Design and Analysis of Large-Scale Tests of a Self-centring Seismic-Resilient Steel MRF

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Abstract. Conventional seismic design methods rely on structural inelastic hysteretic response to dissipate seismic energy. This approach often results in extensive damage and substantial direct and indirect losses following high-intensity earthquakes, thereby affecting the overall resilience of communities. To address this issue, modern earthquake engineering is facing an extraordinarily challenging era in providing affordable, high-seismic-performance structures able to minimise both seismic damage and repair time. To this end, the ERIES SC-RESTEEL (Self-Centring seismic-RESilient sTEEL structures) project examines the structural response, repairability, resilience, and performance recovery of low-damage self-centring steel Moment-Resisting Frames (MRFs) equipped with friction devices and post-tensioned bars with disc springs at column bases and beam-to-column joints. Shaking table tests will be conducted at LNEC (Laboratório Nacional de Engenharia Civil) in Lisbon, Portugal, to investigate the performance of a large-scale 3-storey steel MRF. Key objectives include evaluating the seismic performance of the structure, its reparability strategy, and the performance after repairs. This paper presents the test specimen design, advanced Finite Element analyses of various joint configurations, and the preparatory work for the tests. The findings offer valuable insights into the expected experimental outcomes.

Keywords: Self-Centring · Steel Moment-Resisting Frames · Seismic Resilience · Reparability · Finite Element Analyses

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1 Introduction

Earthquakes are destructive natural hazards, causing extensive structural damage and significant economic losses. Conventional seismic design methods (e.g., Eurocode 8 [1]) rely on structural damage to dissipate seismic energy and meet the life safety requirements. While this approach achieves its primary objective of protecting the occupants, it often results in severe damage, high repair costs and extended downtime.

To overcome these drawbacks, modern earthquake engineering faces an extraordinarily challenging task of providing seismic-resilient structures that can minimise both seismic damage and repair time, thereby allowing for limited socio-economic losses after severe earthquakes. Well-established solutions include the use of supplemental damping [2–5] and base isolation systems [6, 7]. Other strategies also aim to reduce residual deformations [8–13] and have recently gained recognition for their distinct advantages. In steel Moment Resisting Frames (MRFs), a promising solution involves integrating dissipative devices (e.g., Friction Devices (FDs)) and Self-Centring (SC) systems (e.g., Post-Tensioned (PT) bars) in Beam-to-Column Joints (BCJs) [14, 15] and Column Bases (CBs) [16–21]. These systems reduce structural damage and limit residual deformations, enhancing repairability and recovery time [22]. Although several studies on such SC structures have been conducted in recent years, demonstrating their advantages, there remains a significant need for advanced research to inform policy-making and building codes, thereby promoting their application in practice.

Previous studies investigated the use of SC-CBs [18–21], and performed large-scale Pseudo-Dynamic (PsD) tests to investigate the seismic performance and repairability of the system [22]. These studies demonstrated the benefits of the SC-CBs in minimising residual drifts and the effectiveness of the repair method. However, several open issues still need to be addressed. For example, one challenge related to the use of SC-BCJs is the potential frame expansion due to the rocking behaviour of beams, potentially inducing damage in the slab and compromising the self-centring capability of the joints [15]. Additionally, past studies [14] demonstrated that the placement of SC-BCJs could be optimised to limit structural complexity. Moreover, while proof-of-concept studies are widely available for such innovative systems, large-scale shaking table tests remain quite limited [e.g., 23, 24].

Within this context, the ERIES SC-RESTEEL (Self-Centring seismic-RESilient sTEEL structures) project aims to advance knowledge on such structural configurations by experimentally investigating the seismic performance, repairability, and effective placement of SC devices. The research involves large-scale shaking table tests on a 3-storey steel MRF equipped with both SC-BCJs and SC-CBs at LNEC in Lisbon, Portugal, as well as component tests on subassemblies at the STRENGTH Laboratory of the University of Salerno, Italy.

The solution features SC-BCJs and SC-CBs together with a splice introduced at the beam's midspan to mitigate the frame expansion effect. The shaking table tests aim to evaluate the response under real earthquake scenarios. In particular, they will allow: *1)* to analyse the impact-induced local damage at rocking interfaces and its effect on system damping (which the PsD tests only simulated numerically); *2)* to assess the influence of the vertical component of the ground motion on the self-centring capacity of the CBs;

3) to quantify repairability metrics, e.g., repair time and performance of the repaired structure across multiple scenarios.

This paper presents the test specimen design, the advanced Finite Element (FE) analyses of various BCJ subassembly configurations in ABAQUS [25], the non-linear dynamic analyses on the 3-storey structure in OpenSees [26] considering three different configurations for the joint distribution and the preparatory work for the tests.

2 Test Specimen

2.1 Design of the Test Specimen

The specimen for the shake table tests is illustrated in Fig. 1a. The internal MRF is intended to provide the lateral capacity, while the external frames are designed for gravity loads only. The inter-storey heights are equal to 1.92 m at the first storey and 1.80 m at higher storeys. The longitudinal and transverse bays have span lengths of 3.50 m and 2.00 m, respectively. The specimen has been extracted from a prototype structure characterised by 3 storeys and 3 bays in both directions and scaled based on the material and acceleration scaling identity, with a scaling factor equal to $\lambda = 0.6$.

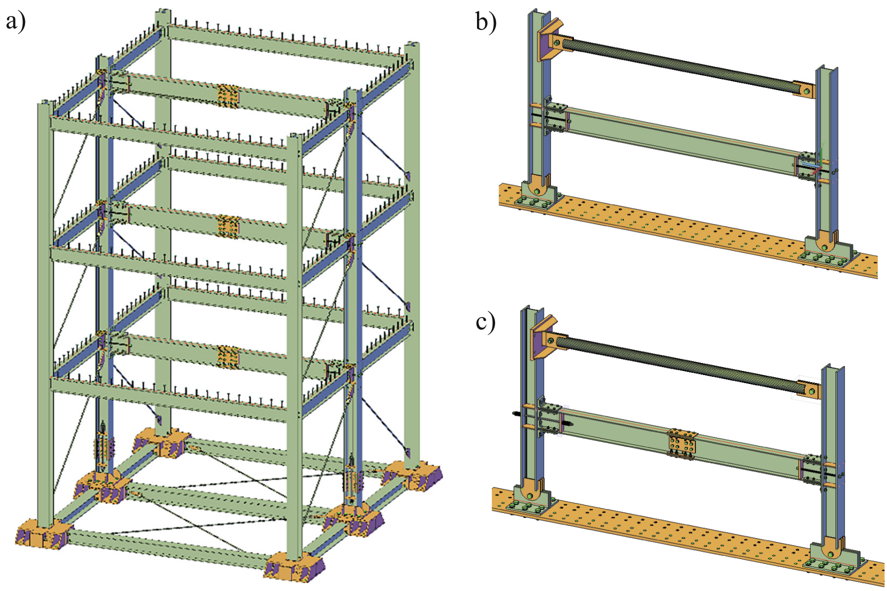

Fig. 1. a) 3D Large-Scale Test Specimen; b) and c) Test Sub-assemblies.

The design was carried out in accordance with 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 D. The Collapse Limit State (CLS) is assumed to have an intensity equal to 150% of the ULS. The behaviour factor based on the Eurocode 8 for MRFs in Ductility Class High (DCH) is assumed as $q = 6.5$. The inter-storey drift limit for the Damage Limit State (DLS) is assumed to be 1% for non-structural elements fixed in a way such as not to interfere with structural deformations. The assumed floor system is a HI BOND A55/P600 steel-concrete composite floor with a total height of 110 mm. The floor masses of the specimen to carry out the test are equal to 11.76 and 10.31 tonnes at intermediate floors and the roof, respectively. Hence, the total mass of the specimen is equal to 33.82 tonnes, which is compatible with the specific equipment available at the research infrastructure (<40 tonnes). Beam and column cross-sections of the MRF are IPE240 and HEB180, while the profiles of the gravity frames are IPE180 and HEA160, respectively. All the profiles are of steel grade S355. The MRF is equipped with BCJs and CBs in two different configurations, *i.e.,* with and without PT bars. For the sake of clarity, hereinafter, the joints without PT bars are referred to as Low-Damage (LD) joints (LD-BCJs and LD-CBs), while joints with PT bars are referred to as Self-Centring (SC) joints (SC-BCJs and SC-CBs).

The specimens of the component tests are shown in Fig. 1b and c. These tests aim to characterise the response of the BCJ subassemblies and evaluate the effectiveness of the proposed solution in mitigating the frame expansion effect. These subassemblies are extracted from the second storey of the 3-storey structure. Two configurations will be tested: *i)* BCJs implemented with a continuous beam (Fig. 1b) and *ii)* BCJs where a splice allowing axial displacements is included at midspan (Fig. 1c). Each frame subassembly will be tested in both LD and SC configurations.

2.2 Design of the Beam-to-Column Joints (BCJs) and Column Bases (CBs)

Figure 2 illustrates the BCJ with and without PT bars, *i.e.,* the SC-BCJ in Fig. 2a and the LD-BCJ in Fig. 2b. In both configurations, the connection is equipped with FDs, which dissipate the seismic input energy through the alternate slippage of the surfaces in contact. The FDs consist of properly coated steel friction shims and steel cover plates clamped with pre-loadable bolts. The self-centring system is composed of PT bars symmetrically placed with respect to the column's depth and arranged in series with a system of disc springs, ensuring an adaptable stiffness-resistance combination. Slotted holes are included at the beam's flanges to accommodate the target rotation (*i.e.,* 0.04 rads). In the case of the SC-BCJs, the moment-rotation behaviour is the typical flag-shape curve, where M_1 is the moment at the gap opening. Conversely, in the case of LD-BCJ, the moment-rotation behaviour is a hysteretic rectangular curve where M_{slip} is the slippage moment of the FDs.

Figure 3 illustrates the CB connection with and without PT bars, *i.e.,* the SC-CB in Fig. 3a and the LD-CB in Fig. 3b. Similar to the BCJ, in both configurations, the column base is connected by a combination of FDs and a SC system composed of PT bars and disc springs. The mechanism and moment-rotation behaviour of both CBs is similar to the BCJ.

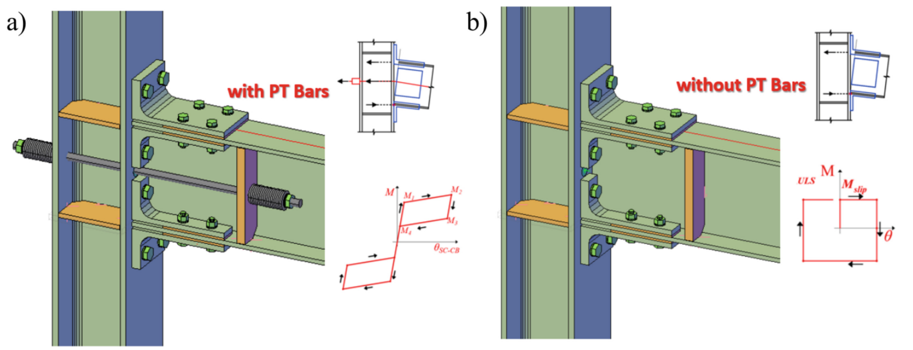

Fig. 2. 3D view & moment rotation behaviour for: a) SC-BCJ; b) LD-BCJ.

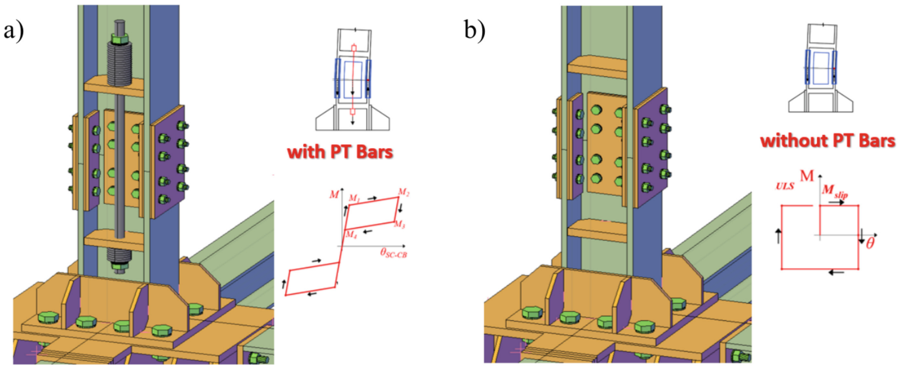

Fig. 3. 3D view and moment rotation behaviour of: a) SC-CB; b) LD-CB.

3 Experimental Programme

Table 1 summarises the proposed test programme. Phase 1 of the programme investigates the local behaviour of materials and components, including steel coupons, friction shims, and PT-bars with disc springs. Phase 2 includes quasi-static tests on the BCJ subassemblies, both with and without the central splice, considering both the LD- and SC-BCJs. The tests will be performed using cyclic loading with increasing amplitudes up to a target rotation of 0.04 rad, according to AISC 341–16 [27]. Phase 3 investigates the dynamic response and seismic performance of the 3-storey structure through shaking table tests. These tests will be performed considering different layouts of the SC joints' placement along the height of the structure and a set of ground motion records with increasing intensities from the DLS to the CLS. Such tests will evaluate the seismic performance, SC capacity, and repairability of the structure. Each test will be preceded by characterisation tests, such as white noise tests, to estimate damping ratios and natural periods. Phase 4 of the programme evaluates the performance of the repaired structure under repeated records and the influence of the vertical component of the ground motion.

Wire transducers and accelerometers are used at each level to measure horizontal displacements and accelerations. Additionally, the local response of the structure and its components are assessed through strain gauges and Linear Variable Differential Transformers (LVDTs). LVDTs also allow for tracking the opening and closing of the gap in the splice mechanisms. Load cells and strain gauges are installed to monitor tensile forces and deformations in the PT bars along with the test. Finally, advanced sensors (*i.e.,* https://tokbo.it) are used in bolts and PT bars to monitor the force variation.

Table 1. Experimental programme.

Phase	Description
1	Material and components characterisation tests, coupon tests, double lap-shear friction joints, and tests on PT bars with disc springs
2	Subassemblies cyclic tests, with and without splice, with LD- and SC-BCJs, and considering different levels of PT bars prestressing
3	Shaking table tests of the 3-storey large-scale test specimen with different placements of the self-centring joints
4	Additional tests with and without vertical ground motions and repeated tests for reliability assessment

4 Finite Element Analysis

4.1 Finite Element Analysis of the Subassemblies

Figure 4a shows the ABAQUS model developed to simulate the tests on the subassemblies and provide insights to inform experimental testing design. For the sake of brevity, only the configuration with a splice at midspan is represented. The FE models have been developed using a procedure similar to the one used in Elettore *et al.* [21].

To comprehensively analyse the response of the connection, the numerical study was conducted in sequential phases. Initially, the isolated SC-BCJ was subjected to a monotonic loading. Subsequently, the two different configurations of the single-bay frame (with and without splice) were examined under the same monotonic conditions and successively under cyclic loading.

Figure 4b shows the comparison of the axial force evolution in the beam between the two frame configurations: with and without splice. The results demonstrate the suitability of the proposed solution in avoiding the frame expansion and the consequent increase of the axial force in the beam. Figure 5 shows the comparison of the monotonic and cyclic moment-rotation responses of the different models. Figure 5a shows a consistent slippage moment, corresponding to the activation of the FDs, among the three different configurations. The results also show the detrimental effect deriving from the frame expansion. This results in an axial force increase in the beam and, consequently, in a moment hardening response, leading to plastic deformations in the beam and column web. Similarly, Fig. 5b illustrates the cyclic moment-rotation response of the SC-BCJs with and without splice. The results show a slightly better self-centring capability for the frame with splice. The benefits are limited in this configuration but are expected to be more pronounced in other configurations with different forces in the PT bars and FDs, as well as multiple bays. These preliminary results highlighted the importance of the splice in reducing damage, ensuring self-centring capability, and ensuring a more controlled and predictable structural response.

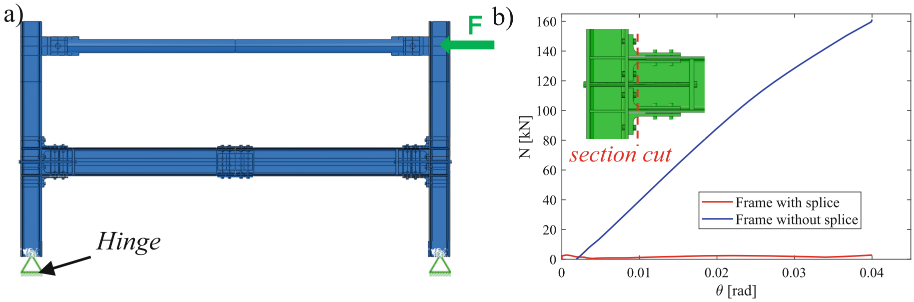

Fig. 4. ABAQUS model and results: a) Frame configuration with splice; b) Axial force comparison between the two frame configurations.

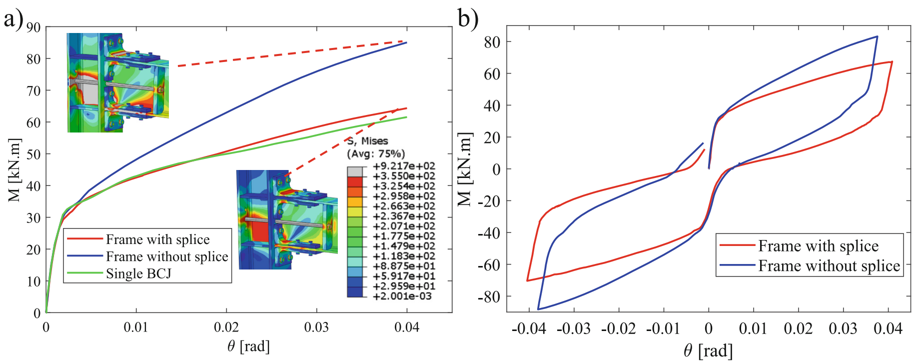

Fig. 5. Comparison in the response of SC-BCJ: a) Monotonic moment-rotation behaviour; b) Cyclic moment-rotation behaviour

4.2 Finite Element Analysis of the 3-Story Frame

2D non-linear FE models are developed in OpenSees [26] (Fig. 6). Three different models have been developed considering different configurations of the joints. In particular: *1)* the MRF equipped with LD-BCJs and LD-CBs (*i.e.*, LD-MRF); *2)* the MRF with LD-BCJs and SC-CBs (*i.e.*, LD-MRF-CB); and *3)* the MRF with SC-CBs and SC-BCJs (*i.e.*, SC-MRF). Numerical simulations are conducted to investigate and compare the seismic performance of the structures equipped with different connection typologies and to verify their compatibility with the test equipment's capacities. The LD- and SC-BCJ modelling strategies are shown in Fig. 6b and c and are consistent with Pieroni *et al.* [14]. On the other end, the LD- and SC-CB modelling strategies are shown in Fig. 6d and e, and are consistent with Elettore *et al.* [20].

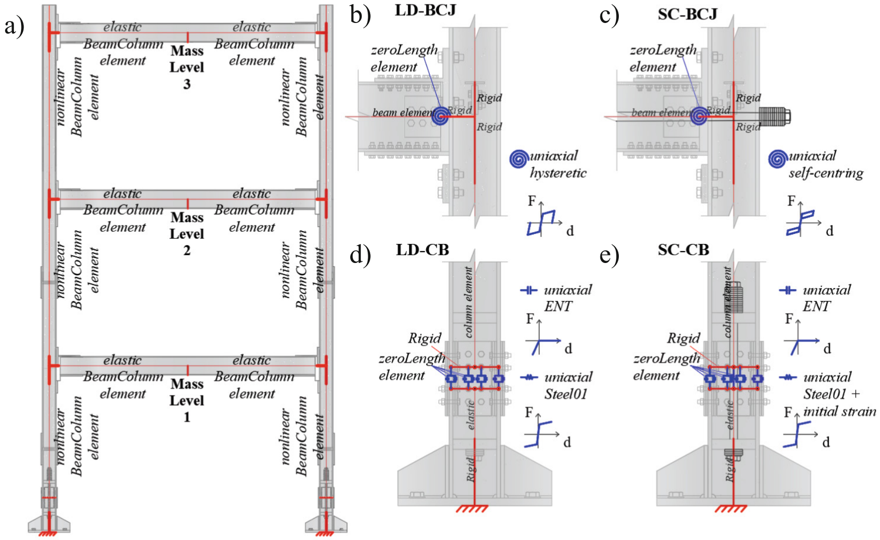

Fig. 6. 2D OpenSees Modelling of: a) MRF; b) LD-BCJ; c) SC-BCJ; d) LD-CB; e) SC-CB.

The three models have an almost identical natural vibration period $T_1 = 0.43$ s. A large set of ground motion records was originally considered for the record selection. This set was restricted to 5 records, as reported in Table 2. In all cases, the records were scaled in time by a scaling factor of $\lambda^{1/2} = 0.6^{1/2} = 0.77$ to match the specimen scaling criteria. Moreover, their acceleration intensity was scaled at the ULS and at the CLS intensities (*i.e.,* $S_{a,ULS}$ $(T_1) = 1.182$g and $S_{a,CLS}$ $(T_1) = 1.773$g). All ground motion input records were verified to ensure compliance with the shake table's requirements in terms of Peak Ground Displacement (PGD), Peak Ground Velocity (PGV) and overturning moments for all intensities of interest.

Figure 7 shows the results of the non-linear time-history analyses for a single ground motion record, *i.e.,* Northridge-01. The comparison of the time histories of the Inter-storey Drift Ratios (IDRs) among the three configurations at the CLS intensity demonstrates that, as expected, frames with self-centring connections (*i.e.,* the LD-MRF-CB and SC-MRF) exhibit a significant reduction in the residual IDRs at all storeys, confirming the effectiveness of the solution. The SC-MRF structure results in a completely self-centring response with almost zero residual IDRs for both seismic intensities. Additionally, despite having SC joints only at the base, the LD-MRF-CB exhibits a significant reduction in residual drifts at all storeys, in all cases below the reparability limit of 0.5%. Conversely, this limit is never satisfied for the LD-MRF, which experiences larger residual IDRs of approximately 4% for the CLS.

Table 2. Selected ground motions evaluated at the CLS complying with shake table capacity.

Earthquake	Horizontal			Vertical	
	PGA [g]	PGV [mm/s]	PGD [mm]	PGV [mm/s]	PGD [mm]
Northridge-01	0.92	476.40	111.41	191.95	49.91
Ferndale-891	0.81	469.79	71.94	81.34	16.67
Niigata, Japan	1.12	527.45	114.27	164.95	85.15
Chi-Chi-2951	0.80	382.58	164.27	174.81	107.75
Ferndale-905	0.74	423.51	51.52	298.79	56.75
Limit of Shake Table	**-**	**600.00**	**200.00**	**400.00**	**200.00**

Such numerical analyses strongly supported the record selection, identifying records that, while ensuring compliance with the shake table's requirements, allow exploring the seismic response considering different ground motions' characteristics.

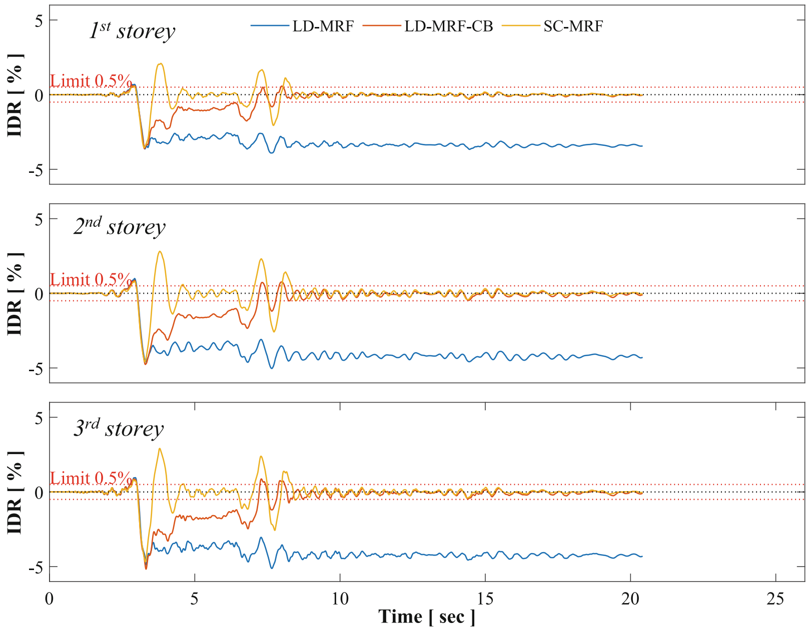

Fig. 7. Comparison of the Inter-storey Drifts Ratios (IDRs) time histories among the three configurations for a single ground motion record (Northridge-01) at the CLS.

5 Conclusions

The present paper illustrates the preliminary numerical work conducted for the design of the experimental campaign of the ERIES-SC-RESTEEL (Self-Centring seismic-RESilient sTEEL structures) project. The project examines the structural response, repairability, resilience, and performance recovery of low-damage self-centring steel Moment-Resisting Frames (MRFs), including friction devices and post-tensioned bars with disc springs at Column Bases (CBs) and Beam-to-Column Joints (BCJs). The experimental campaign includes a series of shaking table tests on a large-scale 3-storey steel structure considering different Self-Centring (SC) joint placements, configurations and properties. The shaking table tests will be conducted at LNEC in Lisbon, Portugal, while additional tests on subassemblies will be carried out at the STRENGTH Laboratory of the University of Salerno, Italy. Finite Element (FE) models were developed in ABAQUS for the subassemblies. The results highlighted the importance and effectiveness of the proposed solution in mitigating frame expansion effects, hence reducing damage to the connection and promoting the self-centring response. Additionally, numerical models of the 3-storey frame were developed in OpenSees, and non-linear dynamic analyses were performed to investigate the performance of the structure considering three distributions of self-centring and/or low-damage joints. The outcomes offer useful insights for the design of shaking table tests and for the prediction of the expected experimental results. The results confirmed the effectiveness of the SC connections in reducing the residual deformations. Moreover, the numerical study allowed defining the preliminary set of records to be used in the shaking table tests.

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