Response Analysis of Column-Base Connections in Existing Steel Frames

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Abstract. The seismic response of existing steel frames is significantly affected by the behaviour of column-base connections. Depending on their design, these connections can exhibit significantly different stiffness, strength, and ductility. While extensive research has been conducted to understand the response of these connections across a wide range of configurations, most studies have focused on uniaxial loading. However, the three-dimensional nature of earthquakes typically subjects these connections to biaxial bending and shear forces. To address this research gap, the ERIES-HITBASE (Earthquake Assessment of Base-Column Connections in Existing Steel Frames) project experimentally investigated the response of exposed column-base connections via bi-directional pseudo-dynamic (PsD) tests. These tests were carried out on a full-scale, three-dimensional steel frame at the Structures Laboratory of the University of Patras, Greece. The steel frame featured two types of column-base connections, *i.e.,* unstiffened and stiffened, representing respectively the base connections of an external moment-resisting frame and an internal gravity frame, respectively. The response of each component of column-base connections was monitored during the PsD-tests to capture their behaviour. This paper presents the preliminary results of numerical simulations conducted for the tested column-base connections. Local and response quantities are investigated, and threshold limits of damage are identified.

Keywords: Existing steel frames · base-column connections · Pseudo-dynamic tests · seismic performance · finite element modelling

1 Introduction

Column-base connections in steel frames typically consist of steel plates welded to the base of columns and anchored to the foundation system. These connections transfer axial forces, shear forces, and, in some cases, bending moments and represent essential components for the stability of the structure. However, several post-earthquake studies [e.g., 1–5] highlighted that, in existing structures, such components are often highly

G. O'Reilly and G. M. Calvi (Eds.): ERIES-IW 2025, LNCE 718, pp. 159–169, 2025.
https://doi.org/10.1007/978-3-031-98893-6_16

vulnerable to seismic actions. In this context, there is a need for advanced assessment and retrofitting methods, for which limited guidance is offered in current European codes. For instance, the framework implemented in Eurocode 8-Part 3 [6] for assessing existing steel buildings primarily accounts for beam-to-column connections and lacks explicit guidance for column bases. Additionally, for such connections, there is also a need to establish proper definitions of moment-rotation relationships beyond their peak strength capacities [7, 8] and quantify deformation response for innovative displacement-based design/assessment approaches.

Previous studies have significantly enhanced our understanding of the behaviour of column-base connections across various configurations, including exposed base plate connections [e.g., 9-11] and embedded connections [e.g., 12-14], the latter being commonly used in many European countries for low- to medium-rise steel buildings. However, experimental work in the literature has been limited, with most studies focusing on uniaxial bending [e.g., 7, 15-20], while only a few have considered the effects of biaxial bending [e.g., 21, 22].

To this end, the ERIES-HITBASE project (Earthquake Assessment of Base-Column Connections in Existing Steel Frames) experimentally investigated the behaviour of exposed column-base plate connections. Bi-directional pseudo-dynamic tests (PsD) were conducted at the Structures Laboratory (STRULAB) of the University of Patras, Greece. These tests involved a full-scale specimen sub-structured from a non-seismically designed steel frame, featuring two types of exposed column-base plate connections, one representing moment connections and the other simple connections. This paper introduces the steel frame used as a test specimen and presents the preliminary validation of the finite element (FE) models in ABAQUS that will be used to further expand and generalise the experimental results.

2 Experimental Tests

2.1 Description of Case Study Building

The case study building is a two-storey, three-bay by three-bay steel frame; the geometry is shown in Fig. 1. The building was primarily designed for gravity loads following the European design code Eurocode 3 (EC3) [6], which considered the self-weight of partitions equal to 0.5 kN/m^2 and an imposed load of 3 kN/m^2. Thus, HEB140 and HEB160 were used for perimeter and internal columns, respectively; such profiles were made of S355 steel. Moreover, the depth of the composite slab was 250 mm, which was made of C20/25 concrete and grade B450C reinforcement. It is worth noting that the bases of the perimeter columns were designed to be fixed connections to simulate the external moment-resisting frames, while those of the internal columns were pinned connections, representing internal gravity frames.

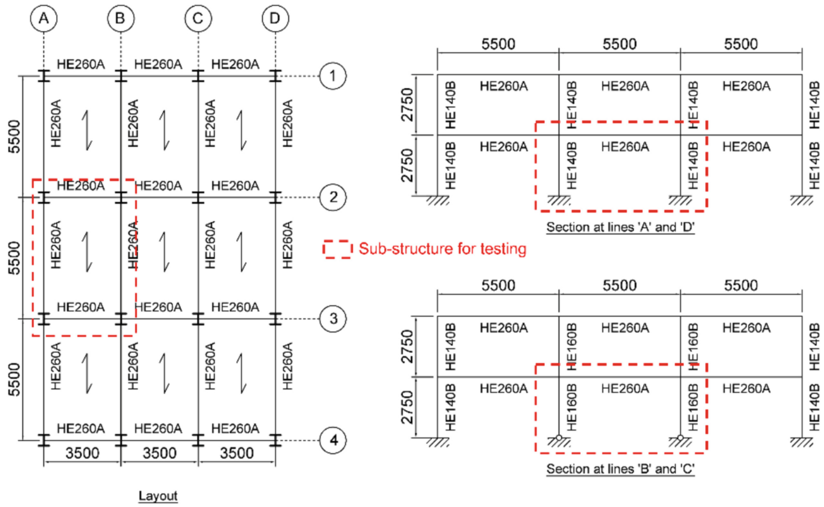


Fig. 1. Layout and section views of the case study steel frame (units in mm).

2.2 Description of the Test Mock-Up

Figure 2 shows the test mock-up, which was extracted from the case study building, as highlighted in Fig. 1. The specimen spans 5.5 m in the longitudinal direction and 3.5 m in the transverse direction and has a storey height of 2.75 m. Beams and columns were made of S355 steel, while the composite slab was made of C20/25 concrete and B450C reinforcement. Concrete footings supporting each column-base connection were also constructed in the lab to investigate the behaviour of column-base plate connections. These footings were made of C20/25 concrete and reinforced with B450C steel bars.

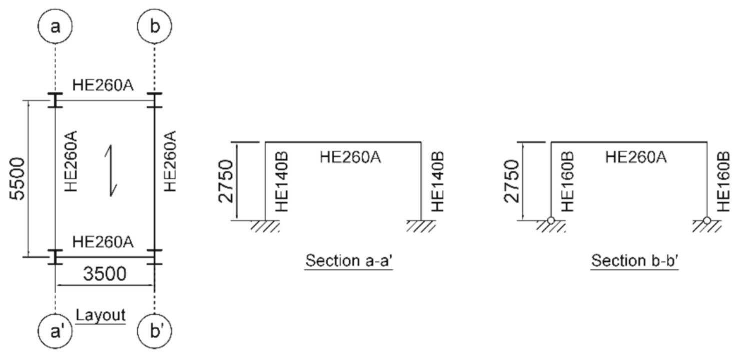


Fig. 2. Test specimen (units in mm).

The specimen had two types of column-base plate connections, one stiffened and the other unstiffened, corresponding to the fixed and pinned connections in the case study building. Lastly, additional masses totalling 15.76 tons were placed on the slab to simulate the load imposed by the non-structural components and other loads.

2.3 Material Tests

Table 1 summarises the mechanical properties of the materials obtained from characterisation tests. The mean compressive strength of the C20/25 concrete used for the slab and foundation was determined from six samples, yielding values of 32.3 MPa and 34.2 MPa, respectively. The yield strength of the steel profiles ranged from 370 to 431 MPa, while the ultimate strength varied between 487 and 560 MPa. Additionally, the mean compressive strength of the mortar, measured using 50 mm cube samples, was found to be 47.1 MPa.

Table 1. Mean mechanical properties of materials (units in MPa).

	Concrete		Steel				Mortar
	Slab	Foundation	HE 260A	HEB 140	HEB 160	IPE 220	
Mean strength	32.3	34.2	-	-	-	-	47.1
Yield strength	-	-	431	370	431	391	-
Ultimate strength	-	-	549	505	560	487	-

2.4 Pseudo-Dynamic Tests

Figure 3 illustrates the test setup. The PsD-test method of the 3D-frame required the use of a number of actuators to achieve the desired deformation pattern, including translational displacements along the main axes and rotation about the vertical axis. The loading scheme to provide the necessary kinematics involved a pair of actuators acting in tandem along the long direction of the frame (*i.e.,* controllers 1 and 2 in Fig. 3a) and a third actuator operating in the transverse direction (*i.e.,* controller 3 in Fig. 3a). The former controlled the displacement of the frame along the longitudinal axis as well as its rotation, whilst the latter controlled the displacement of the structural system along the transverse axis.

Two diagonally opposite columns of the specimen, *i.e.,* Columns C1 and C3 in Fig. 3c, were densely instrumented. Figure 4 provides an overview of the instrumentation of both column bases, including the type and position of the relevant sensors, which enabled monitoring the key response parameters (*i.e.,* strains and inclination) at several points and sections.

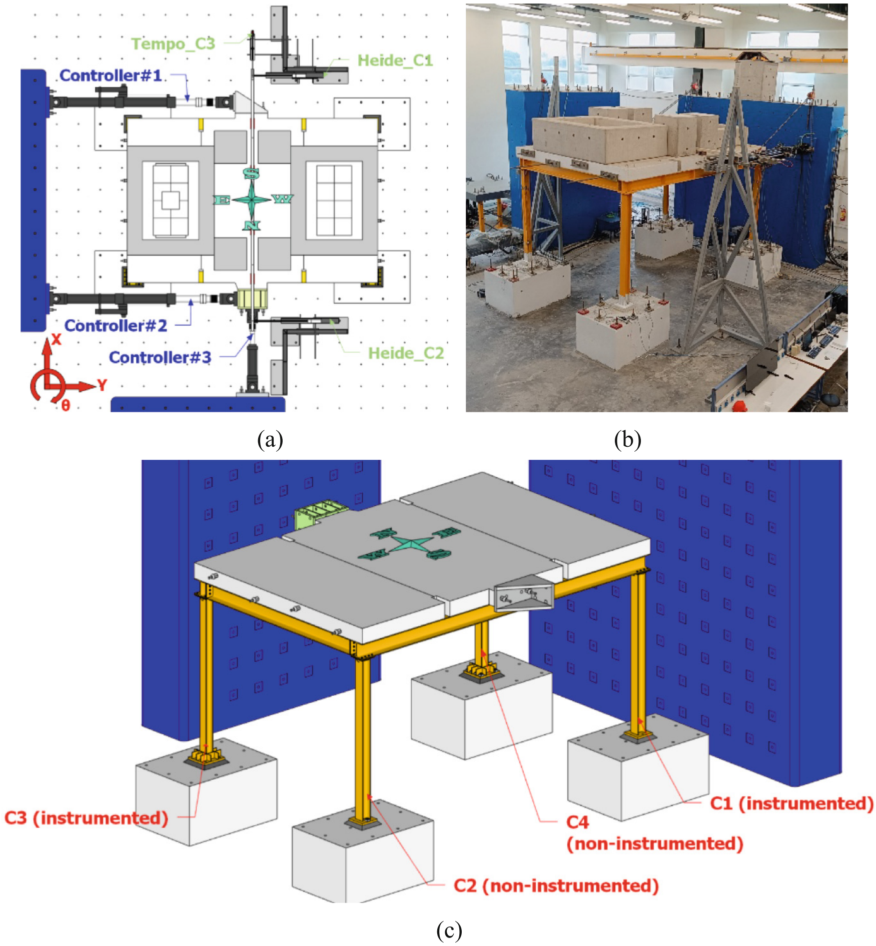


Fig. 3. Test setup: (a) plan view of the control equipment and labelling; (b) photo of the setup; (c) 3D view of the setup and column labelling.

The scope of the tests includes investigating the effects of sequential earthquakes and the influence of cumulative damage on the column-bases on the response of the structure. For this, a pair of natural seismic records was selected and sequentially applied to the structure, accounting for both horizontal components of the earthquakes. The two selected ground motion records referred to the 2016 Central Italy earthquakes and were extracted from the Engineering Strong-Motion Database (ESM) [24]. Preliminary analyses considered various combinations of the specimen axis along which each pair of records and their direction (sign) was applied. These analyses concluded that the most detrimental combination involved applying the record in Fig. 5a along the longitudinal (E-W) specimen (Y) axis, while the record in Fig. 5b applied along the N-S specimen (X) axis.

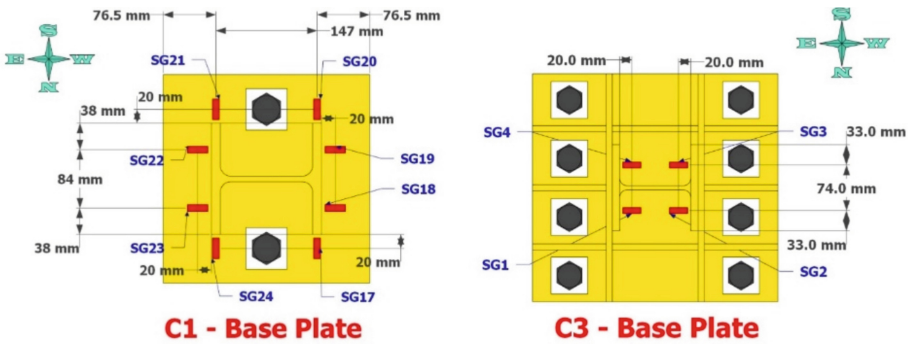


Fig. 4. Instrumentation located at the base plates (units in mm).

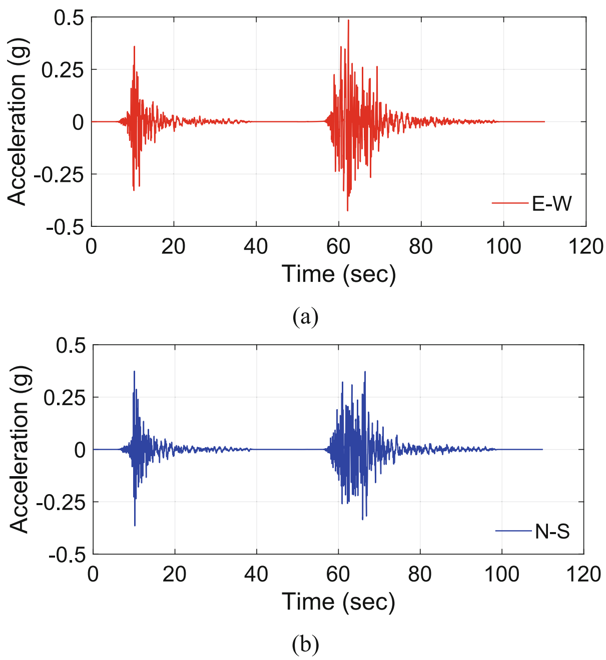


Fig. 5. Ground motion records for (a) longitudinal, Y-direction; (b) transverse, X-direction.

The test matrix of the experimental campaign is summarized in Table 2. Initially, the specimen underwent free vibration tests along both of its main axes to determine its modal properties. Following this, the specimen was subjected to quasi-static cyclic tests along both axes, achieving a maximum floor displacement of 27.5 mm in each direction. Finally, a series of PsD-tests were conducted on the specimen using the pre-selected ground motion records, with incremental scaling factors for the ground motion intensity (SF) ranging from 0.2 to 1.5.

Table 2. Test matrix for the 3D steel frame specimen in the laboratory.

No	Description	Note
1	Free vibration test: Y direction	10-mm pull-back
2	Free vibration test: X direction	10-mm pull-back
3	Quasi-static cyclic test: X direction	max. Displacement: 27.5 mm
4	Quasi-static cyclic test: Y direction	max. Displacement: 27.5 mm
5	Pseudo-dynamic (PsD) tests	Two concurrent sequences of records applied

3 Numerical Simulations

3.1 Description of the FE Model

An advanced 3D-FE model of the tested specimen was built using the ABAQUS software [25] to advance the understanding of the structural response observed in the tests. Figure 6 shows the FE model of the entire specimen, while Fig. 7 shows the modelling details for the connections (*i.e.,* base plates and beam-to-column joints). Bolts and anchor bolts were modelled explicitly to capture the local response of connections. The Concrete Damage Plasticity (CDP) model was used to define the concrete material, while the von Mises criterion was used to simulate the material properties of the steel elements. The composite concrete slab was assumed to behave elastically with a Young Modulus of 33 GPa. This assumption was based on test observations, where no damage or plastic response was detected in the slab. This allowed for a simplified modelling strategy and reduced computational effort during the analysis.

The interactions between the components were simulated by surface-to-surface contacts or tie constraints. For instance, the interaction between the grout and base plate, anchor bolts and plates, holes and anchor bolts, and bolts with beams and plates were modelled via surface-to-surface contact. The tangential behaviour was modelled using a penalty friction formulation, and "Hard" contact was employed for the normal behaviour. The friction coefficient for steel-to-steel was assumed to be 0.3 [26], while 0.1 for concrete-to-steel [27]. Conversely, for other surfaces without potential tangential or normal displacements, such as the slab with beams and welds attached to the plates, tie constraints were implemented. The slab was also tied to the main and secondary beams due to the presence of the studs. All parts were meshed with C3D8R elements. Fixed boundary conditions were assumed at the base of the foundations.

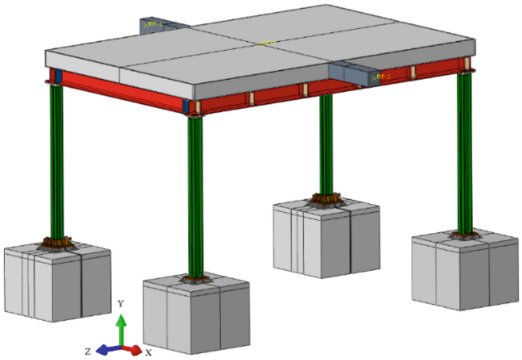
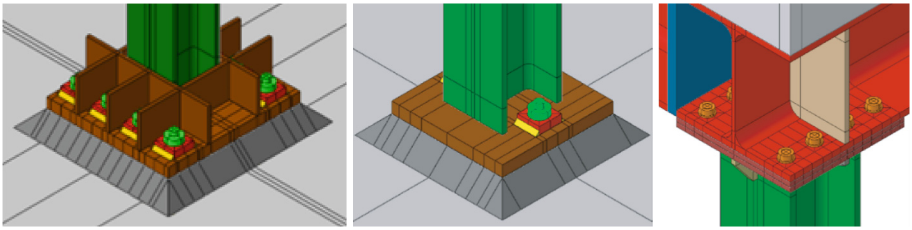


Fig. 6. 3D model of the test specimen in ABAQUS.



(a) (b) (c)

Fig. 7. Details of modelling of connections: (a) stiffened column-base connection; (b) unstiffened column-base connection; (c) beam-to-column connection.

3.2 Model Validation

A displacement-controlled load, with a time-history shown in Fig. 8, was applied alongside in the X direction and imposed in correspondence with Controller 3 (see Fig. 3a). This displacement history aims at simulating the experimental data extracted from the

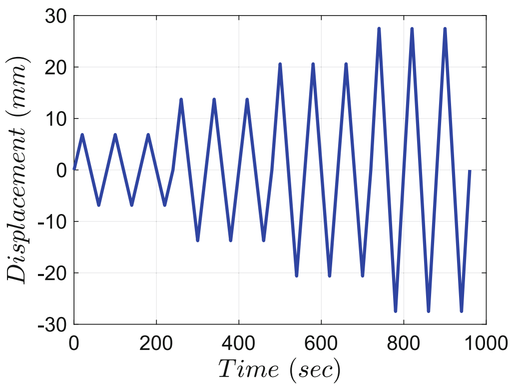
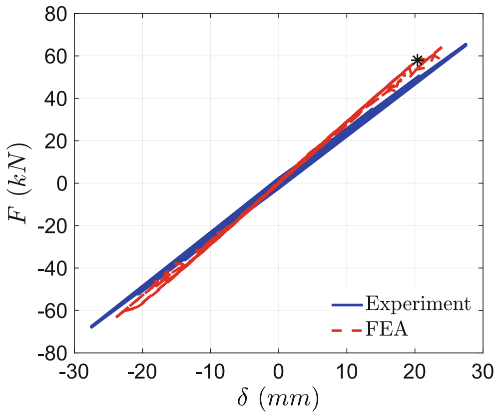
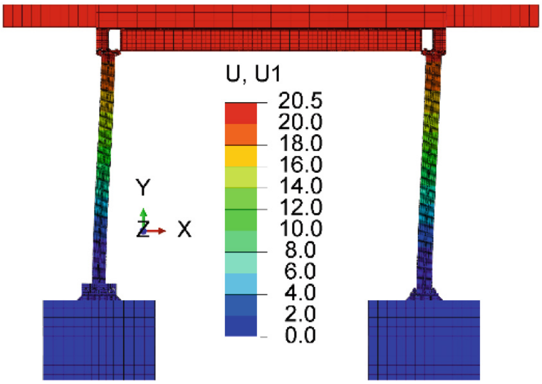


Fig. 8. Loading protocols implemented in the 3D model.

sensor named Tempo_C3 (see Fig. 3a). The resultant force-displacement curve in the X direction obtained from the numerical analyses is then compared with the experimental results, as shown in Fig. 9a. Moreover, Fig. 9b shows the deformed shape of the FE model corresponding to an imposed displacement of 20 mm (*i.e.,* corresponding to the black star in Fig. 9a). It is worth highlighting that the deformation is shown with a scale factor of 5. The results highlight the acceptable accuracy of the numerical model despite some discrepancies.



(a)



(b)

Fig. 9. Results from FE simulation: (a) force-displacement response; (b) deformed shape.

4 Conclusions

This paper summarises the preliminary results of an experimental and numerical study devoted to investigate the seismic response of exposed base-plate connections representative of gravity-load designed steel frames. Full-scale PsD-tests have been carried out on a single-story, one-by-one bay steel frame representing a sub-structure of a non-seismically designed structure. The scope of the tests includes investigating the effects of sequential earthquakes and the influence of cumulative damage on the column-bases on the response of the structures. Preliminary finite element simulations have also been carried out, and the numerical predictions satisfactorily mimic the experimental results. Further calibration will also be carried out to compare the local response at column bases. The calibrated model will then be used to perform numerical parametric analysis to investigate the seismic behaviour of column base connections.

Acknowledgements. This work is part of the transnational access project "ERIES-HITBASE", supported by the Engineering Research Infrastructures for European Synergies (ERIES) project (www.eries.eu), which has received funding from the European Union's Horizon Europe Framework Programme under Grant Agreement No. 101058684. This is ERIES publication number C79.

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