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DEMOUNTABLE COLUMN BASE FOR REUSABLE MOMENT-RESISTING STEEL FRAMES

Summary: An innovative joint, constructed to allow steel columns to be easily removed and reused from concrete foundations, is proposed, contributing to the design for deconstruction and reuse practices. The connection assembly primarily consists of anchor couplers and anchors embedded in a concrete foundation, and a demountable upper part of the anchors, complemented by a base plate as well as bolts, flange and web cleats. Experimental tests and finite element modelling were employed to evaluate the joint performance. Advanced numerical models of the proposed joint were developed, validated against experimental data, and incorporated into numerical models of steel frames. Large-scale numerical models of frames were used to evaluate the structural performance and efficiency of the proposed joint. The study assessed the rotational stiffness and moment-rotation response of the proposed joint across different frame dimensions. The analysed joint was classified in compliance with the provisions specified in the standard EN 1993-1-8.

Keywords: column foundation joint, design for disassembly and reuse, moment-rotation characteristics, demountable steel frames

DEMONTAŽNO REŠENJE OSLANJANJA STUBOVA U CILJU PONOVNE UPOTREBE ČELIČNIH OKVIRNIH NOSAČA

Rezime: Sa ciljem da se u inženjersku praksu implementiraju principi projektovanja u svrhu demontaže i ponovne upotrebe konstrukcijskih elemenata, u radu je prikazano rešenje demontažnog oslanjanja čeličnih stubova na betonsku temeljnu konstrukciju. Konstrukcijsko rešenje ovakve veze integriše primenu mehničkih spojnica i ankera prethodno ubetoniranih u temelj, kao i demontažne gornje delove ankera uz upotrebu oslonačkih čeličnih ploča, zavrtnjeva i dodatnih komponenata za vezu ankera sa čeličnim stubom. Ponašanje veze opisano je rezultatima eksperimenta i numeričkim modelima. Složeni numerički modeli predložene veze razvijeni su i validirani na osnovu eksperimentalnih rezultata. Ovakav numerički model je potom integrisan u modele okvirnih čeličnih nosača, na kojima je vršena analiza efikasnosti predloženog rešenja demontažne veze u pogledu rotacione krutosti i nosivosti. Analizom su obuhvaćeni okvirni nosači različitih visina i raspona. Na osnovu dobijenih rezultata numeričke analize izvršena je klasifikacija veze u skladu sa odredbama standarda EN 1993-1-8.

Ključne reči: oslanjanje stubova, projektovanje u svrhu demontaže i ponovne upotrebe, moment-rotacija karakteristika veze, demontažni čelični okvirni nosači

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1. INTRODUCTION

With a linear economy as the dominant model, which relies on the "take-make-dispose" model, the construction industry is one of the major contributors to the generation of waste from construction and demolition [1]. The built environment demands intensive resource allocation, consuming half of all extracted raw materials. At the same time, EU construction and demolition activities contribute over 35% to waste production [2]. Therefore, the construction industry is experiencing growing pressure to be more resource-efficient and to reduce construction and demolition waste. To overcome this issue, effective integration of circular economy principles should be performed, and the primary objective should shift toward the prolonged, repetitive use of raw materials and structural elements, enhancing the long-term value of structural components. Nevertheless, less than 15% of structural steel components are currently reused across Europe [3]. Embracing the potential of structural elements and materials recycling and reuse, and putting the design for deconstruction and reuse (DfDR) processes into practice, is essential to implementing principles of the circular economy. Success demands cross-disciplinary collaboration, innovative design, early lifespan assessment, and demountable joint technologies.

1.1. DESIGN TOWARDS STEEL COLUMN BASE JOINT DEMOUNTABILITY

Considering traditional structural solutions for steel buildings, the demolition process often prioritises destructive and quick deconstruction methods, involving cutting and breaking of structural components, rather than careful dismantling. A crucial aspect in implementing DfDR principles is the design of innovative joint solutions that provide efficiency in the deconstruction process so steel structural elements can be easily disassembled, transported and reassembled at the end of each building's life cycle. Numerous innovative joint solutions, specifically designed for reusable moment-resisting steel frames, have been proposed in recent periods. Most of them are typically designed with adjustable beam-to-column joints which promote flexibility in structural element lengths, making it easier to adapt the structure to new layouts in future lifecycles [4-7]. Also, the efficient disassembly and reuse of the steel frame structures depend heavily on designing a fully demountable steel column base joint, which eliminates the need for extensive refurbishment. Demountable steel column base joints have recently been developed and tested through full-scale tests and monotonic or cyclic loading [8-11].

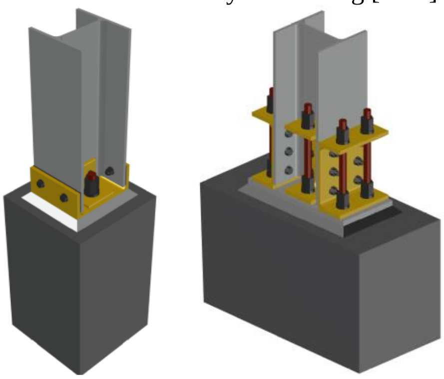

Figure 1: Demountable steel column-to-concrete foundation joint

Following the main DfDR principles, innovative design solutions for a fully demountable steel column-to-concrete foundation joint were developed and investigated at the University of Belgrade Faculty of Civil Engineering within the Horizon Europe project Circ-Boost. The proposed solutions, as shown in Figure 1, offer several advantages: (i) fully demountable joint with no welded connections, simplified and accelerated assembly and disassembly process; (ii) use of mechanical fasteners, i.e. anchor couplers and bolts for foundation connection and individual steel components connections, providing an easy and independent fabrication process; (iii) inclusion of supplementary connection components, within various geometries and lengths of upper part of the anchors which allows adjustment of the steel joint and concrete foundation geometry. As part of the Circ-Boost Horizon project, a demountable steel column joint was evaluated through both experimental laboratory testing and subsequent finite element (FE) analysis. Furthermore, this innovative joint configuration was integrated into the steel frame of a pilot house, which will be constructed within the project.

The paper details the structural performance and efficiency of the demountable steel column base joint, performed through experimental prototype testing and numerical FE analysis. Advanced FE models were developed and validated against the test results and incorporated into large-scale numerical models of steel frames. This study evaluated the rotational stiffness and moment-rotation response of the proposed joint across various frame dimensions. Comparison of the results with the provisions specified in the standard EN 1993-1-8 [12] was obtained.

2. EXPERIMENTAL WORK

2.1. TEST MATRIX

The prototype testing within the Circ-Boost Horizon project was conducted under laboratory conditions to evaluate three demountable column base joint configurations within four large-scale specimens. The influence of the joint geometry on its structural behaviour was examined relative to the dimensions and position of the cleat components and the lengths of the upper portions of the anchors. Also, joints were tested to evaluate the effect of concrete foundation reusability and to demonstrate the joint demountability through the assembly and disassembly process. The detailed geometry of the one experimentally tested specimen is given in Figure 2.

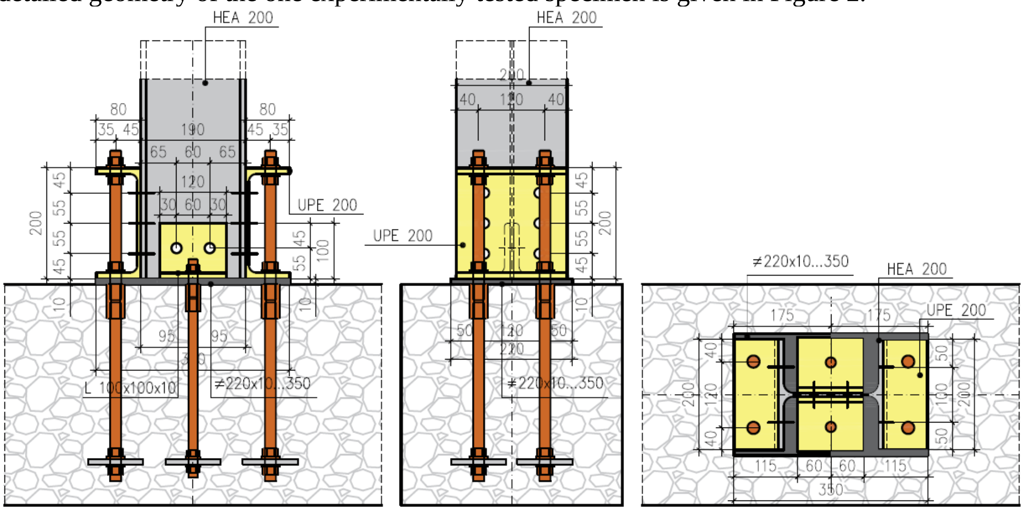

Figure 2: Experimentally tested demountable steel column joint geometry

The steel column features a hot-rolled HEA 200 profile, assembled using flange and web cleats fastened with fully threaded M16 bolts. Specifically, six bolts connect each column flange to the hot-rolled UPE 200 flange cleats, while two bolts secure the double-sided hot-rolled L100x10 web cleats. All bolt holes have a diameter of 18 mm. During assembly, the bolts were tightened to 75% of their nominal preload force [12]. To anchor the connection assembly to the foundation, fully threaded 20 mm diameter anchors attach to the flange cleats (two per cleat), whereas 16 mm anchors are utilised for the web cleats. The corresponding anchor hole diameters feature 2 mm clearance. The specimen also incorporates a 220x10x350 mm base plate. The column foundation, measuring 40x40x180 cm, includes embedded reinforcement along with the lower sections of the anchors and anchor couplers.

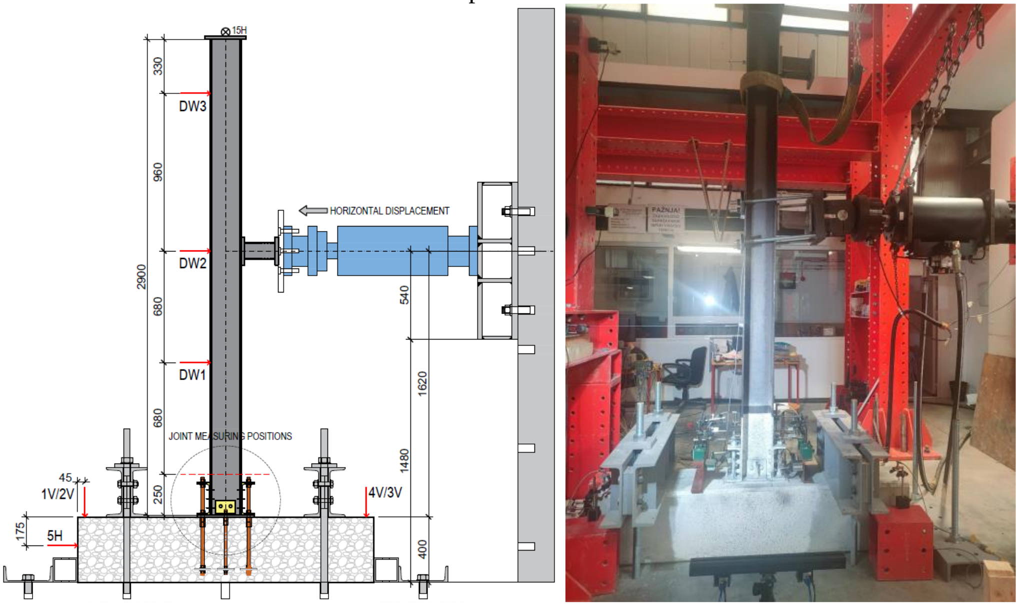

Figure 3: Test set-up

The experimental setup is given in Figure 3. The horizontal load was applied to the column through a hydraulic actuator, 1620 mm above the upper surface of the concrete foundation, with displacement controlled at a constant loading rate of 4.2 mm/min. Horizontal movement of the column in the plane of the hydraulic actuator was monitored using three draw-wire (DW) sensors over the column height, while out-of-plane movement of the column top was monitored using one linear variable displacement transducer (LVDT). To monitor the efficiency of the foundation fixing, five LVDTs were used to measure vertical and horizontal displacements relative to the laboratory strong floor. Moreover, in the proximity of the foundation, nine LVDTs were positioned to measure horizontal and vertical displacements of the steel column and flange and web cleats, together with a non-contact optical system based on the technology of Digital Image Correlation (DIC) [11]. Strain development in the steel column, cleat components and M20 anchors in the tension zone of the joint were monitored using 16 strain gauges (SG).

2.2. RESULTS OF EXPERIMENTAL TESTING

To evaluate the performance of the demountable column base joint, material properties of steel components and concrete foundation were determined. Flat coupons were machined from the web and flange of the hot-rolled steel profiles used for the specimen, whereas round coupons were obtained from the bolts and anchors. The yield strength f_y and ultimate tensile strength f_u, obtained from the tensile tests, are summarised in Table 1. Based on these outcomes, all hot-rolled steel sections conform to structural steel grade S355. The tensile testing of the round coupons verified property class 8.8 for the bolts and anchors. The concrete compressive and tensile strength were continuously monitored after pouring till the day of the steel column-to-concrete foundation joint testing. Compressive strength and modulus of elasticity were determined on cylinders at 28 days (f_{cm}=53.4 MPa, E_{cm}=39.5 GPa). The tensile strength was also established from tests after 28 days (f_{ctm}=3.65 MPa). These tests confirmed that the concrete achieved the C45/55 strength after 28 days.

Table 1: Material properties of steel joint components

Joint component	Specimen position	f_y [MPa]	f_u [MPa]
Column, HEA 200	web	439.0	555.6
	flange	427.0	546.5
Flange cleat, UPE 200	web	404.0	513.2
	flange	370.0	522.6
Web cleat, L 100x10	flange	315.0	439.2
Bolt M16		661.3	867.9
Anchor M20		795.0	927.5
Anchor M16		854.8	952.1

Test results of the demountable column base joint testing are given in Figure 4a, representing the moment-rotation curve, which is determined based on the DIC measurement of the steel column in the proximity of the connection to the steel base plate and concrete foundation. Moment is determined by multiplying the obtained horizontal force by the lever arm at the position of rotation measurements. The demountable column base joint was not tested till the failure, since the actuator's stroke limit was reached. Nevertheless, the results given in Figure 4a indicate that the joint exhibited a high level of post-plastic behaviour. Bending moment resistance, within the actuator's stroke limit, was reached at 96.45 kNm, with the ultimate rotation capacity of 154.4 mrad. The obtained initial stiffness of the joint was 4790 kNm/rad, representing the elastic behaviour of the joint. Considering classification requirements for the steel column base joint given in EN 1993-1-8 [12], test results indicate that the joint can be classified as a semi-rigid joint regarding stiffness classification and a partial-strength joint regarding classification by strength, as indicated in Figure 4b. The steel joint components and concrete foundation did not fail before the actuator reached its stroke limit. While the steel column, as the main joint component, remained in the elastic stress region, significant plastic deformation occurred in the flange cleats and long M20 anchors. Additionally, the long M20 anchors showed complex bending in both the tension and compression zones, with heavy plastic deformation in the accompanying nuts and washers in the tension zone close to the foundation connection, as shown in Figure 5a.

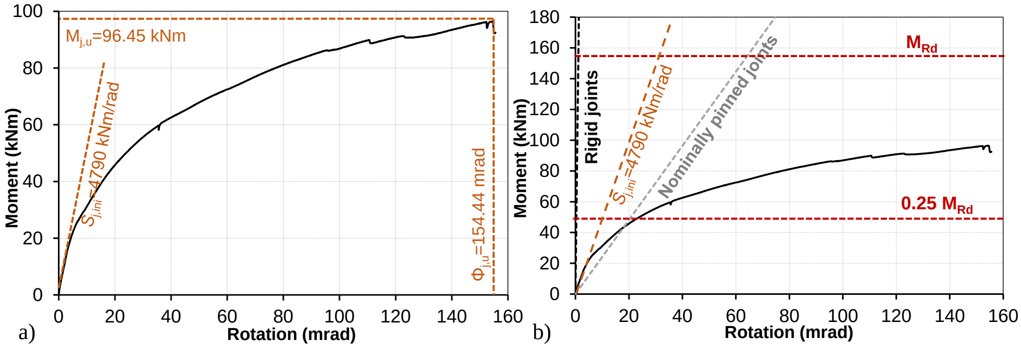

Figure 4: Test results: a) moment-rotation curve; b) joint classification

Demountability of the joint is demonstrated through the unbolting of all bolts from the main steel components and the anchors from anchor couplers, as shown in Figure 5b and 5c. This is supported by the absence of failure in the concrete and maintained structural integrity between the anchors and the anchor couplers. The flange cleats and anchors, which undergo a high level of plastic deformation, do not compromise disassembly, but it is not expected that they can be reused, while the column, as the main joint component, can be reused. The aforementioned conclusions relate to the loading levels close to the joint’s resistance. However, under reduced loading, approximately 70% of the established resistance, which aligns with the serviceability limit state, the cleats stay within the elastic range, making them suitable for reuse.

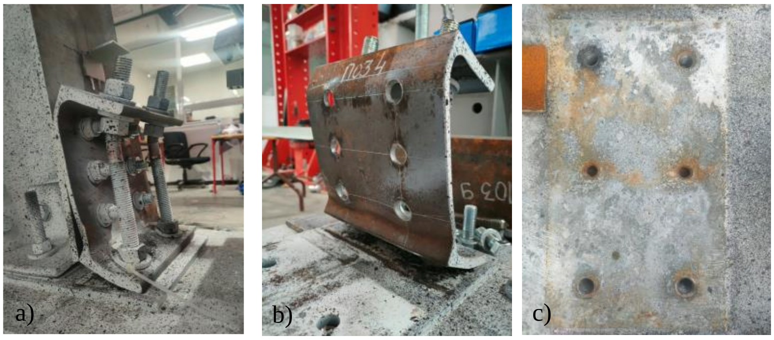

Figure 5: Specimen disassembly: a) joint upon testing; b) flange cleats upon unbolting; c) concrete foundation after steel joint components demounting

3. NUMERICAL ANALYSIS OF DEMOUNTABLE STEEL COLUMN BASE JOINT

3.1. JOINT FE MODEL DEVELOPMENT AND APPLICATION IN STEEL FRAMES

Numerical FE analysis for both the experimentally tested column base joint and steel frame FE model was performed using the software Abaqus [13], with the Dynamic Explicit Solver.

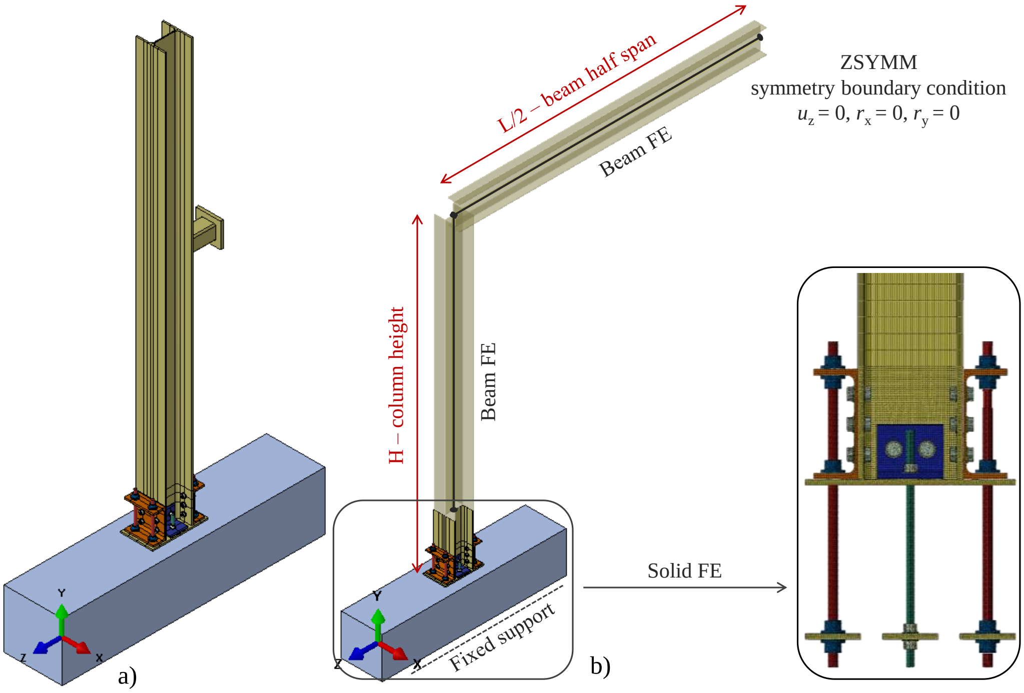

Figure 6: FE models: a) steel column base joint test; b) steel frame model

The first part of the numerical analysis was focused on the FE model development for the experimentally tested column base joint and validation of this model against the test results. All joint components were modelled as solid parts, as illustrated in Figure 6a. The FE simulation was performed through two steps: bolt preloading and horizontal load application. To simulate bolt preloading, a specific temperature gradient was applied. The horizontal load was applied as displacement control, using a smooth step amplitude function and a 1E-06 time increment for the mass scaling method. The following boundary conditions were implemented: fixed supports for the concrete foundation bottom surface, whereas the end of the short steel element, used to apply horizontal load by the actuator, was restrained from lateral displacement and longitudinal rotation. Contacts between different FE model components were defined using general contact: "hard" contact in the normal direction, and penalty contact in the tangential direction, with a friction coefficient of 0.15 for steel components, 0.4 for contact between the steel base plate and foundation upper surface and 0.9 for embedded anchors within the foundation. All steel components were meshed with C3D8R elements and varied mesh sizes throughout the model, from 2 mm in bolts and bolt holes, to the 10 mm elements at the column upper end. The concrete foundation was meshed with C3D10M finite elements with varied sizes from 4 mm around anchors to 25 mm to the edge of the foundation. The material behaviour was modelled to match the experimental testing, i.e. steel material properties were assigned as true stress-strain curves according to the tensile test, and the Concrete Damage Plasticity model was used to describe concrete behaviour under uniaxial compression according to the model proposed by Pavlović et al. [14] and for tension according to Vigneri et al. [15].

The second phase of FE analysis was focused on the evaluation of the joint behaviour across various steel frame spans and heights. Therefore, the validated FE model of the steel column base joint was incorporated in the steel frame FE model, as illustrated in Figure 6b. Beam elements B31 with a 50 mm size were used to model the column and beam, while the joint region was modelled using solid elements, following the previously validated numerical joint models. The solid and beam parts, as well as two beam parts, were connected using an MPC constraint type Beam. The analysis comprised two steps retained from the validated joint models: bolt preload and load application. Uniformly distributed line loads were applied: a vertical line load with an amplitude of 20 kN/m on the beam, and an 8 kN/m horizontal line load on the steel column (direction from the adjacent support). To reduce computational time, symmetry boundary conditions were imposed at the beam mid-span, while the fixed supports were imposed on the concrete foundation bottom surface. The cross-sections, HEA 200 for the column and IPE 240 for the beam, were kept constant throughout the analysis, while the steel frame dimensions varied between 6.0 m and 8.0 m for beam span and 3.0 m and 6.0 m for column height. Contacts between different FE model components, as well as the mesh size of solid FE model parts and material models, were kept the same as previously described for the FE model of the steel column joint.

3.2. VALIDATION OF JOINT FE MODEL BASED ON EXPERIMENTAL RESULTS

The comparison of moment–rotation curves between experiments and FE analysis is given in Figure 7. The FE analysis indicates the sensitivity of the results considering the size of the holes in the specific joint components. The notation in the FE model name is: COL – column, CLE – cleat components, C – 2 mm clearance and WC – without clearance on the related component.

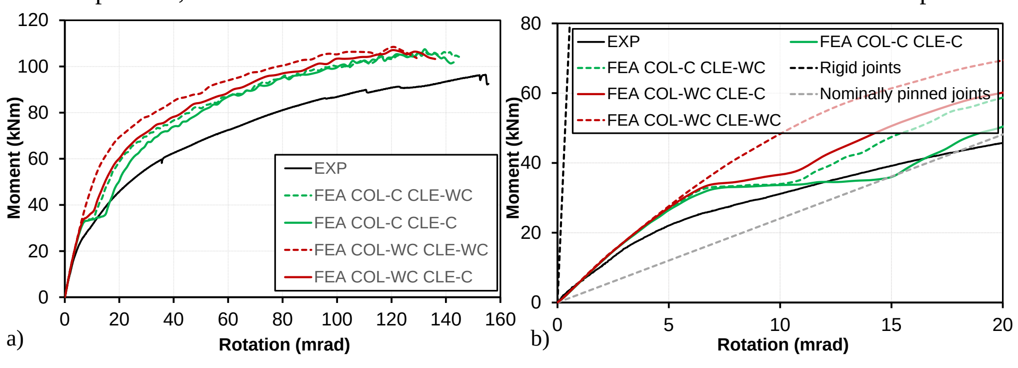

Figure 7: FE analysis results: a) moment-rotation curve; b) initial stiffness

The test results do not indicate that the preloaded bolts slip, while the FE analysis indicates small sensitivity of the test results considering the size of the bolt holes. This influence is mostly related to the overall moment-rotation behaviour, while the initial stiffness of the joint is not influenced by hole size, as shown in Figure 7b. Nevertheless, the observed difference in joint rotation and moment resistance between FE analysis and test results is 7% and 12%, respectively.

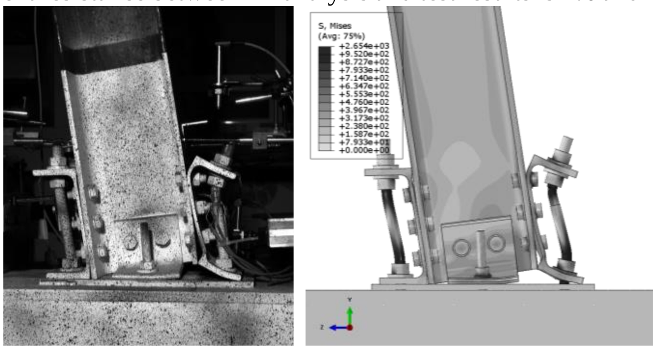

Figure 8: Deformed joint configuration – experimental vs. FE

The difference in the obtained results is highly sensitive to geometric imperfections of the specimen upon bolting and anchoring vs. geometric idealisation and centric position of bolts and anchors in accompanying holes, contact modelling and friction coefficient assumptions, and bolt pretensioning and installation conditions of the anchor assemblies. However, the deformed configuration of the joint gained through FE analysis gives satisfactory agreement with the test results, as presented in Figure 8. Also, numerical simulations indicated that the concrete sustained only minor damage in both compression and tension, localised in the proximity to the anchors.

3.3. RESULTS OF STEEL FRAME FE ANALYSIS

Moment–rotation curves obtained from steel frame FE models, together with joint classification by stiffness [12], are presented in Figure 9. Following EN 1993-1-8 [12], the lower limit for rigid joints is defined as $30EI_c/L_c$. The upper limit for nominally pinned joints is not explicitly defined, but the limit defined as $0.5EI_c/L_c$ was used. Results given in Figure 9 indicate that the proposed joint within the steel FE frame models behaves as semi-rigid.

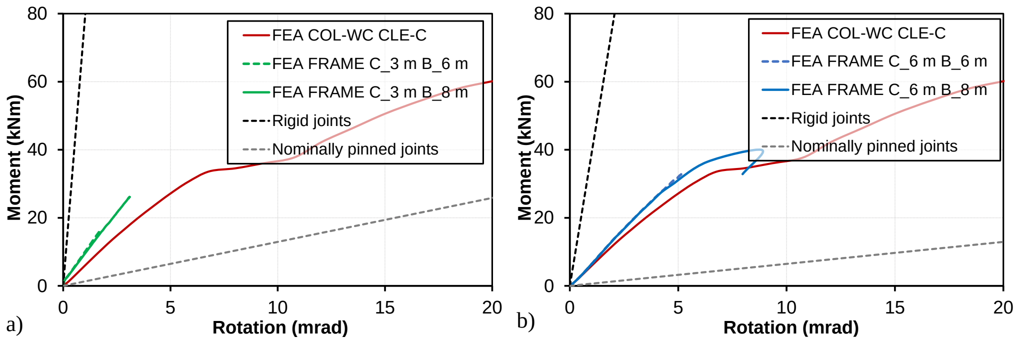

Figure 9: Moment-rotation curves: a) 3.0 m column height; b) 6.0 m column height

Stiffness classification of steel column base joint is influenced by Young's modulus of steel E, the column second moment of area I_c, and the column height L_c. The frame FE analysis included two column heights, 3.0 and 6.0 m, in combination with 6.0 m and 8.0 m beam spans, even though the stiffness classification according to EN 1993-1-8 [12] is not influenced by beam length. The variation in beam spans was adopted to obtain a higher level of bending moment at the steel column base joint, under the same line loads. As illustrated in Figure 9, the beam length has a minor influence on the initial stiffness, and for all analysed steel frames the moment-rotation curves are within the elastic limit behaviour, except the steel frame with 6.0 m column height and 8.0 m beam length, which developed a high level of plastic deformation. On the other hand, as expected, the column height has a significant influence on the joint initial stiffness.

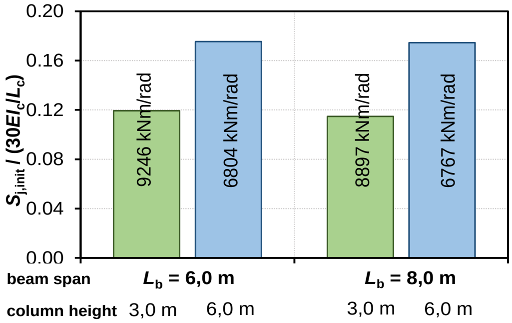

Figure 10: FE frame analysis – initial stiffness ratios

As shown in Figure 10, the ratio of the initial stiffness to the lower stiffness bound for rigid joints ranges from approximately 0.11 to 0.18. Although the lowest initial stiffness values are observed for column heights of 6.0 m and both analysed beam spans, these cases exhibit the highest ratio $S_{j,ini}/(30EI_c/L_c)$, ranging from 0.17 to 0.18. This low stiffness ratio also accounts for the plastic behaviour observed in the highest steel frame analysed, which featured the longest beam span. The redistribution of internal cross-section moments and forces, when compared to normal (idealised) fixed or pinned support conditions, led to early plastification of critical cross-sections. Figure 10 also illustrates the minor influence of the beam span on the initial stiffness, with a reduction of approximately 4% for the column height of 3.0 m. On the other hand, for the same beam length, an increase in column height to double results in an approximately 26% reduction of initial stiffness. The maximum initial stiffness for the analysed steel frames does not exceed 10000 kNm/rad.

4. CONCLUSIONS

This paper presents a performance evaluation of the fully demountable steel column-to-concrete foundation joint, conducted through a combination of testing and FE analysis. The joint was specifically designed to investigate the reusability of structural elements and to demonstrate its demountability. The results presented lead to the following conclusions:

- The moment resistance within the actuator stroke limit of the experimentally tested joint is determined as 96 kNm with 154 mrad of ultimate rotation capacity. The initial stiffness of the joint was determined to be 4790 kNm/mrad. The obtained results place the joint within a partial-strength and semi-rigid joint.
- The joint behaviour under increasing load is governed by the plastic deformation of the flange cleats engaged in load transfer, together with long anchors. FE joint models calibrated against test results give satisfactory agreement, with the observed difference in joint rotation and moment resistance being 7% and 12%, respectively.
- Joint behaviour within the steel FE frame models is also described as a semi-rigid joint, with results which demonstrate high sensitivity to the column height and minor influence of the beam span. Initial stiffness of the analysed joint within FE frame models does not exceed 10000 kN, with the maximum obtained value approximately double that of the test results.

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