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Finite Element Analysis of Isolated Composite Joints: Validation against Experimental Data

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Abstract The study investigates the mechanical performance of isolated steel–concrete composite joints subjected to both positive and negative bending moments through an advanced finite element modeling approach. The research addresses a critical gap in existing design codes, which often overlook the nonlinear interaction between steel and concrete components in semi-rigid connections. The primary aim is to evaluate the joint behavior under realistic service and extreme loading conditions, offering a validated numerical framework that can support future enhancements in structural design standards. A three-dimensional nonlinear finite element model was developed using ABAQUS**,** integrating the Concrete Damaged Plasticity (CDP) model to capture concrete cracking, steel yielding, and interfacial slip. Experimental data from composite specimens tested in Warsaw University of Technology and replicated at the Libyan Concrete Materials Laboratory were used for calibration and validation. Parametric analyses considered variations in end-plate geometry, bolt arrangements, and column dimensions to assess their influence on joint stiffness, ductility, and load transfer mechanisms. The results demonstrated excellent agreement between experimental and numerical findings, with a correlation coefficient exceeding 0.95 for moment–rotation relationships. Among the tested configurations, the CSB7 joint (eight-bolt symmetric extended end plate) exhibited the highest performance, achieving sagging and hogging moments of 144 kNm and 269 kNm, respectively. These results highlight the joint's superior ductility and robustness under nonlinear loading, indicating its suitability for structures exposed to exceptional conditions such as seismic or fire events. The research contributes to the ongoing development of Eurocode-based composite joint design**,** emphasizing the need for nonlinear performance criteria and predictive modeling tools. While the study was limited by the absence of cyclic and high-temperature testing, its implications extend to safer, more resilient, and sustainable structural systems, promoting optimized connection design and improved global design standards.

Keywords Numerical Modeling, Steel, Concrete, Composite, ABAQUS, Finite Element Method

1. Introduction

The Finite Element Method (FEM) has emerged as a powerful and reliable analytical tool for evaluating the structural behavior of isolated concrete–steel composite connections, particularly under the influence of both positive and negative bending moments. This method enables engineers and researchers to discretize complex structural systems into smaller, manageable elements, allowing for precise simulation and detailed interpretation of physical behaviors under realistic loading conditions. The integration of FEM into structural engineering has greatly advanced the ability to assess mechanical performance, predict failure modes, and improve design efficiency. This study is primarily concerned with exploring the behavior of isolated composite joints subjected to varying bending moments, utilizing FEM as the core analytical approach. While established structural design codes—such as the Eurocodes [1] provide guidelines for standard steel connection designs, they often lack provisions for capturing the nuanced behavior associated with internal force redistribution. Such limitations can lead to vulnerabilities in design, particularly in scenarios where unexpected loading or localized damage occurs. A comprehensive understanding of joint flexibility is essential for ensuring the resilience of structural systems. Flexible connections can redistribute loads and prevent progressive failure by redirecting forces from compromised joints to surrounding, undamaged areas. Assessing this flexibility accurately necessitates the use of numerical modeling techniques that can quantify the influence of connection damage on the overall structural response. By focusing on the role of endplate components in joint flexibility, this research seeks to determine the extent to which these elements contribute to damage tolerance and load path redundancy [2], [3], [4]. Composite connections that integrate steel and reinforced concrete offer a reliable mechanism for mitigating disproportionate structural collapse. Their capacity to undergo considerable deformation without immediate failure makes them ideal candidates for critical infrastructure applications. In this context, finite element-based modeling and simulation of such joints play a pivotal role in understanding their response under static and dynamic conditions. Ultimately, this study aims to expand the current body of knowledge related to the mechanical behavior of connections. Special emphasis is placed on evaluating their performance under nonlinear loading scenarios and on developing strategies to enhance their resistance to sudden or disproportionate collapse. By doing so, the research aspires to contribute to safer and more resilient structural designs in modern engineering practice.

2. Composite Joint Methodology

2.1. Experimental Setup and Protocol

This experimental investigation was originally conducted at the Warsaw University of Technology, as part of a broader scientific study aimed at understanding the structural performance of isolated steel and steel–concrete interfaces under extreme loading conditions. The laboratory tests focused on evaluating joint behavior under both positive and negative bending moments, offering critical insights into their mechanical response, stiffness degradation, ductility, and failure mechanisms. All stages of the experimental program were carefully supervised and monitored to ensure consistency and reliability, both in the original testing at Warsaw and in the replicated tests, with a clear focus on assessing practical performance under severe service loads, such as those encountered during seismic or accidental conditions.

According to Eurocode 4 and recent literature, composite joints exhibit complex interaction between steel and concrete elements, significantly affecting their moment–rotation response and energy dissipation capabilities, particularly under asymmetric or cyclic loading [1], [2]. Therefore, experimental validation is crucial to refine and calibrate component-based design models. To validate and extend the findings of the initial study, the same experimental protocol was later replicated at the Concrete Materials Laboratory in Libya, under controlled conditions. This replication provided cross-laboratory verification, confirming the reproducibility and consistency of the results obtained in Warsaw. Such repetition eliminates possible biases due to localized environmental or equipment-specific factors [3], [4].

The specimens were divided into three test groups CSB5, CSB6, and CSB7 as described in Table 1, Table 2. All groups shared identical material characteristics for steel, concrete, and reinforcement. The only variable was the endplate configuration, which allowed the study to isolate its effect on the structural performance under moment loading:

- CSB5 utilized 4 M20 bolts,
- CSB6 employed 6 M20 bolts,
- CSB7 incorporated 8 M20 bolts.

Table 1. Specifications of samples CSB5, CSB6, and CSB7

No	Joint Symbol	Endplate Type	End-plate Thickness	Number of Bolts
1	**CSB5**	**Symmetric Flush**	**10 mm**	**4**
2	**CSB6**	**Asymmetric Extended**	**10 mm**	**6**
3	**CSB7**	**Symmetric Extended**	**10 mm**	**8**

Table 2. Average mechanical qualities of the concrete used in the test

Concrete Class	E MPa	fc	Ɛu	ft Ɛ0
	MPa	**MPa**	**-**	**MPa**
C25/C30	**36515**	**45.7**	**0.003**	**3.20.1**

Each specimen was constructed using IPE300 beams and HEB200 columns fabricated from S235JR structural steel. Bolted connections were employed, utilizing grade 10.9 high-strength bolts. Composite action between the steel and concrete components was achieved through the use of Cofraplus 60 ribbed steel decking, overlaid with C30-grade concrete slabs. These slabs were reinforced with 10 mm transverse bars and four 12 mm longitudinal bars, aiming to control cracking and enhance flexural capacity. Shear connectors (SD #19 × 100 mm) were welded to the steel beams to ensure full composite interaction, in accordance with the recommendations of Eurocode 4 [1]. As shown in Figure 1, part (a) presents a detailed view of the specimen and the test setup, while part (b) illustrates the dowel configuration and reinforcement detailing. Endplate geometry and bolt layout have been previously shown to significantly affect connection behavior. Increasing the number of bolts generally improves joint stiffness and strength, but may introduce other failure modes, such as bolt shear or endplate yielding [5].

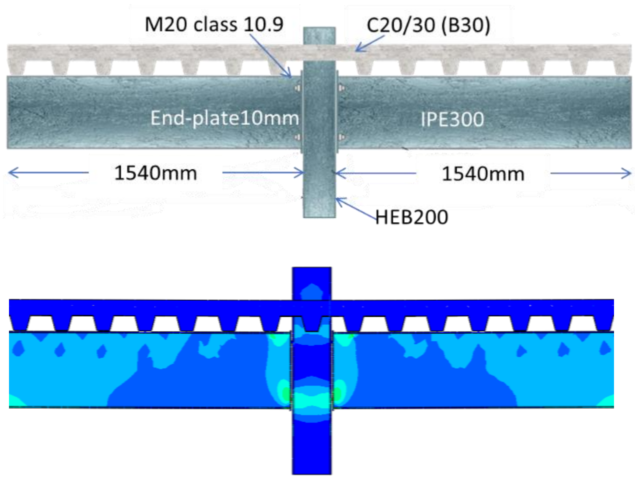

Figure 1. (a) Experimental and (b) FE Modeling and Numerical Details – Symmetric End Plate

All specimens were subjected to incrementally increasing static loads, applied through calibrated cranes placed 1540 mm from the cantilevered ends. Testing and evaluation were conducted in accordance with the Eurocode component-based design method, enabling precise assessment of joint failure modes, such as panel zone yielding, slippage, or endplate plasticity. By repeating the tests in both Warsaw and Libyan laboratories, the study provides robust verification of its findings, supports international reproducibility, and contributes to future code development for semi-rigid composite joints in demanding structural applications [6], [7].

2.2. Composite Joint Simulation

This study aims to analyze the structural susceptibility to disproportionate collapse by employing three distinct types of end plates:

- Flush end plate with four bolts,
- Extended end plate with six bolts,
- Reinforced extended (symmetrical) end plate with eight bolts.

Careful consideration was given to the engineering characteristics of nonlinear assemblies, ensuring that the steel sections used in the CSB5, CSB6, and CSB7 specimens match those in the previously tested steel samples ES1, ES2, and ES3 [8], [9], [10], [11], in order to maintain consistency in comparative assessment. For the analysis of reinforced concrete behavior, the ABAQUS/CAD software [12], [13], [14], [15] was employed, offering advanced analytical capabilities such as:

- The Smeared Crack Concrete model,
- The Brittle Crack Concrete model, and
- The Concrete Damaged Plasticity (CDP) model.

Among these, the CDP model was particularly effective for simulating the structural response of reinforced concrete under different installation and loading conditions, especially in scenarios involving both positive and negative bending moments. It also accounts for variations in the mechanical properties of concrete. The simulations incorporated average material values obtained from experimental testing, with a tensile stress limit set at 0.1 [10], [16], [17], [18].

Structural components, including shear connectors, steel reinforcement, and reinforcing bars, were modeled as Type B31 beam elements with circular cross-sections. The concrete slab was modeled using C3D8 solid elements with eight nodes, incorporating the relevant concrete parameters.

The Cofraplus 60 profiled steel deck was modeled as a shell with defined thickness, with ribs oriented perpendicular to the beam axis. The cantilever beam, end plates, main beam, and column were positioned as three-dimensional components above the profiled sheet, using reinforced elements to minimize unrealistic deformations in the numerical model. Finally, the geometric and mechanical specifications of the CSB5, CSB6, and CSB7 composite samples are illustrated in Figure 2 and Figure 3. It is important to emphasize that this simplified yet carefully constructed model closely replicates the structural components used in the physical experiments, thereby ensuring high reliability and scientific accuracy of the results.

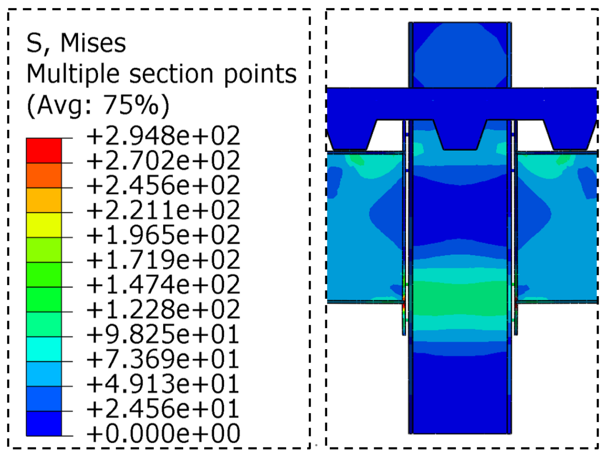

Figure 2. Deformed shape of the, CSB7 joints under Hogging

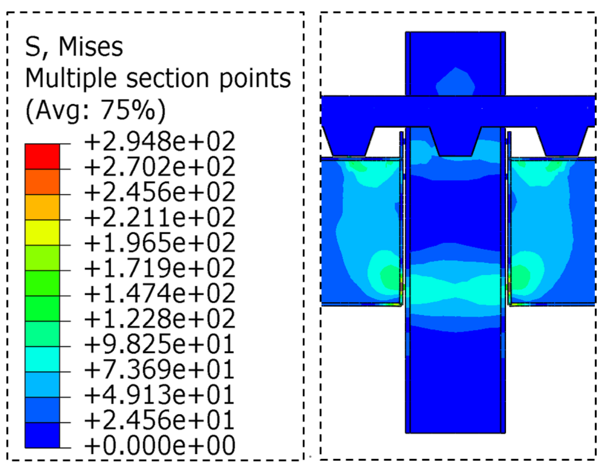

Figure 3. Deformed shape of the CSB5, CSB6, joints under Hogging

3. FEM Validation and Analysis

To minimize the influence of dynamic effects, the experimental system was intentionally loaded at a slow and controlled rate. Despite this, the numerical simulations successfully replicated the same loading history with high fidelity, as supported by previous studies [10–12].

The validation process was conducted by comparing the mechanical response of locally tested joints. The moment–rotation correlation achieved a high degree of agreement ($R^2 > 0.95$), validating the numerical approach observed between the moment–rotation relationships, affirming the reliability of the finite element (FE) modeling approach.

Upon analyzing the local behavior of the composite specimens, two distinct behavioral patterns emerged. The first pertains to weaker beam-to-column connections, in which the axial force transmitted from the column fails to fully reach the beam ends. This inadequate force transmission compromises stress distribution and ultimately reduces joint strength. A significant contributing factor to this weakness is the progressive degradation of stressed steel end plates, particularly in the heat-affected zone (HAZ), which reflects the structural system's limited performance especially in flush endplate joints.

Figure 4a presents the structural performance of the CSB5 joint in comparison with experimental and analytical results. The convergence of the data depicted in Figures 4a and 4b underscores the accuracy of the numerical model, demonstrating its capacity to effectively predict joint behavior under loading conditions. This confirms the model's suitability for simulating both experimental outcomes and theoretical expectations.

The credibility of the FE model was further assessed through comparisons of joint toughness and flexibility, using experimental findings as benchmarks. For the CSB5 and CSB6 composite specimens, joint behavior again fell into two categories.

In cases of insufficient joint strength, particularly in the CSB5 configuration, the joint may fail to meet structural performance requirements. Such failures are typically initiated by axial forces transmitted from the cantilever edge, which can lead to premature deformation and localized collapse, as illustrated in Figure 4b.

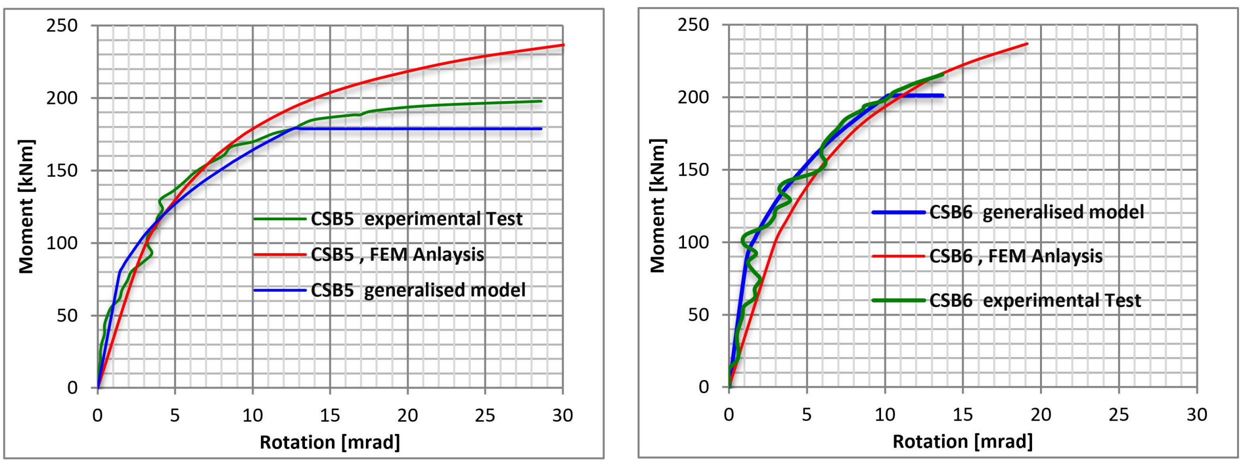

Figure 4. (a) FEM and Tests results for CSB5, (b) FEM and Tests results for CSB6

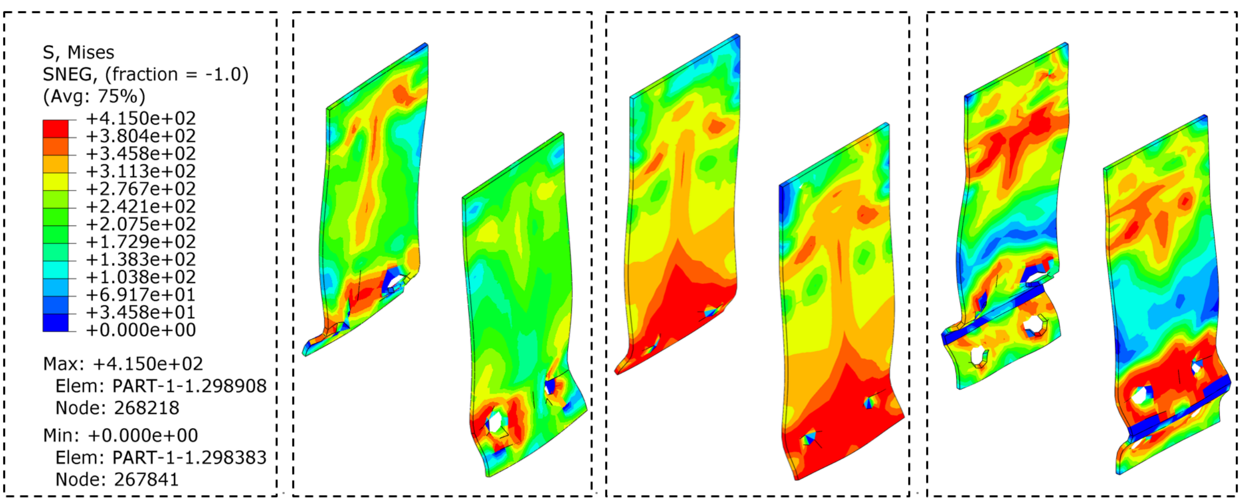

Figure 5. Geometric and mechanical specifications of the CSB5, CSB6, and CSB7 composite samples

Figure 5 highlights the extent of joint distortion, providing insight into the flexibility and adaptability of the connections. Analysis reveals that the CSB5 joint exhibits the greatest flexibility and deformation capacity. Its ability to undergo significant bending and stretching without structural compromise demonstrates superior ductility and resilience. These characteristics render the CSB5 joint a highly adaptable and robust solution for integration in diverse structural and mechanical systems.

This phenomenon is typically associated with the delayed fracture of end plates made from high-strength steel. It initiates with microcracks that progressively propagate under high stress levels, followed by a sudden failure in which the plate rapidly detaches from the weld zone. Such behavior reflects the weak performance of the CSB5 joint, often marked by insufficient toughness and strength.

This conclusion is supported by the data presented in Table 3, which shows that the maximum sagging and hogging bending moments for the CSB5 and CSB6 joints were significantly lower, recorded at 240 kNm and 89 kNm, respectively. However, as illustrated in Figures 6 and 7, the CSB6 joint demonstrated slightly higher strength in both sagging and hogging scenarios, particularly in hogging, reaching bending moments of 265 kNm and 97 kNm, respectively, thereby indicating improved structural robustness. Figure 6 illustrates the deformation behavior of joints CSB6 and CSB7 at the failure stage. It is evident that the flexibility of these joints is significantly lower compared to joint CSB5, which led to bolt failure at lower deformation levels. This suggests that the joints may not be suitable for applications requiring high flexibility, indicating the need for additional secondary treatments or enhancements. However, the results demonstrated that the joints exhibit superior durability, exceeding that of joint CSB5. This makes them a highly durable option for applications where strength and toughness are prioritized, albeit at the expense of reduced flexibility.

Figure 7(a) highlights the discrepancy between numerical and experimental results for the CSB5 model, emphasizing the effect of increasing fractures in the joint's end plate during testing—a phenomenon not captured in the numerical simulation. Meanwhile, Figure 7(b) shows that although all end plates exhibit high consistency in the elastic phase, completing the analysis in the plastic phase remains challenging. This stage is not accurately predicted by Eurocode standards, which currently lack design guidelines for post-elastic behavior.

The evaluation of joint flexibility, plastic deformation, and strength is based on comparing bending moment versus rotation curves, as detailed in Table 3. The recorded negative bending moments for joints CSB5, CSB6, and CSB7 are 240 kNm, 265 kNm, and 269 kNm, respectively, with corresponding rotations of 32 mrad, 33 mrad, and 31 mrad. Likewise, the positive bending moments are 89 kNm, 97 kNm, and 144 kNm, with respective rotations of 29 mrad, 28 mrad, and 27 mrad.

Figure 8 illustrates the joint deformations derived from finite element analysis, revealing that the CSB5 joint undergoes significantly more deformation compared to CSB6 and CSB7, the latter two being recommended in this study. This underscores the necessity of designing joints capable of withstanding extreme loads.

Among the tested configurations, the CSB7 joint—fitted with eight bolts—demonstrated the highest level of durability. It was able to sustain sagging and hogging moments of 144 kNm and 269 kNm, respectively, while meeting design requirements for both positive and negative bending moments. These findings highlight the need for advanced design criteria to ensure resilience against extraordinary loads such as those induced by explosions, fire, or seismic activity—conditions not currently addressed by most international design codes.

Finite element (FE) analysis can play a critical role in establishing design standards for joints subjected to such exceptional loading conditions. The numerical simulation results for the CSB7 joint using FEM are both promising and reliable, although experimental validation is still pending. Nevertheless, numerical modeling serves as a valuable proactive tool that facilitates early identification and mitigation of potential issues during laboratory testing. The CSB7 joint exhibits a rotation capacity of 27 mrad, which could potentially be enhanced through optimized bolt distribution or by reducing the end-plate thickness.

Table 3 shows a comparison of end plates values moment (kNm) vs. rotations (mrad).

Table 3. Shows a comparison of end plates values moment vs. rotations

No	Endplate Type	Joint Type	Specimen Symbol	Moment (kNm)	Rotation (mrad)
1	Symmetric Flush	Hogging	CSB5	240	32
		Sagging		89	29
2	Asymmetric Extended	Hogging	CSB6	265	33
		Sagging		97	28
3	Symmetric Extended	Hogging	CSB7	269	31
		Sagging		144	27

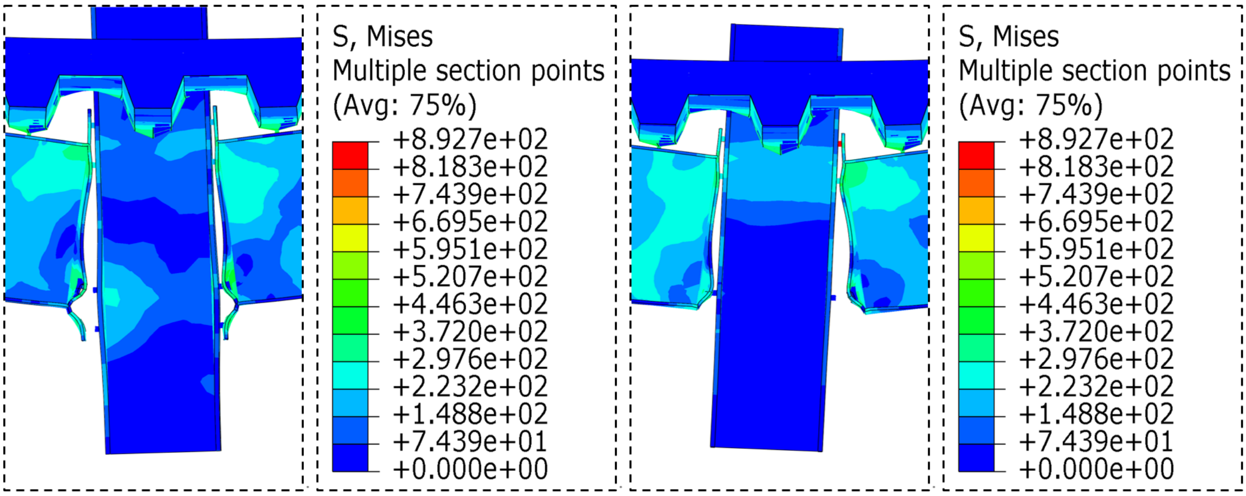

Figure 6. Deformed shape of the CSB6, CSB7 joints under Sagging Bending

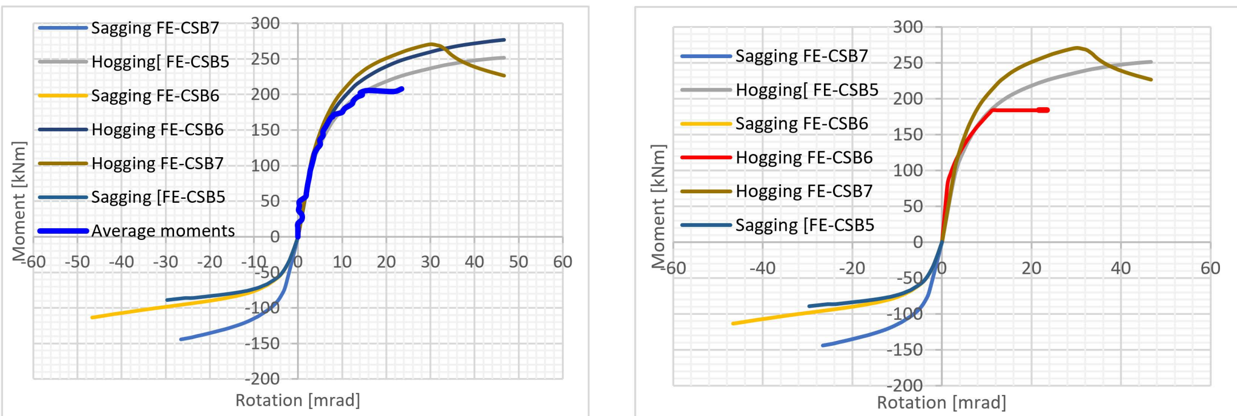

Figure 7. Comparison of moment–rotation behavior for joints CSB5, CSB6, and CSB7

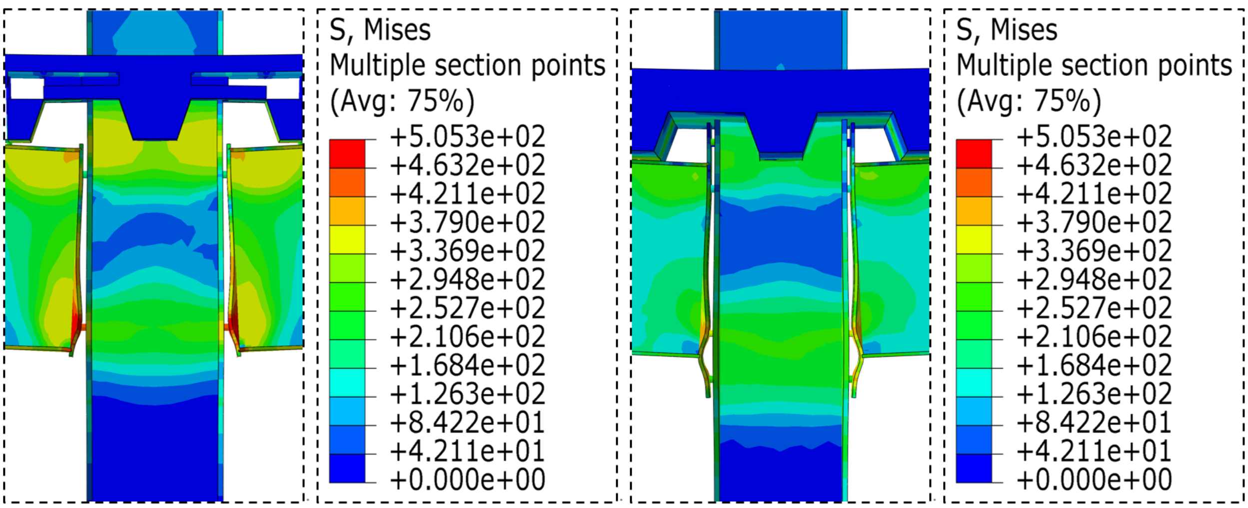

Figure 8. Compares deformation in CSB5, CSB6, and CSB7 joints

4. Conclusions

The validation of the Finite Element Model (FEM) confirmed its high fidelity in replicating the load-time behaviors observed during experimental testing. The model successfully captured the complex interaction between applied bending moments and the resulting rotational responses in various beam-to-column joints. This enabled the precise identification of structural vulnerabilities, particularly in the progressive degradation of high-strength steel end plates subjected to sustained stress.

Despite acceptable performance in terms of flexibility for some joints, several challenges remained—most notably, limitations in the robustness and fracture resistance of the end plates made of high-strength steel. These findings emphasize the critical need for designing structural joints that can reliably endure extreme or abnormal loading conditions, such as those caused by explosions, fire, or seismic events.

Among all the tested configurations, the CSB7 joint, characterized by its use of eight bolts, exhibited the best performance. It was the most capable in accommodating both sagging and hogging bending moments, while complying with essential structural design standards. Although experimental validation for this joint remains ongoing, the FEM simulations have already demonstrated its potential as a robust and reliable connection. Furthermore, FEM has proven to be an effective predictive tool for identifying possible weaknesses and enabling early corrective measures before physical testing, thereby enhancing safety and efficiency.

The outcomes of this study underscore the necessity of further advancing numerical modeling techniques—particularly to improve the prediction accuracy of joint behavior in the plastic range. The CSB7 joint, in this context, emerges as a promising solution for applications requiring high-strength and high-ductility connections, making it a valuable candidate for use in critical structures where performance under exceptional loads is non-negotiable.

This research contributes meaningfully to the ongoing development of design standards for steel-concrete composite joints. It calls for a redefinition of structural performance criteria to better account for both serviceability and resilience under unforeseen loading scenarios.

Looking ahead, future investigations should prioritize enhancing the balance between flexibility and structural safety in joint design. Developing connections that offer high adaptability to variable loads while maintaining integrity under severe conditions will be essential. Additionally, refining simulation tools and expanding current design guidelines will play a crucial role in improving the overall reliability, efficiency, and sustainability of structural joints in next-generation engineering projects.

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