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Resilience Assessment of a two-storey Steel Structure equipped with Innovative Connections

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Abstract

In the last few decades, increasing research efforts have been devoted to the definition of innovative seismic resilient design strategies with the aim of reducing direct and indirect losses. Among others, the use of Friction Devices (FDs) for Beam-to-Column joints (BCJs) has emerged as an effective solution to ensure the damage-free behaviour of steel Moment Resisting Frames (MRFs). Additionally, more recent research studies have revealed the benefits of replacing traditional full-strength Column Bases (CBs) with innovative CBs promoting the residual drift reduction of steel MRFs. Additionally, several research studies developed and investigated structures that could be easily repaired after an extreme event, promoting a functional recovery of the structures and able to reinstate the original seismic performance in a short time. However, experimental research on suitable structural repair techniques is still marginal and the lack of confidence in the performance of repaired structures are relevant issues contributing to the high demolition rates. In this direction, an experimental campaign has been performed on a large-scale steel structure equipped with BCJs with FDs and innovative CBs. Several pseudo-dynamic tests have been performed and at the end of each test, the structure have been repaired by simply loosening the bolts of the FDs. Results demonstrated the effectiveness of repairing methodology.

Keywords

Experimental tests, Innovative connections, Friction Devices, Reparability, Resilience.

1 Introduction

According to the seismic design philosophy implemented in current codes and guidelines (*e.g.,* [1]), conventional lateral force-resisting systems are conceived to dissipate the seismic energy through the inelastic behaviour of their structural members. For steel Moment Resisting Frames (MRFs) this strategy consists in adopting over-strengthened columns, weak beams, and full-strength connections, by promoting the concentration of damage at the beams' ends (**Errore. L'origine riferimento non è stata trovata.**[2]). However, in the aftermath of severe seismic events, the inelastic response of the structural components can lead to significant permanent displacements, which are often costly to reinstate. This leads to post-earthquake scenarios where structures may be difficult to repair or in need of demolition/reconstruction, thus leading to considerable direct (*i.e.,* repair costs) and indirect (*i.e.,* downtime) losses, which are not acceptable from both social and economic perspectives (*e.g.,* [4]). To address these issues, increasing research efforts have been devoted to the definition of more performing structural solutions, addressing social expectations and the need for seismic resilience.

A widely investigated strategy for steel MRFs is based on replacing the full-strength Beam-to-Column joints (BCJs) with dissipative partial-strength joints with Friction Devices (FDs) (*e.g.,* [5]-[8]), allowing high energy dissipation capacity while also limiting the damage within replaceable elements. However, although these solutions efficiently protect the frame components from local damage, in some cases, high-intensity seismic events may still induce large residual displacements, thus compromising the building's reparability. To overcome these issues, for steel MRFs, further studies have focused on the inclusion of high-strength Post-Tensioned (PT) steel bars/strands within BCJs to provide the joints' self-centring capability, aiming at returning to the undamaged, fully functional condition in a short time (*e.g.,* [9][10]).

Besides, it has been demonstrated that Column Bases (CBs) are fundamental components of the structural systems; hence, their protection is paramount to achieve structural resilience (*e.g.,* [11]-[14]). In this direction, more recent research studies have developed innovative

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CBs by a combination of rocking systems, dissipative devices, and PT bars, demonstrating their potential in terms of damage-free behaviour and self-centring capability (*e.g.,* [15]-[19]). This is the case of a type of Self-Centring CB (SC-CB) investigated by Latour *et al.* [20] through component experimental testing of an isolated specimen, demonstrating a satisfactory self-centring capability of the joint with negligible residual deformation in the column.

In addition, a few research studies are currently focusing on repairing methodologies for the structural performance recovery of buildings (*e.g.,* [21]-[22]). For example, Zhang *et al.* [21] demonstrated the efficiency of a simple repairing technique (*i.e.,* re-tightening the bolts of the FDs) applied on a novel steel CB in restoring the initial performance of the structural system without loss of strength and stiffness. However, to date, research on system-level performance recovery of repaired structures is still marginal because of the limited availability of suitable structural repair techniques.

Within this framework, the present paper investigates the experimental response of a large-scale steel structure equipped with BCJs with FDs and with the proposed SC-CBs. The experimental program has been carried out at the STRENGTH laboratory of the University of Salerno through pseudo-dynamic tests [23]. At the end of each test, the bolts of the FDs were loosened to investigate the effectiveness of the proposed repairing methodology on the residual drift reduction of the structure. This paper presents 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 performance of the structure, including their contribution regarding the structure's resilience and reparability.

2 Case-study structure

Figure 1 shows the plan and elevation view of the case-study structure. It consists of a two-storey steel structure where two longitudinal MRFs withstand the seismic actions, and two transversal bracings prevent undesired accidental torsional and/or out-of-plane effects. This structure is a large-scale (i.e., 75%) representation of a more complex reference structure, characterised by two storeys and three bays in each direction.

The design is performed following the Eurocode 8 provisions [1] and the Theory of Plastic Mechanism Control (TPMC) [24]. The Type 1 elastic response spectrum with a Peak Ground Acceleration (PGA) equal to 0.35g and soil type B is considered for the Ultimate Limit State (ULS). The behaviour factor is assumed equal to q = 6, as allowed by Eurocode 8 [1] for MRFs in DCH. The interstorey drift limit for the Damage Limit State (DLS) requirements is assumed as 1% [1]. The selected profiles are IPE 270 for beams and HE 200B for columns, with S275 and S355 steel grades, respectively.

The adopted beam-to-column joint is the low-damage BCJ equipped with FDs [7][8] shown in Figure 2. It is composed of a haunch, and two L-stubs which are bolted to the haunch and the column's flange. The top beam flange is connected to the column flange with a bolted T-stub, where the Centre of Rotation is located. The friction pads, made of steel plates coated with thermally sprayed material, are located between the L-stub and the haunch. These elements are clamped together with high-strength preloadable bolts, used to tune the FD friction force.

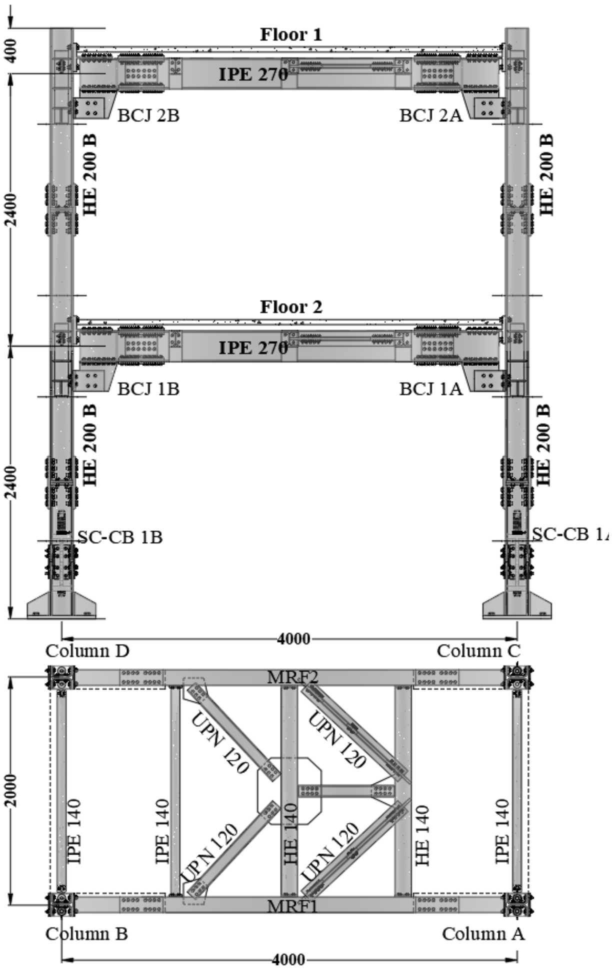

Figure 1 Plan and elevation view of the case-study structure

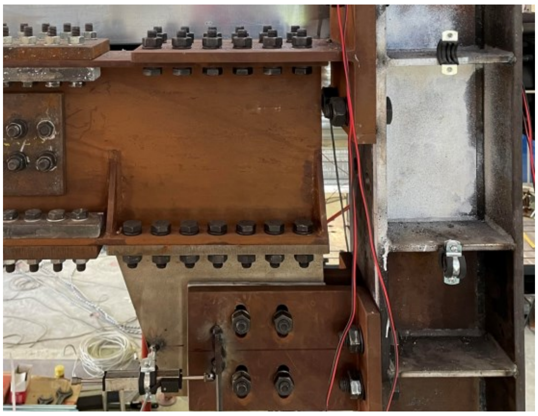

Figure 2 Beam-to-column joint (BCJ) with FDs

The SC-CB connection is shown in Figure 3. It consists of a rocking column splice joint where the seismic behaviour is controlled by a combination of FDs and PT bars with disk springs. The FDs provide energy dissipation capacity and are realised by slotting the column section, adding cover plates, and including friction pads coated with thermally sprayed metal, pre-stressed with high-strength preloadable 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 control the rocking behaviour of the SC-CB. The design methodology of the SC-CB is based on a step-by-step procedure, and simple analytical equations can easily calibrate the moment-rotation behaviour. Additional details on the SC-CBs configuration and design procedure are provided in [12]-[14].

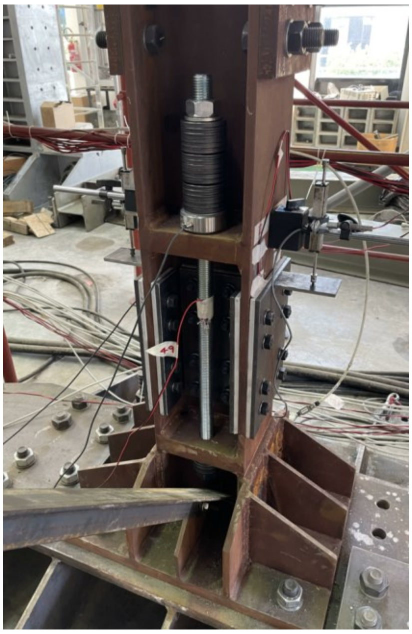

Figure 3 Self-centring column base (SC-CB) connection

3 Test setup, instrumentation and sequence

The experimental campaign was performed at the STRENGTH laboratory of the University of Salerno. Two actuators connected at each level were used to apply the horizontal loads. The floor displacements were measured with wire transducers in the two main directions while also checking for possible deck rotations (Figure 4). The local response of the BCJs was monitored using potentiometric transducers to assess the rotations. Strain gauges were applied to the column top and bottom sections to check the bending moments at the columns' ends. The local response of the SC-CB connections was monitored using potentiometric transducers. Load cells were installed in the SC-CB connection to monitor the forces in the PT bars. A sequence of 8 tests was performed within the experimental campaign using the pseudo-dynamic [23] procedure with amplified PGAs. Several zero acceleration points have been added to the end of each record to allow the free vibrations to stop and correctly capture the residual displacements.

In this paper, the attention is focused on two tests (Table 1), which have been performed to assess the influence of the PT bars on the structural response of the tested structure. Consequently, the structure has been subjected to the same ground motion input (*i.e.,* Imperial Valley accelerogram with PGA = 1.10 g) with and without the contribution of the PT bars (*i.e.,* without applying the initial PT force). At the end of each test, the bolts of the FDs were loosened, and the measurements of the wire sensors were monitored for the first (*i.e.,* WS1, WS2) and the second storeys (*i.e.,* WS3, WS4) during the whole loosening process.

Table 1 Tests to assess the influence of the PT bars

Test	Input [-]	PGA [g]	PT bars
1	Imperial Valley	1.10	With
8	Imperial Valley	1.10	Without

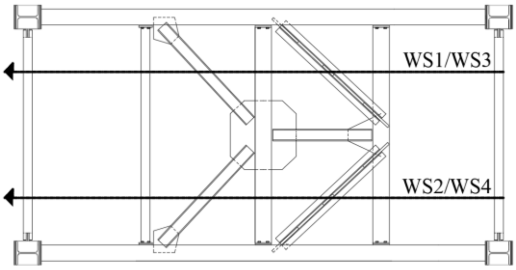

Figure 4 Instrumentation: plan view of the wire transducers' position

4 Influence of the PT bars

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, results are reported for a single ground motion record (*i.e.,* Imperial Valley PGA = 1.10g) with and without the contribution of the PT bars.

Figures 5 shows the comparison between Test 1 (*i.e.,* with the contribution of the PT bars) and Test 8 (*i.e.,* without the contribution of the PT bars) in terms of interstorey drift histories for the first storey. The residual interstorey drifts (IDR Res) are compared with two limits: 0.5% [25], conventionally assumed as a permissible residual drift to ensure the building's repairability, and 0.2%, which is the FEMA P58-1 [26] limit value, to ensure that no structural realignment is necessary.

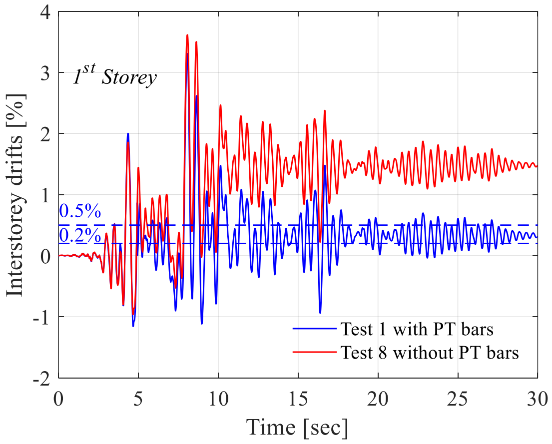

Figure 5 Global results for Test 1 (*i.e.,* Imperial Valley accelerogram)

The comparison between the two curves highlights the crucial role of the PT bars in significantly reducing the residual interstorey drifts for both stories, as highlighted in Table 2. In addition, the structure with PT bars experiences residual interstorey drifts lower than the 0.5% limit threshold [25], 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 responses (IDR Peak) between these two tests.

Table 2 Global results in terms of peak and residual interstorey drifts

Test	Storey	IDR Peak [%]	IDR Res [%]
1	1	3.30	0.30
	2	3.11	0.51
8	1	3.62	1.47
	2	3.58	1.62

5 Resilience and Reparability

At the end of each test, all the high-strength pre-loadable bolts belonging to the FDs of both BCJs, and SC-CBs were loosened using a torque wrench, as shown in Figure 6. The entire loosening process consisted of two steps: *i)* loosening the bolts belonging to the FDs of the BCJs; *ii)* loosening the bolts belonging to the FDs of the SC-CBs. The aim was to assess the residual drift reduction during repair while investigating the system-level performance recovery in terms of restoration of the initial configuration (*i.e.,* before the test).

Figure 6 FDs bolts' loosening process for the BCJs.

Results are illustrated in Figure 7 and 8 for Test 1 and Test 8, respectively, in terms of interstorey drifts versus time employed to complete the whole repairing process. As it is possible to observe, for Test 1, the interstorey drifts turned almost to zero, demonstrating that by applying the repairing methodology, the structure is able to return almost to the initial position. Conversely, for Test 8 (*i.e.,* without PT bars), even applying the loosening process, the interstorey drifts did not decrease, as expected, due to the absence of the PT bars.

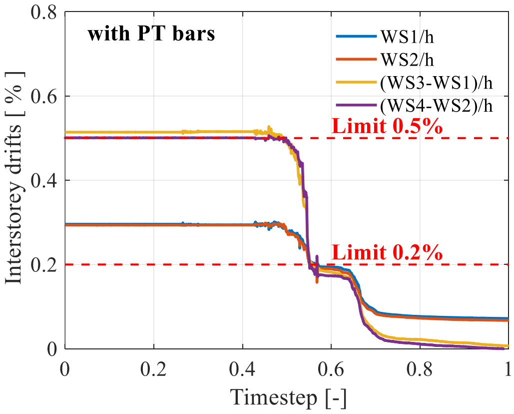

Figure 7 FDs bolts' loosening process at the end of Test 1 (with PT bars).

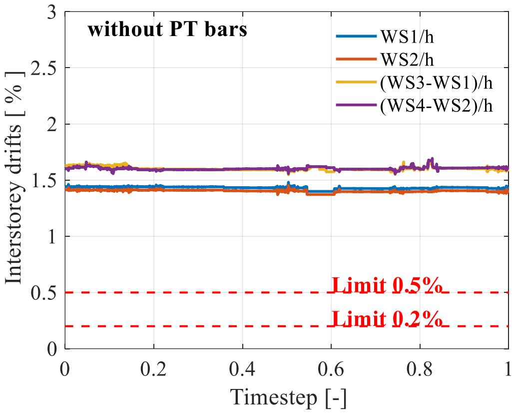

Figure 8 FDs bolts' loosening process at the end of Test 8 (without PT bars).

6 Conclusions

The present paper investigates the experimental response of a large-scale steel structure equipped with Beam-to-Column joints (BJs) with Friction Devices (FDs) and Self-Centring Column Bases (SC-CBs). The experimental campaign consisted of pseudo-dynamic tests performed at the STRENGTH Laboratory of the University of Salerno. At the end of each test, the bolts of the FDs were loosened to restore the structure to the original configuration. In this work the attention is focused on two tests, which have been performed with and without the contribution of the PT bars of the SC-CBs, to assess the influence of the PT bars on the overall structural performance. The following conclusions are drawn *i)* the self-centring behaviour of the SC-CB is effective in limiting the residual drifts of the structure under the reparability limits; *ii)* the presence of the PT bars is crucial in terms of residual drift reduction *ii)* the repairing methodology is effective in minimising the residual drifts of the structure.

7 Ackowledgements

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