Numerical Simulations of a two-storey Steel Moment Resisting Frame with Free from Damage Beam-to-Column Connections and Self-Centering Column Bases

Elena Elettore[1, a)] Fabio Freddi[2], Massimo Latour[1], Gianvittorio Rizzano[1]

[1] *Department of Civil Engineering, University of Salerno, Italy*
[2] *Department of Civil, Environmental and Geomatic Engineering, University College London*

a) Corresponding author: eelettore@unisa.it

Abstract. In the last two decades, increasing efforts have been devoted to the definition of innovative seismic design philosophies, with the aim of reducing direct and indirect costs deriving from the occurrence of destructive seismic events. Among others, beam-to-column connections equipped with friction devices have emerged as an effective solution able to dissipate the seismic input energy, while also ensuring the damage-free behaviour within steel Moment Resisting Frames (MRFs). Additionally, recent extensive numerical studies have demonstrated the benefits deriving from the replacement of conventional full-strength column bases (CBs) with innovative damage-free self-centring CBs, in reducing the residual storey drifts and in preventing the first-storey columns' yielding of low-rise MRFs. This work introduces the preliminary study of an experimental campaign which has been planned on a one-bay two-storey large-scale MRF, equipped with the proposed damage-free self-centring CBs. The present study has the objective to foresee the response that will be observed during the experimental test by advanced numerical simulations in OpenSees.

INTRODUCTION

According to the current seismic design philosophy, suggested by modern codes worldwide [e.g., 1], structures are conceived to behave elastically during frequent seismic events and to concentrate the seismic damage into dissipative fuses characterized by high ductility and energy dissipation capacity, under severe seismic events. Whitin steel Moment Resisting Frames (MRFs), the traditional approach consists of adopting 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.

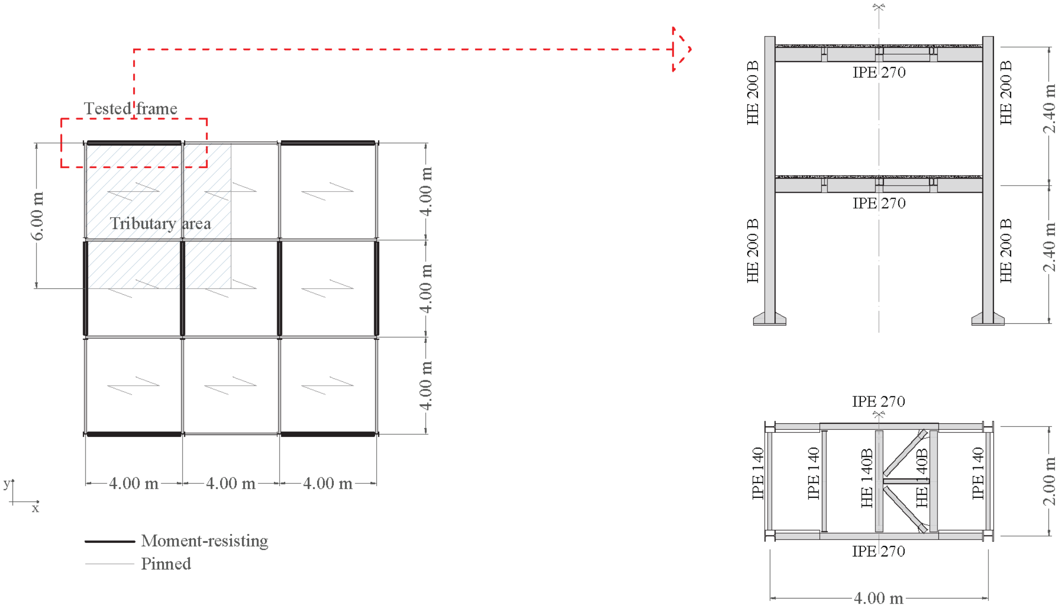
To overcome these drawbacks, in the last two decades, increasing efforts have been devoted to the definition of innovative and more performing structural solutions, addressing social expectations and the need for seismic resilience. Among others, a widely investigated strategy for MRFs is based on substituting the full-strength beam-to-column connections with dissipative partial-strength joints with friction devices (FDs), allowing high local ductility and energy dissipation capacity while also protecting the structure from damage [*e.g.,* 3-6]. Although these latter represent efficient strategies to protect the frame components from local damage, nevertheless, in some cases, the occurrence of large residual deformations may significantly affect the building reparability after a severe seismic event. To address this issue, a further improvement of these systems focused on the introduction of elastic restoring forces able to provide the self-centring (SC) capability. A wide variety of SC seismic-resisting systems has been developed over the past two decades, often based on a gap-opening mechanism located at the beam-to-column interface [*e.g.,* 7-8].

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 [*e.g.,*9-13], based on the combination of rocking systems, dissipative devices, and post-tensioned (PT) bars, demonstrating their potential in achieving a damage-free and SC behaviour. In this framework, a type of damage-free SC-CB connection has been previously investigated by the authors [14-16]. The proposed CB consists of a rocking 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 in the joint. Component experimental testing of the isolated CB have been performed by Latour *et al.* [14], showing the advantages in terms of damage-free and SC capabilities. Additionally, extensive numerical studies have demonstrated that the inclusion of the SC-CBs is particularly effective in reducing the residual storey drifts of low-rise MRFs and in protecting the first-storey columns from damage [15-16].

A new experimental campaign, to be performed on a large-scale one-bay two-storey structure equipped with the FREEDAM beam-to-column connections [5] and the proposed SC-CBs, has been planned at the University of Salerno. The present paper illustrates the preparatory work required for the design of the specimen and tries to foresee the response that will be observed during the experimental test by advanced numerical simulations performed in OpenSees [17]. Non-linear time history analyses are performed considering several ground motion records scaled to several intensity levels. The preliminary results confirm the benefits in terms of residual drift reduction and damage-free behaviour provided by the damage-free SC-CB connections.

CASE-STUDY BUILDING

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. This structure is a large-scale representation of a more complex reference prototype which has 2 storeys and 3 bays in each direction. The design is performed in accordance with the Eurocode 8 provisions [1]. The plan and the elevation view of the case-study building, with the indications of the profiles' cross-sections, are shown in Fig 1. The masses have been assessed considering that the tributary area of each MRF correspond to 1/4 of the total floor are, with an increase of about 10% to account for the weight of structural members and claddings. 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 interstorey drift limit for the Damage State Limitation (DSL) requirements is assumed as 1%, as suggested in the Eurocode 8 [1]. The beam-to-column joints are the low-damage connections, already tested in Di Benedetto *et al.* [6], while the CB connections are the innovative SC-CB connections experimentally tested in Latour *et al.* [14].



(a) (b)

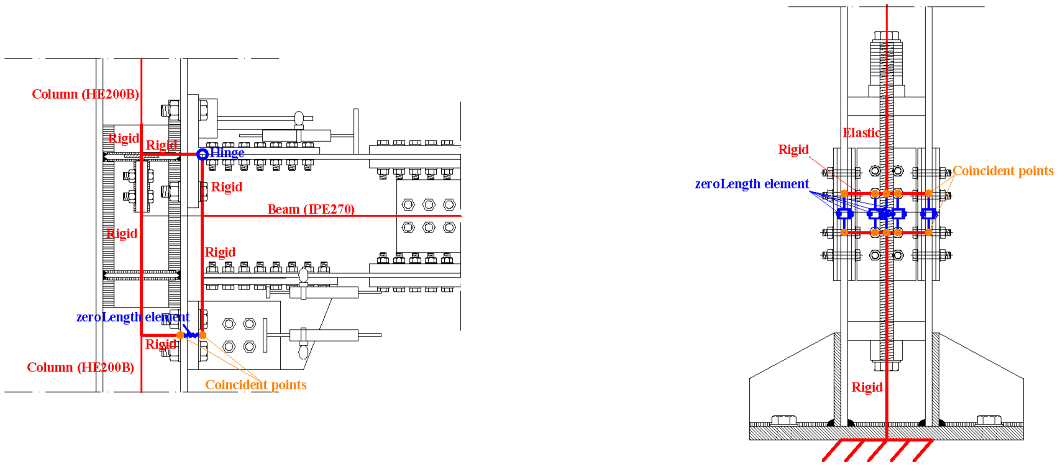
FIGURE 1 Case-study building: (a) Plan view of the prototype structure; (b) Plan and elevation view of the test specimen.

NUMERICAL SIMULATIONS

A two-dimensional non-linear FE model of the structure is developed in OpenSees [17]. Beams and columns are modelled with inelastic force-based elements '*forceBeamColumn elements*' [17] to account for the geometric and material non-linearities with a spread plasticity approach. Each element has been characterised by five integration sections subdivided into at least 120 fibres. The *'Steel01'* material [17] with 355 MPa yield strength and 275 MPa yield strength and 0.2% post-yield stiffness ratio is employed for columns and beams, respectively. Geometric non-linearities 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.

The beam-to-column joint is modelled with a refined strategy modelling which is consistent with the work of Di Benedetto *et al.* [6] and it is shown in Fig 2 (a). The rigid elements of the joints are modelled with '*elastic beam-column elements'* [17] 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 and a '*zero-Length element*' is placed at the centre-line of the FD. This is modelled by using a *'uniaxial hysteretic material'* with a symmetric trilinear force-displacement law, where the yielding force is equal to the sliding force of the FDs and a very low post-elastic hardening, to correctly capture the behaviour of the FDs.

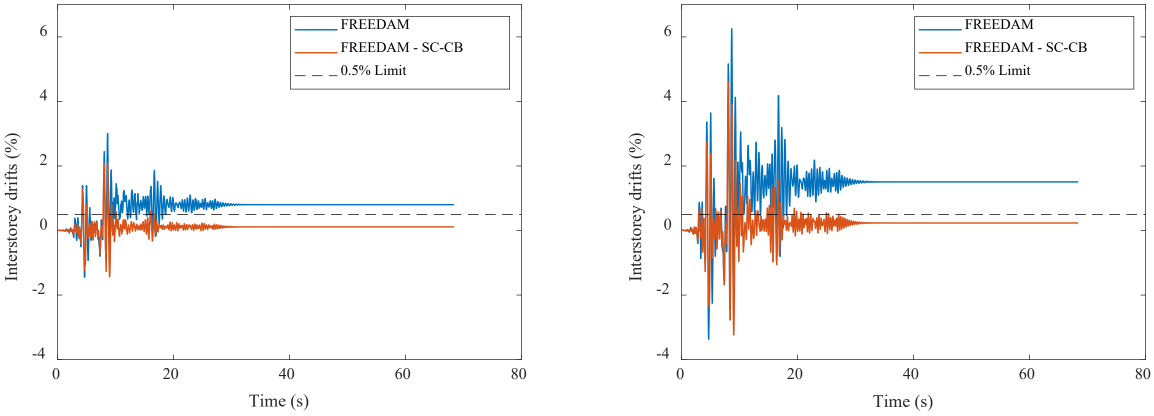
The SC-CB connection is shown in Fig 2 (b). It is composed of a rocking interface which is modelled with 8 '*elastic beam-column elements*' [17] with very high flexural stiffness which are used to connect the lower and the upper part of the column through non-linear springs. These springs are represented by four *'zero-length elements'* in parallel with gap elements to simulate the bilinear hysteretic response of the FDs and the contact behaviour of the column interfaces. FDs for both flanges and web are modelled by the *'Steel01'* material [17] considering a very high initial stiffness and very low post-elastic stiffness. Conversely, the contacts elements are defined by the *'Elastic compression-no tension'* (ENT) material [17], which exhibits an elastic compression-no tension force-displacement behaviour. The SC system composed of PT bars and disk springs is modelled with a single translational spring represented by a single *'zero-length element'* [17] with bilinear elastic-plastic behaviour. The initial post-tensioning force of the PT bars is modelled by using the *'Initial strain material'* [17].



(a) (b)

FIGURE 2 OpenSees models for connections of the frame: (a) FREEDAM beam-to-column joint; and (b) SC-CB joint.

Two configurations have been analysed: the structure equipped with the FREEDAM beam-to-column connections and conventional CBs, versus the equivalent structure, endowed with the SC-CBs. Non-linear time history analyses have been performed to investigate how the proposed SC-CBs influence the seismic response of the frame, considering several ground motion records scaled to several intensity levels. The preliminary numerical results are shown in terms of storey drift time history in Fig 3, for a single ground motion record (Imperial Valley, scaled at 1.10g). The results highlight how the introduction of the SC-CBs results as an effective measure in limiting the residual drifts of the structure. The structure with SC-CBs experiences residual interstorey lower than 0.5% at both stories. This value is conventionally assumed as the threshold beyond which repairing the building may not be economically viable, as suggested by McCormick *et al.* [18]. Conversely, this limit is not satisfied for the structure with full-strength CBs.



(a) (b)

FIGURE 3 Comparison of storey drifts time history for Imperial Valley (1.10g) for: (a) first storey and (b) second storey.

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