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EXPERIMENTAL RESPONSE OF A LARGE-SCALE STEEL STRUCTURE EQUIPPED WITH INNOVATIVE COLUMN BASES

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Abstract

In the last few decades, increasing research efforts have been devoted to the definition of innovative seismic design philosophies aiming at reducing seismic-induced direct and indirect losses. For steel Moment Resisting Frames (MRFs), the use of Friction Devices (FDs) in beam-to-column connections has emerged as an effective solution to dissipate the seismic input energy while also ensuring their damage-free behaviour. Additionally, more recent research studies have revealed the benefits of replacing traditional full-strength Column Bases (CBs) with innovative CBs for both damage and residual drift reductions of steel MRFs. In this direction, an experimental campaign has been performed on a two-storey large-scale steel structure equipped with innovative Self-Centring CBs (SC-CBs). The present paper illustrates the preparatory work required for the specimen's design, the experimental program and the preliminary results. The tests' outcomes demonstrated the effectiveness of the SC-CB connections in minimising the residual drifts of the structure and in protecting the first-storey columns from damage.

Keywords: Experimental tests, Moment Resisting Steel Frames, Self-Centering Column bases, Friction Devices, Residual drifts.

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1 INTRODUCTION

According to the current seismic design philosophy implemented in modern codes and guidelines [*e.g.*, [1]], steel Moment Resisting Frames (MRFs) are conceived to concentrate the seismic damage into specific dissipative fuses characterised by high local ductility and energy dissipation capacity. The traditional design approach for these structural typologies adopts over-strengthened columns and weak beams, with full-strength connections, by promoting the concentration of damage at the beams' ends [2]-[3]. However, post-earthquake inspections after destructive seismic events [*e.g.,* [4]] highlighted the high direct and indirect economic losses related to this design philosophy. In fact, the inelastic response of the structural components can lead to significant permanent structural displacements (*i.e.,* residual deformations), which are often difficult and costly to reinstate, thus compromising the building's reparability.
To address these issues, increasing research efforts have been devoted to the definition of advanced and more performing structural solutions, addressing social expectations and the need for seismic resilience. Among others, a widely investigated strategy for MRFs is based on substituting the full-strength beam-to-column connections with dissipative partial-strength joints with Friction Devices (FDs) [*e.g.*, [5]-[10]], allowing high energy dissipation capacity while also limiting the damage within replaceable elements. Relevant examples of these connections are represented by the Sliding Hinge Joint (SHJ) [6], and the 'FREE from DAMage' FREEDAM beam-to-column joint, which has been conceived, experimentally tested, and numerically simulated within the homonymous European project [8].
However, although it has been demonstrated that using these innovative connections represents an efficient strategy to protect the frame components from local damage, in some cases, high-intensity seismic events may still induce large residual deformations, significantly affecting the building's reparability. To overcome these downsides, further studies have focused on the definition of structures able to return to the undamaged, fully functional condition in a short time. For steel MRFs, this is usually made by including high-strength Post-Tensioned (PT) steel bars/strands able to provide the joints' self-centring capability, combined with replaceable/repairable energy dissipation devices within beam-to-column connections [*e.g.*, [11][12][13]].
Besides, Column Bases (CBs) represent fundamental components of the structural systems; hence, their protection is paramount to achieve structural resilience [*e.g.,* [14]-[17]]. In this direction, more recent research studies have developed innovative CBs based on the combination of rocking systems, dissipative devices, and PT bars, demonstrating their potential in terms of damage-free behaviour and self-centring capability [*e.g.*, [18]-[22]]. This is the case of a type of Self-Centring CB (SC-CB) investigated by Latour *et al.* [22] through component experimental testing of an isolated specimen, demonstrating the self-centring capability of the joint and highlighting the main features of the connection.
Within this framework, the present paper investigates the experimental response of a large-scale two-storey steel structure equipped with the FREEDAM beam-to-column connections and with the proposed SC-CBs. The experimental program has been carried out at the STRENGTH laboratory of the University of Salerno by using the pseudo-dynamic procedure [23]. The present paper shows the specimen's design, the experimental program, the set-up and instrumentation, and the main outcomes of the experimental campaign. Both global and local responses were monitored to investigate the influence of the proposed SC-CBs on the seismic performance of the tested structure. The results demonstrated the effectiveness of the SC-CBs in limiting the residual drifts of the structure and in protecting the first-storey columns from damage.

2 TESTED STRUCTURE

The specimen consists of a two-storey steel structure equipped with two longitudinal MRFs conceived to withstand the seismic actions and two transversal bracings designed to prevent undesired accidental torsional and/or out-of-plane effects (Figure 1 (a)). The interstorey height is 2.40 m at both storeys, and the longitudinal and the transversal bay have spans equal to 4 m and 2 m, respectively. This structure is a large-scale (*i.e.,* 75%) representation of a more complex reference prototype 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 suggested 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 S275JR and S355JR steel grades, respectively.

The adopted beam-to-column joint is the low-damage FREEDAM connection in the horizontal configuration [7], as shown in Figure 1 (b). It comprises 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, fixing the Centre of Rotation (COR). The friction pads, made of steel plates coated with thermally sprayed material, are located between the L-stub and the haunch.

The adopted SC-CB connection (Figure 1 (c)) consists of a rocking column splice joint where the seismic behaviour is controlled by a combination of FDs, providing energy dissipation capacity, and PT bars with disk springs, introducing restoring forces. The FDs are realised by slotting the column section, adding cover plates, and including friction pads coated with thermally sprayed metal, 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 calibrated by simple analytical equations.

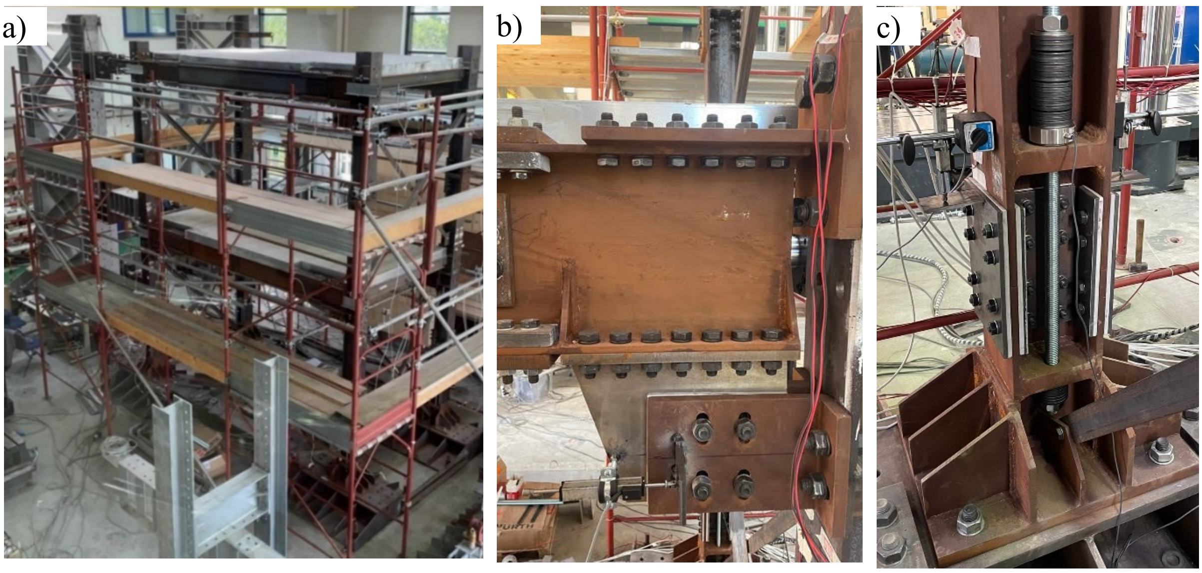

Figure 1: Large-Scale steel tested structure: a) Tested structure; b) FREEDAM beam-to-column connection; (b) SC-CB connection.

3 TEST SET-UP, INSTRUMENTATION AND TEST MATRIX

The experimental campaign was performed at the laboratory STRENGTH of the University of Salerno. Figure 2 shows the test set-up and instrumentation. Two actuators connected at the structure's first and second levels were used to apply the horizontal loads. Wire transducers were used to measure the floor displacements and to control the floors' translations in the two main directions while also checking for possible deck rotations. The local response of the beam-to-column joints 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. In this way, the bending moments at the connection level have been defined using the nodal equilibrium. The local response of the SC-CB connections was monitored using potentiometric transducers to measure the vertical displacements in both column sides to assess the rotation. Load cells were installed in the SC-CB connection to monitor the forces in the PT bars. Several pseudo-dynamic [23] tests were performed within the experimental campaign, adopting a sequence of six different scaled seismic inputs with a spectrum-compatibility selection with the Eurocode 8 [1] design spectrum. The sequence of ground motions has been applied using amplified PGAs (*i.e.,* from 0.5g to 1.10g) and 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, results are reported for a single ground motion (*i.e.,* Test 2, Spitak accelerogram with PGA = 0.8 g).

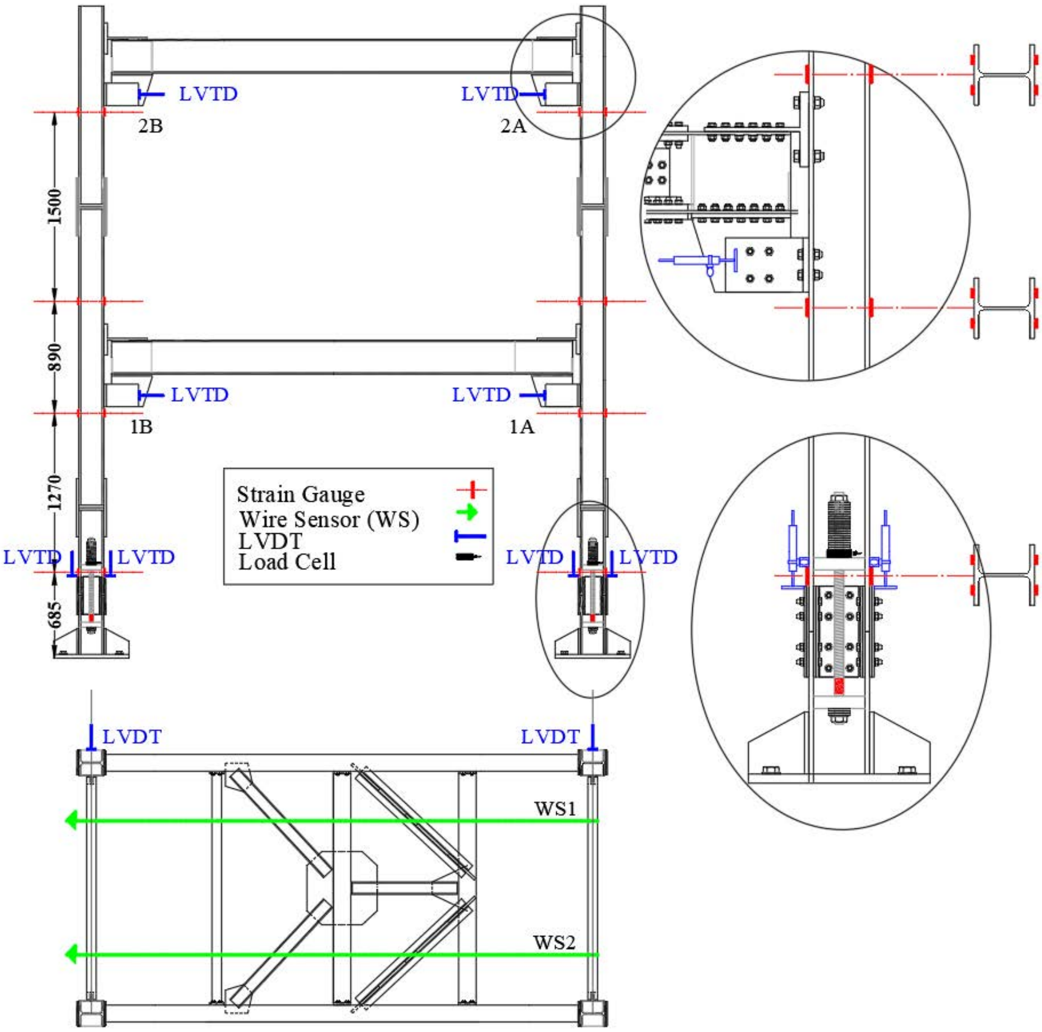

Figure 2: Set-up and instrumentation of the test

4 RESULTS

The structure has been subjected to the entire test sequence and ground motion intensities without significant residual drifts at the conclusion of each test. For the sake of brevity, in this paper, global and local results are reported for a single ground motion record (*i.e.,* Test 2, Spitak accelerogram with PGA = 0.8 g). Figure 3 (a) and (b) illustrate the global response of the tested structure in terms of displacement time history and actuator forces, respectively. 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. In addition, Figure 3 (c) and (d) show the interstorey drifts and the base shear histories for the same ground motion. The residual interstorey drifts are compared with the limit of 0.5% [25], 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 [26] limit value, to ensure that no structural realignment is necessary. For the considered ground motion record, the residual displacements assumed values of approximately 1.52 mm and 5.73 mm at the first and second storey, respectively, corresponding to residual interstorey drifts of 0.06% at 0.18%. These values are lower than the limit for no necessary structural realignment of 0.2%, demonstrating the 'good' self-centring capability of the structure equipped by the proposed SC-CBs.

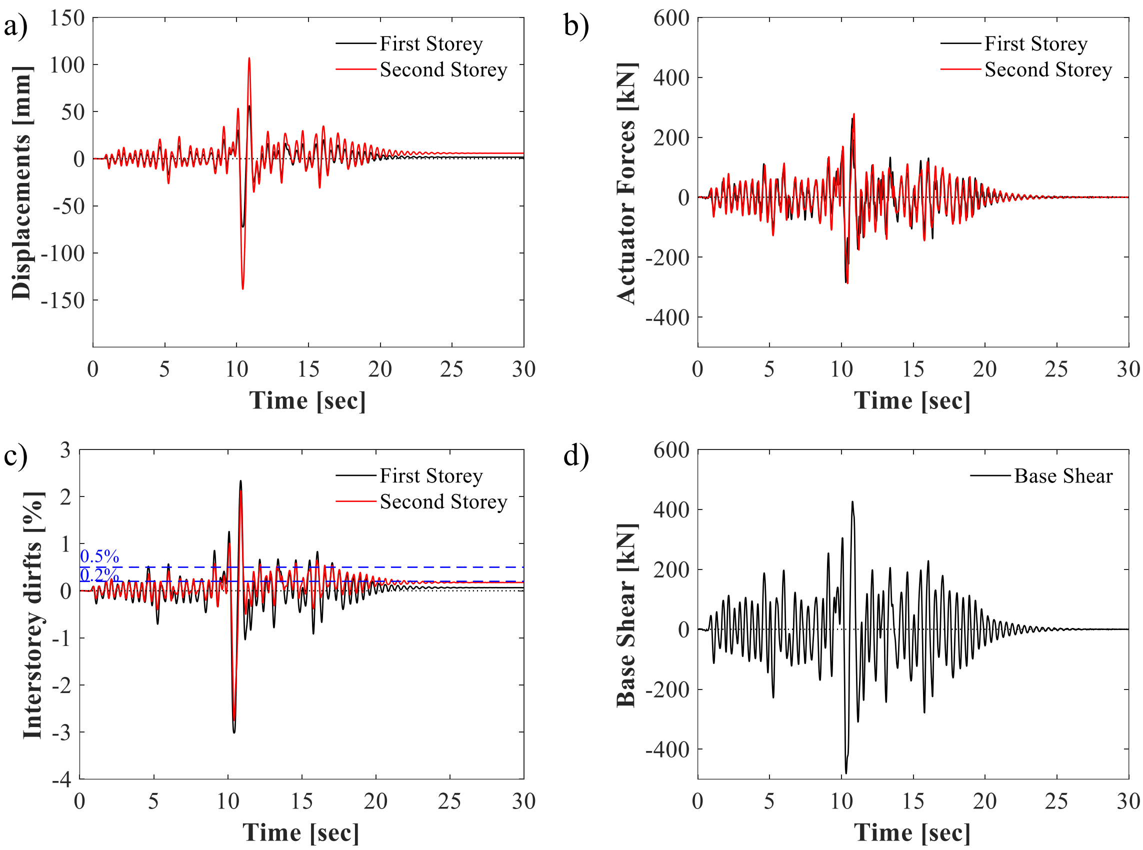

Figure 3: Global results for Test 2 (*i.e.,* Spitak accelerogram)

For the same ground motion, the local results of the FREEDAM beam-to-column connections are shown in Figure 4 in terms of hysteretic curves for the first (*i.e.,* FREEDAM 1A and 1B) and the second storey (*i.e.,* FREEDAM 2A and 2B). The values of the maximum and minimum bending moments corresponding to the activation of the FDs of the FREEDAM connections (*i.e.,* M_{Slip}) are reported in black dotted lines. Generally, it is possible to observe that the FREEDAM connections experienced stable and wide moment-rotation curves, consistently with the theoretical model. The rotations experienced by the connections were similar at both storeys, with values up to 0.03 rad for the first storey and up to 0.02 rads for the second storey.

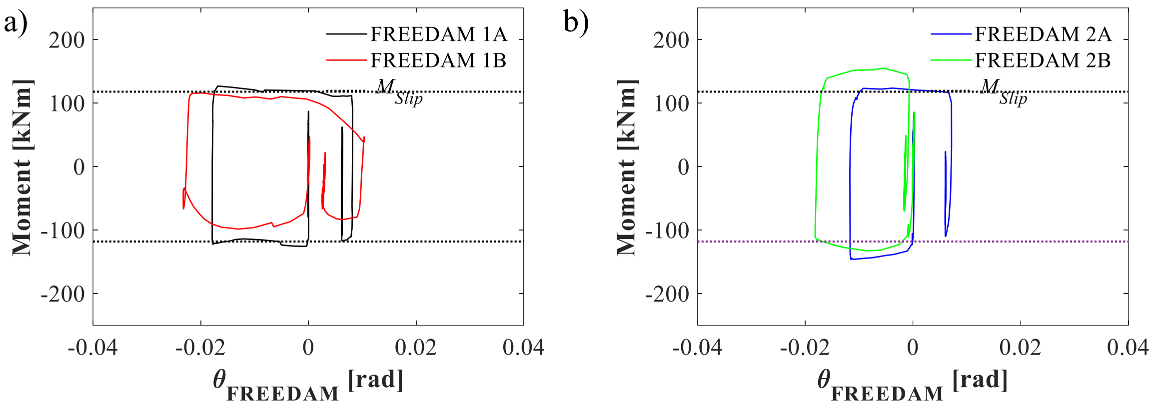

Figure 4: Local results of the beam-to-column connections in terms of Moment-Rotation behaviour for the a) First and b) Second storeys

The local results of the SC-CB are shown in Figure 5 in terms of moment-rotation curves. The theoretical model is also reported in black dotted lines. It is possible to observe that the SC-CB exhibited a flag-shaped hysteretic curve characterised by good self-centring behaviour with very low residual rotations. In addition, the experimental and the theoretical results are in good agreement; nevertheless, a higher dissipative behaviour was observed in the experimental response. Moreover, Figure 5 (b) shows the force variation in the PT bars along the test versus the SC-CB rotation (*i.e.,* θ_{SC-CB}). The PT bars showed an elastic behaviour and the tension force showed the same stiffness for negative and positive values of the rotation, due to length of the lever arm, which is the same in both direction for the symmetry of the SC-CB. In addition, test observations showed that the first-storey columns were fully protected from yielding, and except for the expected wearing of the friction pads, no structural damages were observed in other structural members.

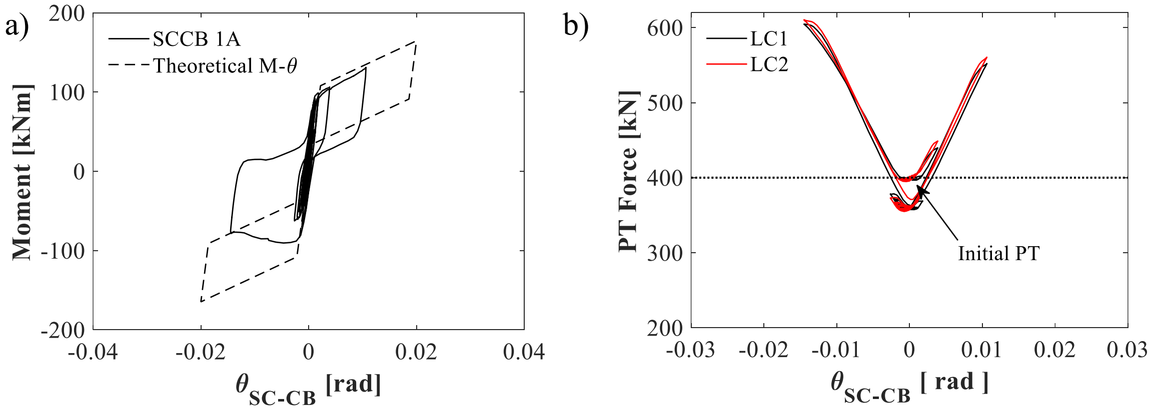

Figure 5: Local results of the SC-CB in terms of a) Moment-Rotation behaviour and b) PT force-Rotation

5 CONCLUSIONS

The present paper investigates the experimental response of a large-scale steel Moment Resisting Frame equipped with FREEDAM beam-to-column and damage-free self-centring column base (SC-CB) connections. The experimental campaign consisted of pseudo-dynamic tests performed at the STRENGTH Laboratory of the University of Salerno. The objective of the experimental campaign was to investigate the benefits deriving from the adoption of the innovative SC-CB connections by evaluating their influence on both global and local structural performances. The present work includes the description of the specimen and the adopted connections, the test set-up, the instrumentation and the experimental program. The experimental results demonstrated the effectiveness of the SC-CB connections in terms of enhanced seismic performance. The following conclusions are drawn *1)* the self-centring behaviour of the SC-CB results as an effective measure in limiting the residual drifts of the structure under the considered limits for reparability; *2)* the structural members are fully protected from yielding, providing significant advantages in terms of repairability, and hence resilience of the structure; *3)* the experimental results are consistent with the theoretical models.

6 ACKOWLEDGEMENTS

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