5 REPARABILITY

To assess the resilience and reparability of the system, two tests were performed applying the same ground motion record (*i.e.,* Hyogo scaled at 1.6DBE) and with and without the contribution of the PT bars at the CBs. Figure 5 shows the comparison between Test 7 (*i.e.,* with the contribution of the PT bars) and Test 9 (*i.e.,* without the contribution of the PT bars) in terms of IDRs histories for the first storey. The comparison between the two curves highlights the crucial role of the PT bars in significantly reducing the residual interstorey drifts for both stories. In addition, the structure with PT bars experiences residual interstorey drifts lower than the 0.5% limit threshold [34], which is not satisfied for the structure without the contribution of the PT bars. Conversely, no significant differences can be observed by comparing the peak response between these two tests.

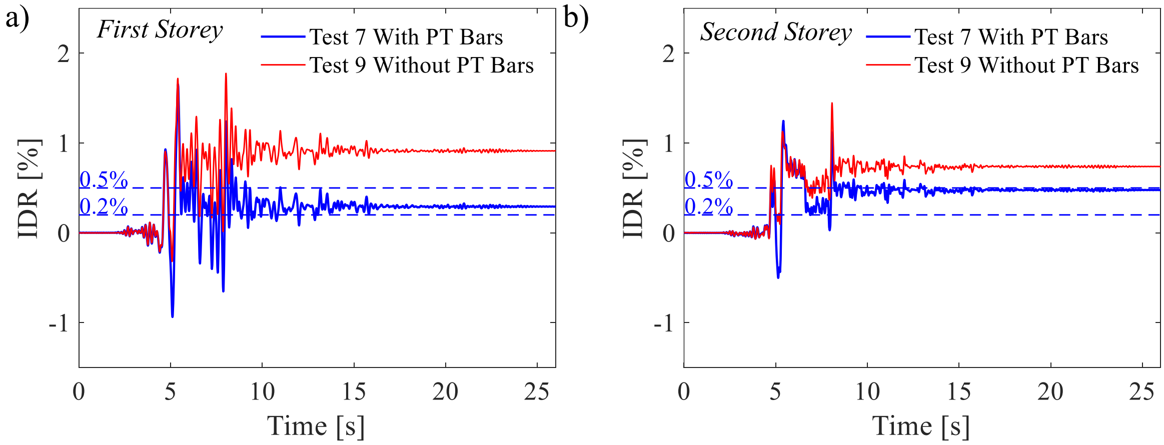

Figure 4: Global results for Test 7 (i.e., Hyogo scaled at 1.6DBE) with PT Bars and for Test 9 (i.e., Hyogo scaled at 1.6DBE) without PT Bars: a) First Storey; b) Second Storey

At the end of each test, all the high-strength pre-loadable bolts in the FDs of the braces were loosened, as illustrated in Figure 5. The loosening process was carried out in two stages: *i)* loosening the bolts in the FD elements of the first storey, and *ii)* loosening the bolts in the FD elements of the second storey. All bolts were loosened with a torque wrench, and the entire operation took approximately 15 minutes with two people working simultaneously. The goal was to evaluate the reduction in residual drift during the repair process and to assess the system-level performance recovery, while also investigating the restoration of the structure to its initial configuration (*i.e.,* before the test). After the loosening process, the bolts were re-tightened to obtain the predefined preloading force.

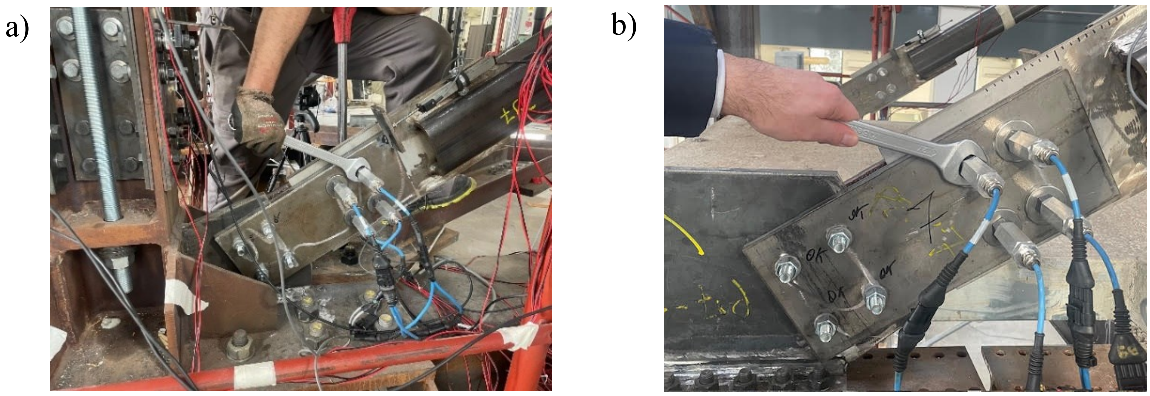

Figure 5: FDs bolts' loosening process for the braces of the a) Base and b) First Storey

Results are presented in Figure 6(a) and (b) for Test 5 and Test 9, respectively, showing in terms of IDRs vs. Timestep (*i.e.,* time employed to complete the whole repairing process). As it is possible to observe, in Test 5, the interstorey drifts nearly returned to zero, indicating that the repair method allowed the structure to almost return to its original position. Conversely, for Test 9 (*i.e.,* without PT bars), the interstorey drifts did not decrease as expected, even with the application of the loosening process, due to the absence of the PT bars. Similar results were obtained while investigating the reparability of a self-centring MRF in Elettore *et al.* [32].

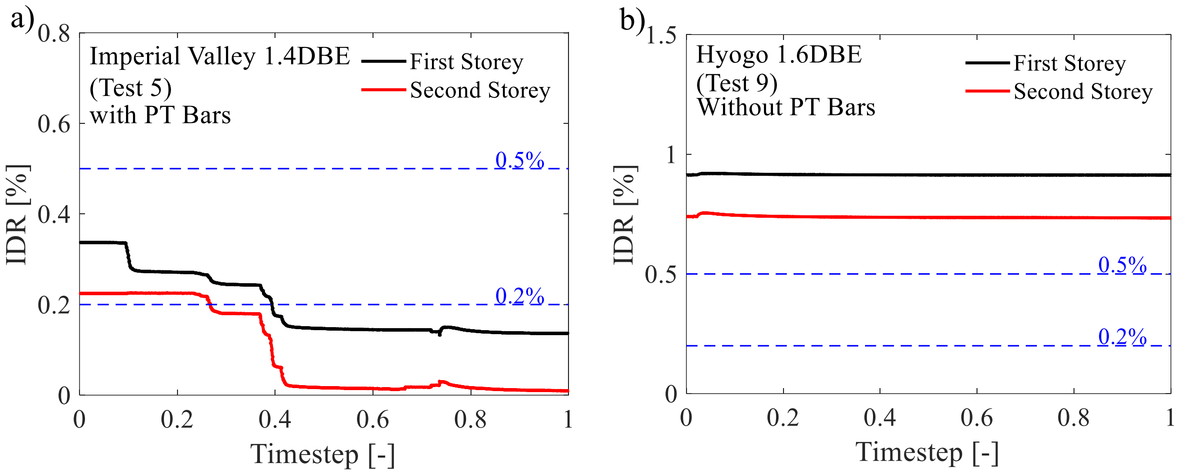

Figure 6: FDs bolts' loosening process for both storeys: a) Test 5, with PT Bars and b) Test 9, without PT bars

6 CONCLUSIONS

The present paper investigates the experimental response of a large-scale steel specimen integrating Concentrically Braced Frames (CBFs) with Friction Devices (FDs) and Self-Centring Column Base (SC-CB) connections. The experimental campaign was conducted through pseudo-dynamic tests at the STRENGTH Laboratory of the University of Salerno, Italy. The aim of the campaign was to assess the reparability benefits associated with the adoption of both types of connections, evaluating their influence on both global and local structural performance. The results demonstrated the effectiveness of the SC-CB connections in enhancing the seismic performance of the structural system. The following conclusions can be drawn: *i)* the self-centring behaviour of the SC-CB is effective in limiting the residual drifts of the structure under the reparability limit; *ii)* the integration of PT bars in the SC-CBs plays a crucial role in facilitating the structure's self-centring behaviour, significantly enhancing its ability to recover to its original configuration after seismic events; *iii)* the repair methodology, which involves loosening the FDs, proved effective in minimizing residual drifts, reducing them to nearly zero, and highlighting the structure's repairability.

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