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Pseudo-dynamic testing of a large-scale steel building with innovative column base connections: design and numerical simulations

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Abstract In the last two decades, increasing efforts have been devoted to the definition of innovative seismic design philosophies, with the aim of reducing seismic induced direct and indirect losses. Among others, beam-to-column connections equipped with friction devices have emerged as an effective solution to dissipate the seismic input energy while also enhancing the damage-free behaviour of steel Moment Resisting Frames (MRFs). Additionally, recent numerical studies have demonstrated the benefits deriving from the replacement of conventional full-strength column bases (CBs) with innovative damage-free and self-centring CBs, for both damage and residual drifts reductions of low-rise MRFs. Within this framework, an experimental campaign has been planned on a two-storey one-bay large-scale case-study MRF equipped with damage-free self-centring CBs. The present paper illustrates the preparatory work required for the design of the specimen, the test setup, and the Pseudo-Dynamic test procedures, and aims at foreseeing the response that will be observed during the experimental test by advanced numerical simulations in OpenSees. Non-linear time history analyses have been performed considering ground motion records scaled to several intensity levels. The preliminary numerical results provide useful information for the selection of the accelerograms to be used during the tests and on the expected response of the structure.

Keywords: Experimental tests, Moment-Resisting Steel frames, Self-centring, Column bases, Residual drifts.

1 Introduction

According to the current seismic design philosophy, suggested by modern codes worldwide [*e.g.*, 1], structures are conceived to concentrate the seismic damage into dissipative fuses characterised by high ductility and energy dissipation capacity. Within steel Moment Resisting Frames (MRFs), the traditional approach adopts over-strengthened columns and weak beams, with full-strength connections, by promoting the concentration of damage at the beams' ends [2]. However, recent destructive seismic events highlighted the high direct and indirect economic losses related to this design philosophy. Additionally, it was observed that the inelastic deformations of the structural components might lead to large residual drifts hance jeopardising the building reparability.

To overcome these drawbacks, in the last two decades, increasing efforts have been devoted to the definition of innovative and more performing structural solutions, addressing social expectations and the need for seismic resilience. 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.*, 3-5], allowing high local ductility and energy dissipation capacity while also protecting the structure from damage. Significant examples of friction beam-to-column connections are represented by the Sliding Hinge Joint (SHJ) [4], developed in New Zealand, and the FREEDAM joint, which has been conceived, experimentally tested, and numerically simulated within a European project [5]. Additionally, large-scale Pseudo-Dynamic Tests have been recently performed at the University of Salerno on a one-bay two-storey steel structure equipped with FREEDAM joints [6]. The results confirmed the enhanced seismic performance of these structures characterised by high energy dissipation and rotation capacity with almost no damage.

It has been demonstrated that the use of these innovative connections represents an efficient strategy to protect the frame components from local damage; nevertheless, in some cases, high-intensity seismic events may induce large residual deformations, hence significantly affecting the building reparability. To address this issue, a further improvement focuses on introducing elastic restoring forces able to provide the self-centring (SC) capability of the joints. This is usually done by including post-tensioned (PT) bars to control gap-opening mechanisms. A wide variety of SC seismic-resisting systems has been developed over the past two decades. One common solution for steel MRFs is based on PT bars controlling the rocking behaviour of beam-to-column connections [*e.g.*, 7-9].

Besides, column bases (CBs) represent fundamental components of the structural systems, and hence, their protection is of paramount importance to achieve structural resilience. Several studies have been devoted to the development of innovative CBs based on the combination of rocking systems, dissipative devices, and PT bars, demonstrating their potential in achieving a damage-free and SC behaviour [*e.g.*, 10-14]. In this framework, a type of damage-free SC-CB connection has been previously investigated by Latour *et al.* [14] through component experimental testing of an isolated CB, demonstrating the advantages in terms of damage-free and SC capabilities. Additionally, extensive numerical studies have been carried out [15-16], demonstrating how the inclusion of the proposed SC-CBs in MRFs can be particularly effective in reducing residual storey drifts and protecting the first-storey columns from damage.

Within this framework, a new experimental campaign, to be performed on a large-scale one-bay two-storey structure, equipped with the FREEDAM beam-to-column connections and the proposed SC-CBs, has been planned at the University of Salerno. The present paper illustrates the preparatory work required for the specimen's design and aims at foreseeing the response that will be observed during the experimental test by advanced numerical simulations performed in OpenSees [18]. Non-linear time history analyses have been performed considering ground motion records scaled to several intensity levels. The preliminary numerical results provide useful information for the selection of the accelerograms to be used during the tests and on the expected response of the structure.

2 Tested structure

The test specimen is a one-bay two-storey steel structure, where two longitudinal MRFs are conceived to withstand the seismic actions, and two transversal bracings are designed to prevent undesired accidental torsional effects. The layout has an interstorey height of 2.40 m, the longitudinal and the transversal bay have span 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 2 storeys and 3 bays in each direction. The plan and one elevation view of the case-study building are shown in **Fig. 1**. The design is performed in accordance with the Eurocode 8 provisions [1]. The masses have been assessed considering that the tributary area of each MRF corresponds to 1/4 of the total floor. The Type 1 elastic response spectrum with a peak ground acceleration equal to 0.35g and soil type B is considered for the definition of the Ultimate Limit State. The behaviour factor is assumed equal to q = 6 in accordance with the requirements of the Eurocode 8 [1] for MRFs in DCH. The structure is conceived to have non-structural elements fixed in a way so as not to interfere with structural deformations. Therefore, the interstorey drift limit for the Damage State Limitation (DSL) requirements is assumed as 1%, as suggested in the Eurocode 8 [1]. The selected profiles are IPE 270 for beams and HE 200B for columns and use 355JR steel grade.

The beam-to-column joint is the low-damage FREEDAM beam-to-column connection, already tested in Di Benedetto *et al.* [6]. A detail of the joint is shown in **Fig. 2** (a). This is based on the use of replaceable friction dampers [19], constituted by a bolted 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. The friction pads, made of steel plates coated with aluminium material, are located in-between the L-stub and the haunch.

The column base connection considered in this work is the damage-free SC-CB connection experimentally tested by Latour *et al.* [14]. A detail of the CB is shown in **Fig. 2** (b). 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 are realised 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 CB's rocking behaviour. The objective of the experimental campaign is to show the benefits deriving from the adoption of both innovative connection typologies assessing their influence on the overall structural performance.

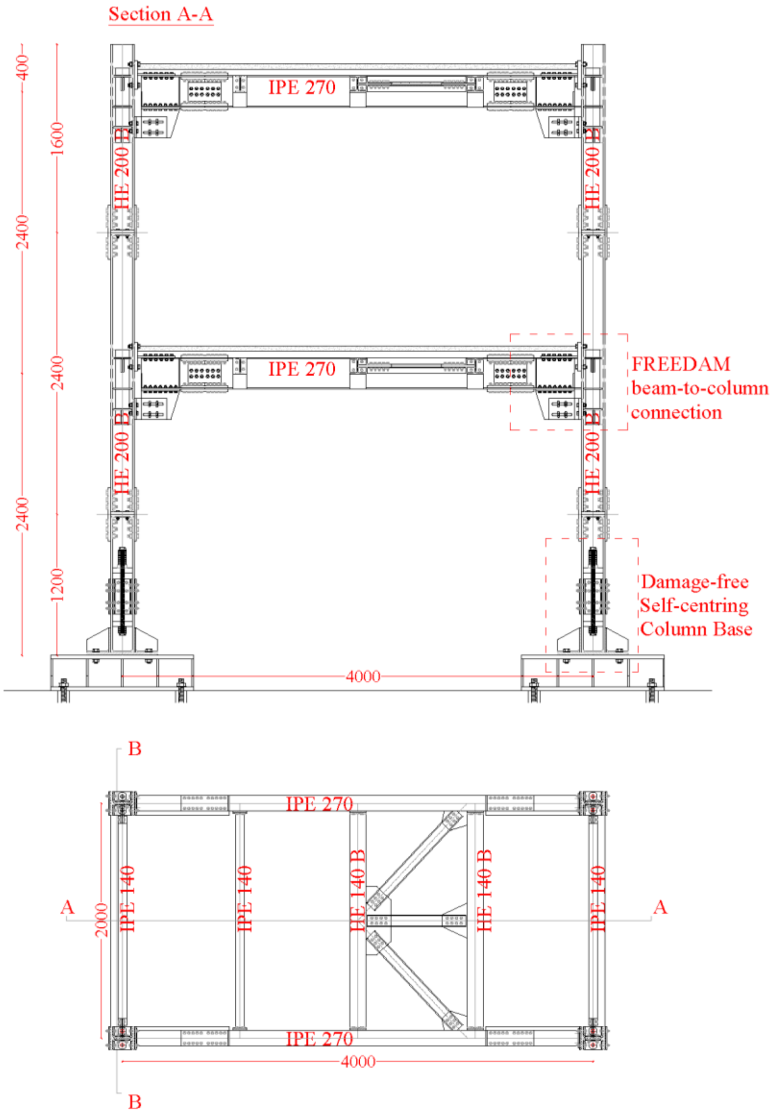
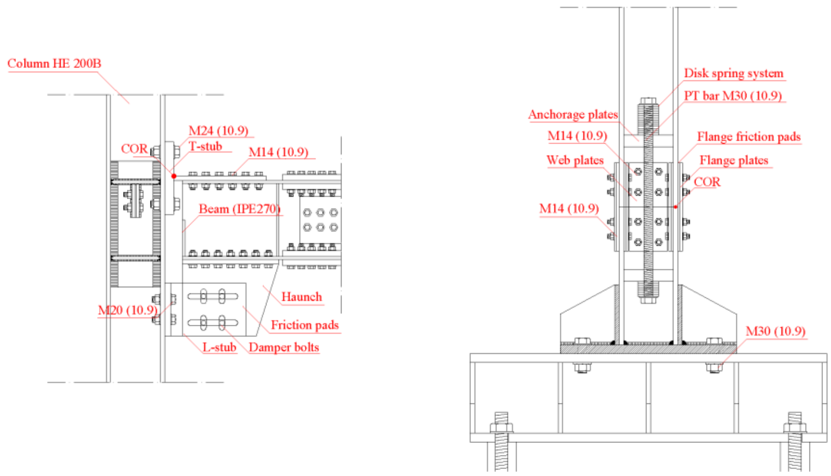


Fig. 1. Plan and elevation view of the tested building.



(a) (b)

Fig. 2. Connections of the tested building: (a) FREEDAM beam-to-column connection; (b) Damage-free self-centring column base.

3 Experimental setup, instrumentation, and test procedure

The experimental campaign will be performed at the laboratory STRENGTH of the University of Salerno. Two actuators will be employed at the first and the second floor of the structure to apply horizontal loads. The actuators are connected to the deck of the tested building on one side, while on the other side, they are fastened to a reaction braced frame. Regarding the measurement devices, wire transducers will be employed to measure the horizontal 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 will be monitored using potentiometric transducers to assess the rotations and strain-gauges 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 will be defined using the nodal equilibrium. Moreover, the local response of the SC-CB connections will be monitored using potentiometric transducers to measure the vertical displacements in both column sides, while load cells will be installed in the connection to monitor the tensile forces in the PT bars and the bolts of the friction dampers.

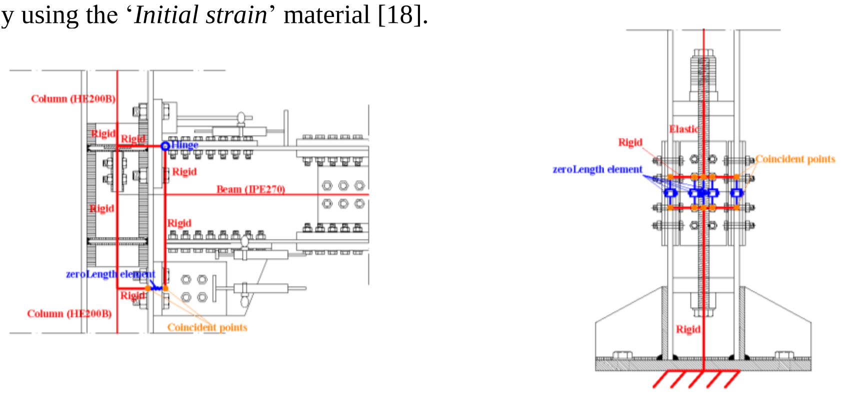
The Pseudo-Dynamic technique [17] will be used to simulate the seismic response of the tested building. This represents an alternative method to the classical shake test, being a numerical-experimental method, which imposes floor displacements to the structure by solving step-by-step equations of motion during the test. Among the main benefits of this test method, this allows the adoption of the same experimental equipment which is used for quasi-static tests. Several tests will be performed within the experimental campaign, adopting different seismic input chosen within a set of natural accelerograms, with a spectrum-compatibility selection with the Eurocode 8 [1] design spectrum.

4 Numerical modelling

A two-dimensional non-linear FE model of the structure is developed in OpenSees [18]. Beams and columns are modelled with a spread plasticity approach, using inelastic force-based elements ‘*forceBeamColumn elements*’ [18], using the ‘*Steel01*’ material [24] with 355 MPa yield strength and 0.2% post-yield stiffness ratio. Geometric nonlinearities are considered in the elements of the structure. Gravity loads are applied on the beams by considering the seismic combination of Eurocode 8 [1], while lumped masses are concentrated below the centre of the spans to model the points of application of the actuators in the testing setup.

The beam-to-column joint strategy modelling is consistent with Di Benedetto *et al.* [6], and it is shown in **Fig. 3** (a). The rigid elements of the joints are modelled with *‘elastic beam-column elements’* [18] with very high flexural stiffness. A hinge is used to model the physical location of the centre of rotation, located at the level of the upper beam flange. The FD is modelled by a ‘*zero-length element*’ characterised by ‘*uniaxial hysteretic material*’ with symmetric trilinear force-displacement law. This material adopts a yielding force equal to the sliding force, and very low post-elastic hardening, to correctly simulate the behaviour of the FDs.

The SC-CB connection is shown in **Fig. 3** (b). It is composed of a rocking interface modelled with *‘elastic beam-column elements’* [18] with very high flexural stiffness. These components connect the lower and the upper part of the column through non-linear springs. These springs are represented by four ‘*zero-length elements*’ in parallel with gap elements simulating the bilinear hysteretic response of the FDs and the contact behaviour of the column interfaces. The SC system is modelled with a single translational spring represented by a single ‘*zero-length element*’ [18] with bilinear elastic-plastic behaviour. The initial post-tensioning force of the PT bars is modelled by using the ‘*Initial strain*’ material [18].

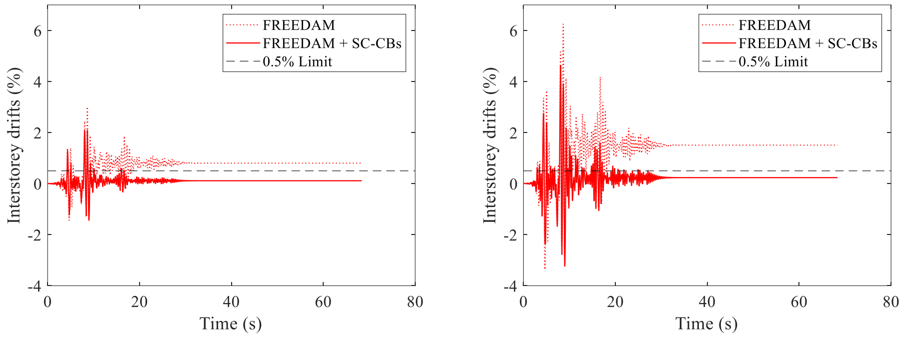


(a) (b)

Fig. 3. OpenSees models for connections of the frame: (a) FREEDAM beam-to-column joint; and (b) SC-CB joint.

5 Non-linear time history analysis

Non-linear time history analyses have been performed to investigate how the proposed CBs influence the seismic response of the frame, considering several ground motion records scaled to several intensity levels. A large number of zero acceleration points (*i.e.*, 40 s) have been added at the end of each record, allowing the free vibrations to stop and correctly capturing the residual deformations. The preliminary numerical results for a single ground motion record (*i.e.*, Imperial Valley, scaled at 1.10g) are shown in terms of storey drift time history in **Fig. 4**. Two configurations have been compared: the structure equipped with the FREEDAM beam-to-column connections and conventional CBs, versus the equivalent structure endowed with the SC-CBs. The results highlight how the introduction of the SC-CBs results as an effective measure in limiting the residual drifts of the structure, and this is observed at both stories, where the values are lower than 0.5% [20]. Conversely, this limit is not satisfied for the structure with full-strength CBs. These preliminary numerical results provide useful information for the Pseudo-Dynamic tests and on the expected behaviour of the structure.



(a) (b)

Fig. 4. Comparison of storey drifts time history for one ground motion record for: (a) first storey and (b) second storey.

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