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SEISMIC PERFORMANCE OF CHS-TO-I-BEAM COMPOSITE JOINTS WITH PASSING-THROUGH PLATES: EXPERIMENTAL AND NUMERICAL APPROACH

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Abstract

This research investigates the seismic behavior of CHS-to-I-beam composite joints with passing-through plates using a comprehensive methodology that integrates both experimental and numerical analyses. To enhance the connection performance and assembly procedure of I beams with tubular CHS columns, the latter are laser-cut, letting the connection plates passing-through, and the beams are bolted to the plates. Columns are then filled with concrete. An experimental test is carried out, allowing to calibrate a finite element model (FEM). The combined experimental and numerical approach ensures robust and accurate results, contributing valuable insights into the joint response and supporting the development of resilient structural systems for seismic applications.

Keywords: Seismic performance; Composite Joints; Finite Element Models; Circular Hollow Section; Experimental Analysis.

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1 INTRODUCTION

The use of circular hollow sections (CHS) in civil engineering structures is appreciated for their excellent structural properties [1], architectural value and their applicability in composite steel-concrete structures. However, the design of beam-to-column connections represents a significant challenge in terms of ductility and seismic performance [2], as traditional solutions exhibit some limitations, primarily due to the lack of flat surfaces for direct welding [3], [4]. Typically, IPE beams are either welded directly to the column or connected using large diaphragms and stiffeners [5].

An alternative to these conventional connections requires the application of laser cutting technology (LCT) that allows the creation of slots in CHS columns for passing-through plates, improving the structural efficiency of the joints [6]. Passing-through plates restore the beam continuity, increase joint stiffness and enhance force transfer efficiency [7].

Previous studies have highlighted the potential of this type of joint, which can create full-strength rigid connections under gravitational loads in both steel and composite structures [8], [9]. However, uncertainties remain regarding the behavior of these joints under seismic loads [10], [11], [12]. Despite the structural benefits introduced by passing-through plates, experimental investigations on bare steel specimens have revealed some critical issues. The absence of concrete infill in the CHS column leads to significant distortions, particularly in the joint area. These distortions, caused by the localized deformation of the thin-walled tubular section, compromise the structural integrity of the connection and may lead to early failure.

This article shows the experimental test and numerical simulation of a sub-structure representing an IPE-CHS joint adopting passing-through plates.

a. First three fabrication steps from left to right – 3D view

b. First three fabrication steps from left to right – Top view

c. Prototype of assembled joints (4th step)

Figure 1: Prototype of assembled 4-way joints with passing-through beams and [6]

2 EXPERIMENTAL TESTS

2.1 Design of specimens

The specimen is assembled with a CHS 355.6/10 filled with C25/30 concrete and IPE 400 beams, both made of S355 steel. The main dimensions are reported in Figure 2. The beam is bolted to passing-through plates that are welded to the column.

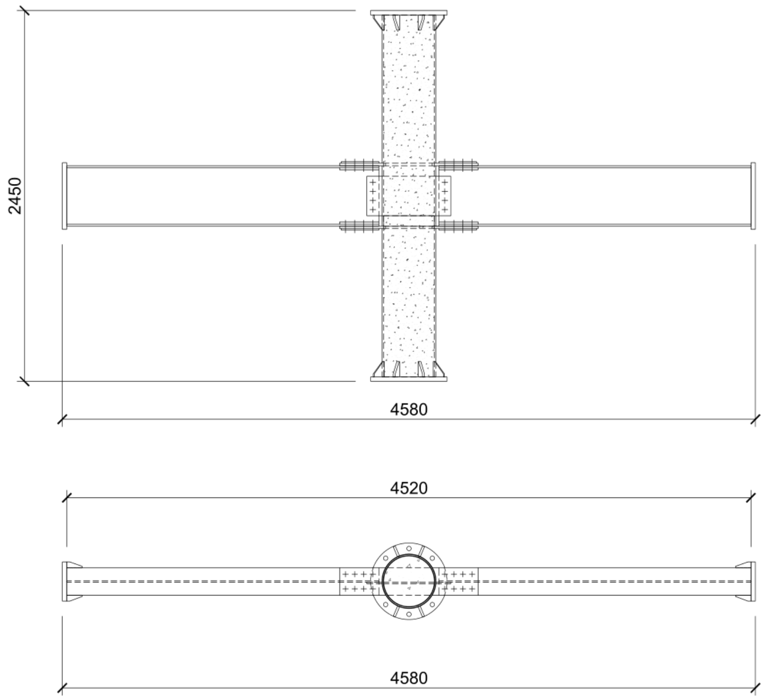

Figure 2: Specimen general dimensions

The passing-through plates had been welded in the shop, after the laser cutting operations, to the CHS with 8mm throat thickness fillets. Beams' web and flanges were connected to passing-through plates to realize the joint of a moment resisting frame (MRF). For this purpose, C10.9 bolts with different nominal diameters were adopted for the connection.

The joint was designed according to Eurocode principles to ensure efficient stress transfer during testing. A previous experimental campaign showed that in 4-way joints, crack propagation in the welds within the tensile zone could lead to brittle failure, resulting in the tearing of the entire section [7], [9]. Therefore, we designed the connection so that the weld-related mechanism would be the nominal weakest failure mode, allowing us to focus on the behavior of the welds.

2.2 Test setup and instrumentation

The experimental tests have been carried out applying a horizontal load to the top of the column through two hydraulic jacks pinned. Each specimen was fixed to the substructure via a pinned connection at the base of the column and two rods linked to the beam ends, as shown in Figure 3.

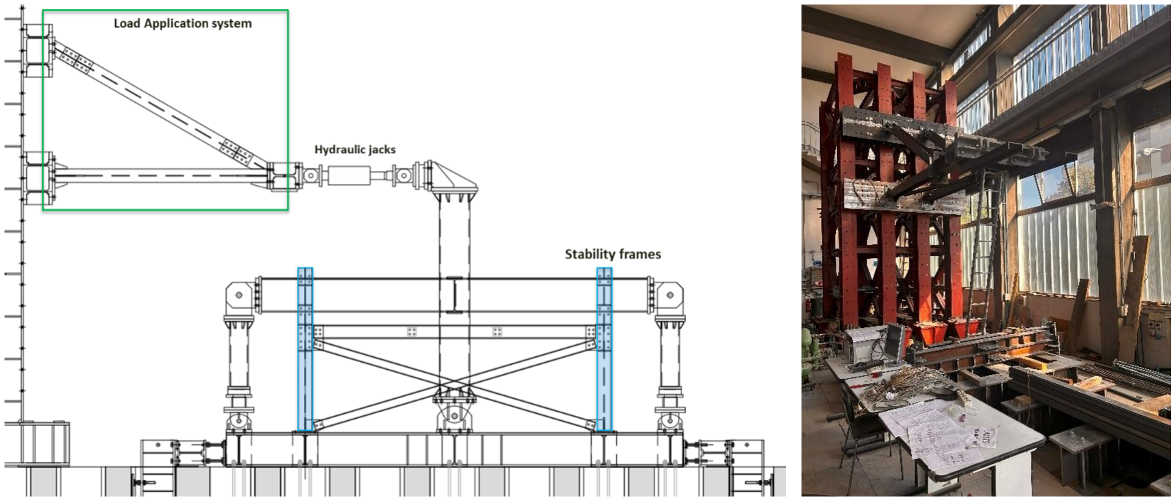

Figure 3: Test setup

2.3 Results

The test was conducted under displacement control until the hydraulic jacks reached their limits. However, since no evident stiffness degradation was observed and the specimen had not yet been damaged, unloading and subsequent reloading of the structure were performed to acquire additional information. Subsequently, we decided to modify the test setup to obtain additional information and allow for greater displacement under the horizontal force. After implementing these modifications, we restarted the test.

The overall force-displacement curve is shown in Figure 4, where it's possible to observe the subsequent load branches. The initial stiffness reduction observed during the test is caused by slip in the bolted connections.

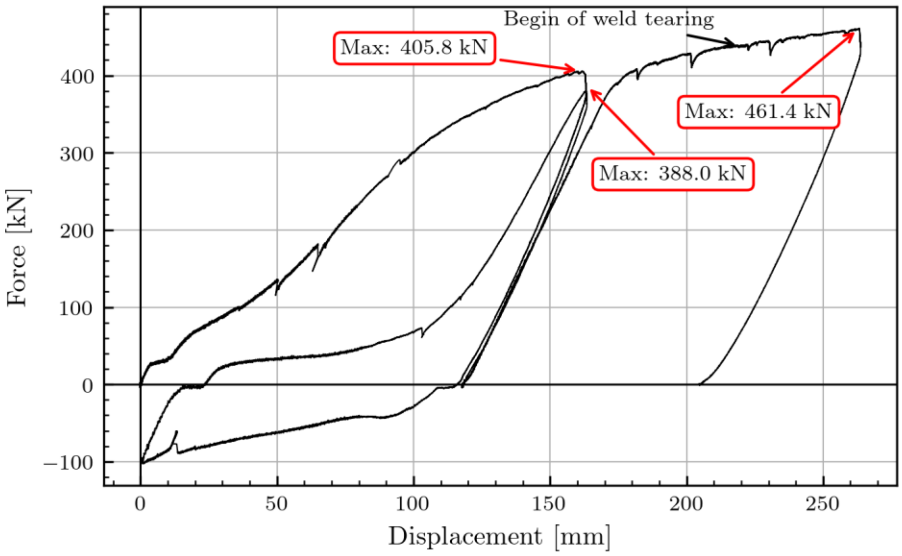

Figure 4: Force-Displacement curve

The second loading branch, after reaching a 100 kN load at the column top in the opposite direction to the expected one at the end of the first unloading branch, shows a clear and significant pinching effect, with a stiffness notably lower than the elastic one up to approximately

100 mm of displacement at the top. After that, the joint regains stiffness and, at the same maximum displacement previously reached, attains a load value almost equal to the initially reached one. The actuators were then unloaded: at the end of the first day, the structure exhibited a residual displacement of 120 mm at the top. The joint remained intact, aside from relative rotations between the beams and the column, as shown in Figure 4. After modifying the loading structure, another loading phase was carried out: initially, the structure exhibited a stiffness equal to that of unloading, while once the virgin loading branch was reached, it continued with a stiffness in line with that obtained at the end of the first loading branch. The first cracks in the lateral weld beads were observed when approximately 435 kN of force was applied by the actuators, as visible in Figure 5.

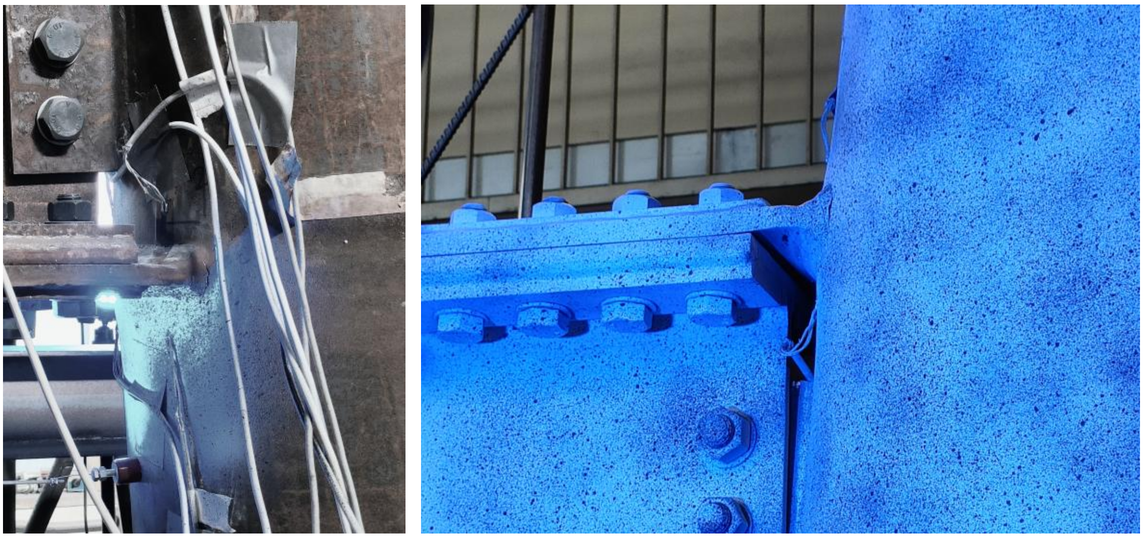

Figure 5: Crack

Additionally, slight tearing phenomena were detected at the location of the tensioned plates, along with distortion of the joint area and rotation between the beams and the column, as shown in Figure 6a. The tearing of the weld and the bending of the passing plate near the slot are visible in Figure 6b. The presence of internal concrete has mitigated the punching effect.

a)  b) 

Figure 6: Residual rotation at the end of the test

The clearance of the connection led to an initial stiffness reduction, that can be observed by the comparison of the first loading branch and the unloading ones.
The phases in which slip occurred in the bolted joints can be qualitatively identified from the reaction force graph of the rods: segments where a plateau is observed correspond to slip events. This behavior highlights the gradual engagement of the bolts as the clearances are taken up, temporarily stabilizing the reaction forces before full load transfer occurs.

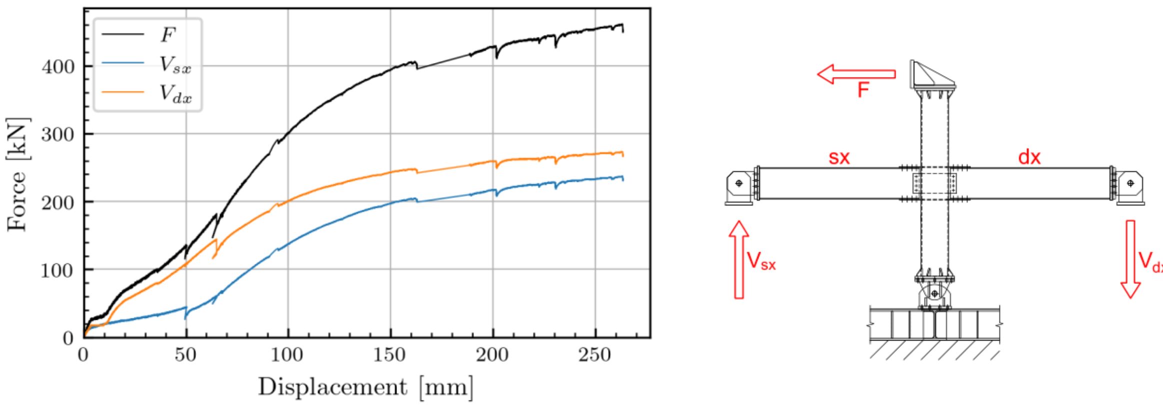

Figure 7: Vertical reaction forces on supports

3 NUMERICAL SIMULATIONS

Finite element analysis (FEA) has been performed to obtain more information about the mechanical behavior of this type of joint. The computational models were calibrated on the results of the experimental campaign.

Since it played a crucial role during the experimental tests, the slip in the bolted joints had to be modeled using connectors with nonlinear behavior to accurately simulate the displacements. Several coupon tests on steel specimens were conducted to assess the material behavior, along with compression tests on concrete cubes. The concrete was modeled using the Concrete Damaged Plasticity (CDP) model, which captures failure under both tensile and compressive stress. The numerical results are in good agreement with the experimental ones, as shown in Figure 8.

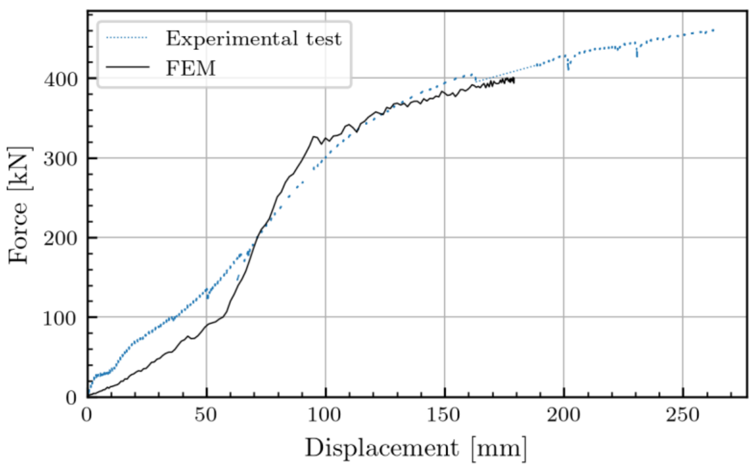

Figure 8: Force-Displacement: numerical and experimental comparison

The numerical model was able to capture the concrete failure in the column core, which wasn't visible during the test. In Figure 9 it's possible to observe the concrete failure, clearly compatible with the stress state in the joint.

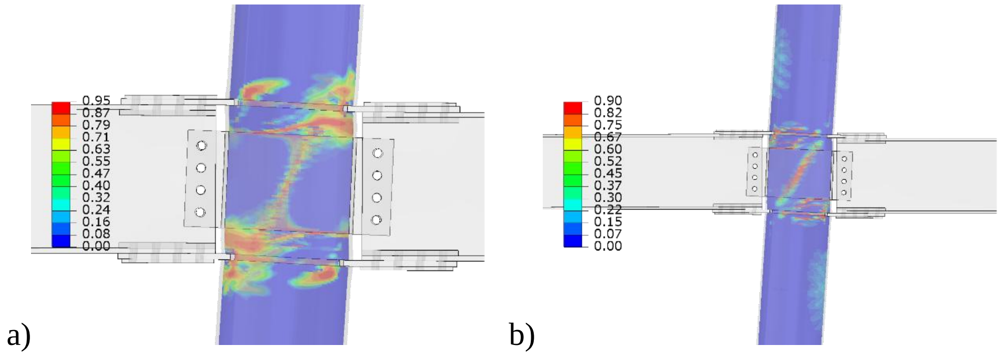

Figure 9: Concrete failure: a) damage in compression; b) damage in tension

Failure in compression was reached in the compressed diagonal of the panel node, as well as the tension failure that leads to material cracks. Diffuse cracks highlighted by the tension damage are observed along the CHS concrete core outside the joint in the tensile zone under loading.

Analyzing the stresses in the passing plate, shown in Figure 10, it can be observed that this element allows the distribution of tensile forces to the opposite side of the column. The internal concrete reduces the punching effect as well as tearing on the opposite side, limiting the deformation of the joint compared to steel-only configurations.

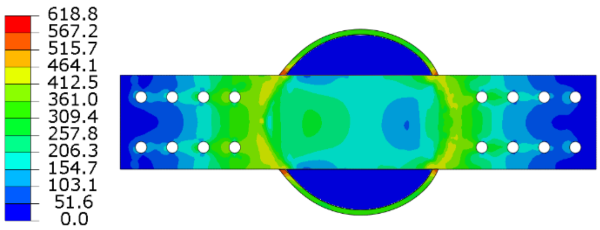

Figure 10: Von Mises stress in passing-through plate

4 CONCLUSIONS

The experimental and numerical investigations conducted on CHS-to-I-beam composite joints with passing-through plates have provided significant insights into their seismic performance. The integration of laser cutting technology (LCT) for the fabrication of these joints has demonstrated its effectiveness in ensuring structural continuity while minimizing the impact on the CHS column.

The experimental results indicate that the joints exhibit a high initial stiffness, which is then influenced by slip in the bolted connections. The presence of passing-through plates enhances force transfer efficiency, mitigating stress concentrations and reducing local deformations in the joint area. However, the experimental test has revealed the formation of cracks in the welds in the tensile zone, possibly leading to failure of the column in the case of cyclic action. The numerical models developed in this study have shown good agreement with experimental results, confirming their ability to capture key behavioral aspects such as stiffness degradation, slip effects, and stress concentration in the welds. Moreover, the simulations have highlighted the role of internal concrete in reducing the punching effect and limiting joint deformations. These findings contribute to a deeper understanding of the seismic behavior of CHS-to-I-beam composite joints with passing-through plates, supporting their potential application in seismic-resistant structures. Future studies could further explore their cyclic behavior and eventual improvements to avoid the formation of cracks in the welds.

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