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Integration of Finite Element Simulations and Experimental Validation in the Analysis of Demountable Clamp Joints for Steel Structures

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Abstract **-** This investigation provides a rigorous assessment of demountable clamp joints in steel structures through the combined application of Finite Element Method (FEM) simulations and empirical testing. Targeting the gap in current research on the mechanical performance and sustainability implications of such joints, the study delineates their efficacy in facilitating reversible, non-invasive connections in structural engineering applications. Quantitative analysis reveals a strong alignment between FEM predictions and experimental data, validating the FEM model's capability to represent the joints' behavior under diverse loading scenarios accurately. This concordance reinforces the potential of clamp joints as a sustainable alternative to traditional methods, supporting reversible constructions and reducing environmental impact. The research methodically underscores the necessity for iterative refinement of simulation models, guided by empirical insights to enhance predictive accuracy and reliability. By integrating advanced simulation techniques with precise experimental validations, this study advances sustainable structural design practices, emphasizing the critical role of demountable clamp joints in the evolution of efficient and adaptable engineering solutions.

Keywords**:** Sustainable Construction; Mechanical Performance; Reversible Connections; Engineering Innovation.

1. Introduction

The evolution of structural engineering has been marked by a steady drive toward more sustainable, efficient, and adaptable solutions. Within this context, clamp joints represent a significant innovation, emerging as viable alternatives to conventional joining methods in steel structures. Traditionally, welding and drilling impose limitations regarding reversibility and environmental impact despite their effectiveness, which are challenges that clamp joints aim to mitigate.

This study focuses on the in-depth evaluation of demountable clamp joints in steel structures, standing out due to the scarcity of detailed investigations on their performance and applicability in the current scientific literature. By integrating Finite Element Method (FEM) simulations with meticulous experimental testing, this research seeks to elucidate not only the mechanical capacity of these joints under various load conditions but also their potential contribution to more flexible and sustainable structural engineering.

Adopting clamp joints in structural projects is notable for facilitating efficient and reversible unions of metallic components without needing permanent material alterations. This approach, grounded in the efficacy of the lever principle, is indispensable for achieving secure and stable connections. Through detailed simulations and experimental tests, this work aims to offer a comprehensive analysis of the mechanical characteristics of these joints, aligning with current standards and contributing to the expansion of knowledge in materials engineering [1-3].

The results obtained are fundamental for advancing the understanding of the mechanical principles that govern the behavior of materials and structures under different loads. The comparative analysis validates the effectiveness of the FEM simulation model, revealing nuances in material behavior essential for future studies in structural and materials engineering. This in-depth knowledge underscores the relevance of demountable clamp joints as a viable technical solution and a step toward construction practices that favor sustainability, efficiency, and adaptability.

Thus, the present study significantly contributes to the existing knowledge of clamp joints in steel structures, offering valuable insights into their design, performance, and applicability. By integrating mechanical principles with strict technical standards, this work strengthens the scientific foundation for the development of new solutions in structural engineering, aligned with the contemporary challenges of sustainability and efficiency.

2. Mechanism and Efficiency of Clamped Joints in Metal Structures

Clamped joints emerge as an innovative solution in structural engineering, facilitating the efficient and reversible union of metal elements without resorting to invasive methods, such as welding or drilling. This operational mechanism, which avoids permanent modifications to materials, enables a safe and effective installation, based on the principle of leverage to maximize the clamping force applied by the central bolt.

This technique prevents invasive structural changes in metal profiles, enabling quick and safe assembly and disassembly. This method is particularly valued for its mechanical efficiency, where the manually applied force on the bolt is amplified by the physical arrangement of the clamp, generating significant pressure that ensures a firm union of the components.

The operability of clamped joints is mathematically supported by two essential formulas. The first outlines the clamping force (F_c) generated by the clamp, a decisive force for the stability of the connection:

$$F_c = F_P \cdot \left(\frac{a+b}{b}\right) \tag{1}$$

In this equation, (F_P) is the force applied to the bolt, while (a) and (b) represent the lengths of the levers on the force side and the support side, respectively. This leverage principle, emphasized by references such as Eurocode [4-7] demonstrates how the design of the clamp is crucial for the effectiveness of the joint.

The second essential formula establishes the preload (P) necessary to initiate the connection between metallic components:

$$P = \frac{0{,}7 \cdot f_{ub} \cdot A_s}{1{,}1} \tag{2}$$

Where (f_{ub}) is the bolt's ultimate tensile strength, and (A_s) is its cross-sectional area. This preload, calculated to ensure an effective union resilient to load variations, adheres to the parameters recommended by Eurocode 3, striking a balance between safety and structural performance.

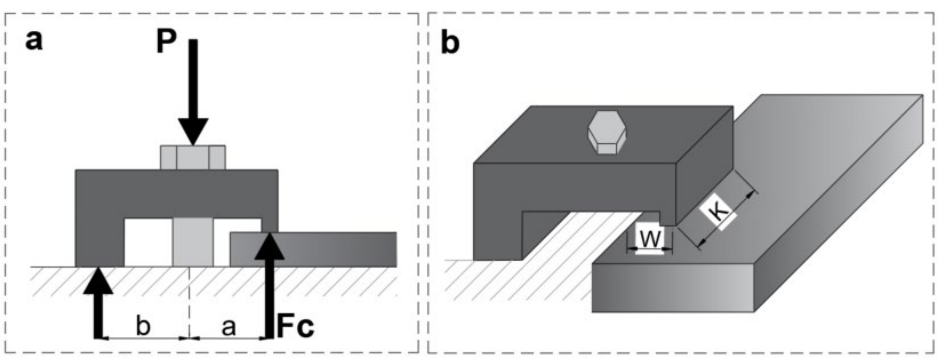

Fig. 1 (a) How the clamp operates using the lever mechanism depicted in the side view; (b) Detail of the clamp support surface on the profile flange seen from above.

Moreover, Figure 1 elucidates the leverage mechanism, showing how applied force (F_P) is transmitted to the clamp resting on the metallic profile's flange. This distribution is crucial for the uniform application of force across the clamp's width (k) and depth (w) and is pivotal for the structural fidelity and reliability of the connection.

Clamped joints, fashioned from high-strength materials such as steel, are designed to distribute pressure evenly, thus preventing potential damage to metal profiles and securing a lasting connection. Studies highlighting the importance of design in force distribution and deformation minimization corroborate this innovative approach.

Additionally, a significant advantage of employing these clamps in 90-degree unions is their capability to facilitate dismountable and reconfigurable connections. This attribute underscores the mechanical efficiency and safety of such joints joints and highlights their role in promoting adaptable structural designs. The ability to easily assemble and disassemble joints at right angles without compromising structural integrity or stability is paramount in dynamic engineering applications applications where modification and adaptability are essential. This inherent flexibility in the clamped joints used for 90-90-degree connections enables structures to be reconfigured according to evolving functional requirements or design preferences, thereby extending the lifecycle of materials and structures. This represents a stride toward sustainable construction practices, as it allows for repurposing structural elements in new configurations with minimal waste and environmental impact.

In summary, integrating clamped joints into structural engineering practice marks a significant advancement, uniting fundamental mechanical principles with strict technical norms set out in Eurocode. Through the effective combination of the lever principle with the precise application of preload, these joints offer a robust and adaptable solution for joining metallic elements, evidencing continual progress in structural engineering.

3. Materials and Experimental Methods

3.1. FEM-Based Simulation of Bolted Beam-Column Joints

The assembly used for simulations and experiments, as illustrated in Figure 2, consisted of IPE200 structural steel beams supported by a column with a height of 1000 mm and a beam with a length of 1000 mm. The connection between the steel profiles was achieved using steel brackets, each measuring 180 mm in length on both sides, with a hole spacing of 100 mm and a thickness of 20 mm, utilizing eight M12 grade 8.8 bolts per joint, along with clamps to secure the brackets to the beam-column assembly.

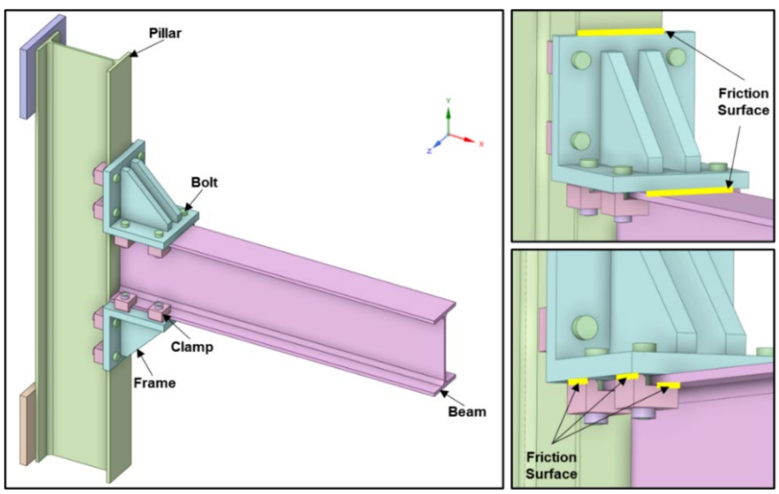

Fig. 2 Three-dimensional schematic of an assembled framework for FEM modeling. Detailing of friction surfaces between connection elements.

The arrangement was modeled and simulated using ANSYS® software. It employed a linear structural steel material with elastic properties, including Young's modulus of 210 GPa, a Poisson's ratio of 0.3, and a density of 7850 kg/m3. The yield strength for the steel beams was considered to be 235 MPa, whereas for the steel bolts, it was considered to be 640 MPa.

The numerical model also accounted for the potential non-linearity associated with the contact area evolution between the profile flange, the clamp, and the base plate. A classical Coulomb friction model was employed for the contact surfaces with a friction coefficient of 0.3, as recommended for untreated steel surfaces according to the Eurocode standards [6] and [7]. For the discretization of the model, second-order hexahedral elements were utilized across all structure components.

Element sizes adopted were: 10.00 mm for the beam-column setup, 5.00 mm for the brackets, and 3.00 mm for the clamps and bolts. A pre-load of 30 kN was applied to the bolts.

This approach enabled a detailed analysis of the mechanical properties of the structural assembly, considering both material specifics and the interactions among components, in compliance with the current regulations expressed in the referenced Eurocodes.

3.2. Experimental Test of Bolted Beam-Column Joints

The experimental tests were conducted to quantify the structural resistance in response to applied loads accurately. Using a high-precision laboratory press equipped with load measurement devices, the accuracy of the data was ensured. Test specimens, consisting of IPE200 rolled steel profiles and S235 structural steel, were fixed to the test structure with through-bolts firmly anchored in the press, as depicted in Figure 3. Precise displacement measurements (±0.01 mm) and strict preload control, adjusted via a calibrated torque wrench at 80 Nm. These steps were critical for validating the Finite Element (FE) model and enhancing the correlation between experimental and theoretical results.

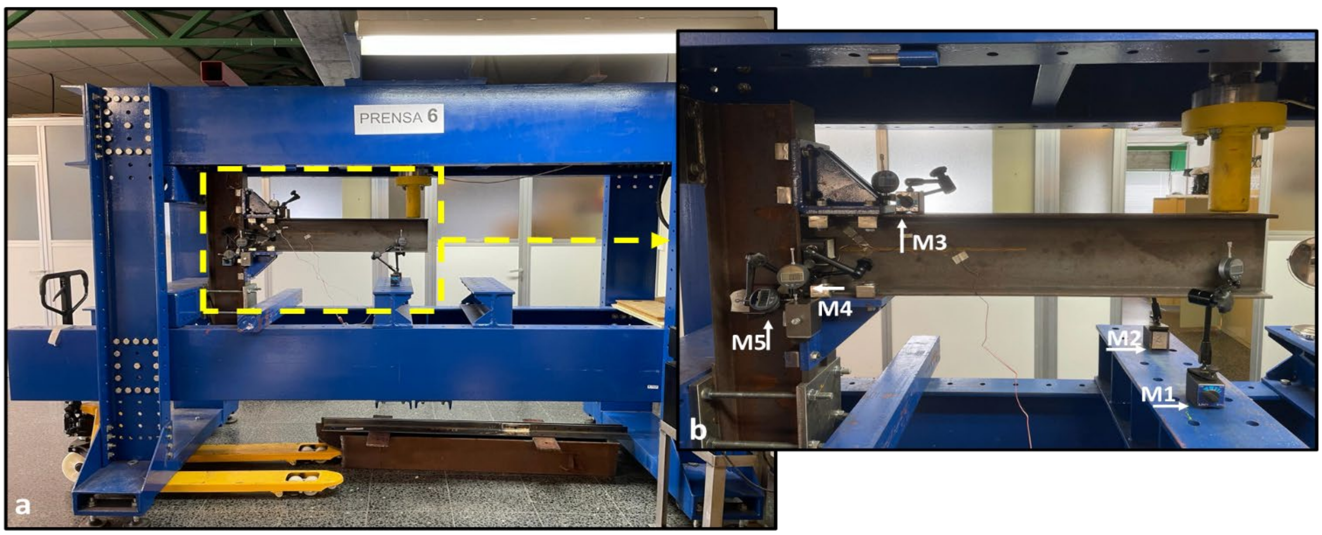

Fig. 3 Laboratory Tests: (a) System Assembly Overview; (b) Detail of the digital indicators' positioning.

4. Results and discussion

The comparative analysis between the outcomes obtained through the Finite Element Method (FEM) and experimental testing forms a crucial foundation for advancing the understanding of material mechanics and structural behavior under various applied forces. This comparison, extensively illustrated in Figures 4 and 5, not only allows for the validation of the FEM simulation model in terms of its capacity to predict realistic material behaviors but also unveils nuances and specificities in material behavior that are vital for engineering and materials research.

Figure 4, which presents the comparison of total deformation between FEM tests and experimental trials, shows a general trend of agreement, indicating that the FEM model has a solid basis for predicting material behavior under load. This concurrence serves as a robust indicator that the FEM model can reliably reflect the behavior of materials and structures under study. Such similarity between simulated and experimental results suggests that, across a broad spectrum of tested conditions, the FEM model acts as an effective predictive tool, offering valuable insights for analyzing structural behaviors under different loads.

However, a more detailed analysis of specific points where discrepancies are observed - such as in the deformation peaks not being as prominently replicated by the FEM model - suggests areas where the model could be enhanced. These discrepancies may be attributed to various factors, including, but not limited to, simplifications in the geometric model, material assumptions that do not fully capture the complexity of real material behavior or the exclusion of microstructural effects in the FEM model.

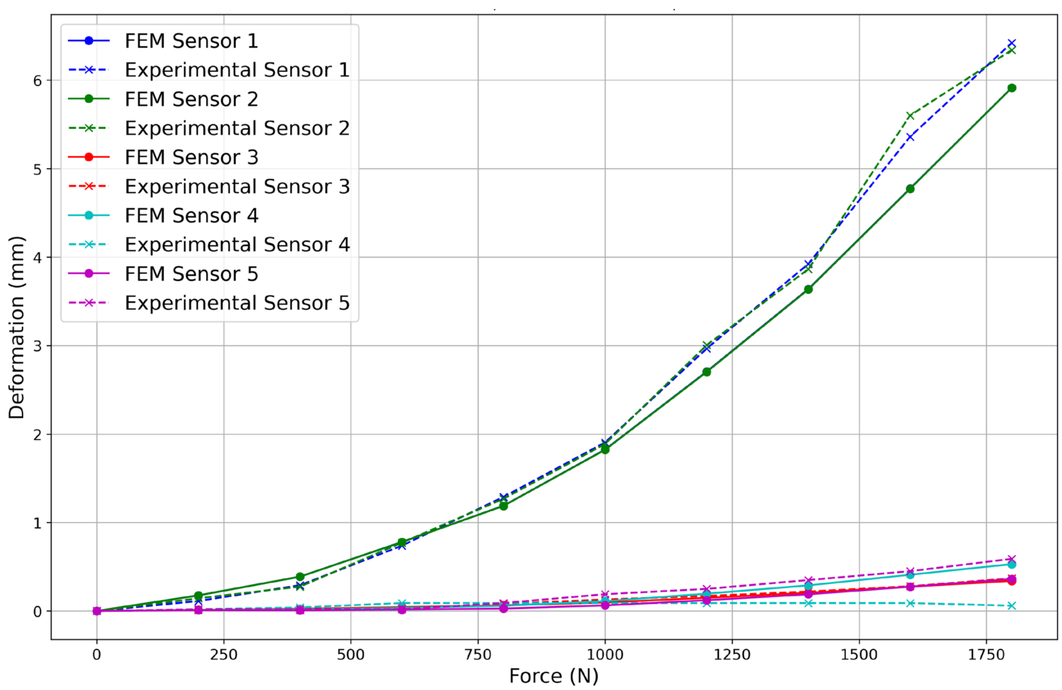

Fig. 4 Total Deformation Comparison: FEM Test vs. Experimental Test

Delving deeper into the analysis in Figure 5, which details various aspects of the comparison between simulation and testing, reveals a wealth of information about the accuracy of the FEM model and the intrinsic characteristics of the experimental results' behavior. This figure, subdivided into parts (a) to (f), encompasses a range of analytical metrics, including deformation trend comparison, the correlation between FEM and experimental results, absolute differences, and percentage errors, as well as assessing the sensitivity of gauges and the observed yield limit.

Figure 5(a), which compares deformation trends, underscores the importance of aligning observed trends between FEM methods and experimental approaches. A strong correlation in this respect enhances confidence in the predictive capability of the FEM model. Discrepancies in trends point to the need for revisions, whether in adjusting material properties or revising applied boundary conditions.

The correlation among tests (Figure 5b) indicates that while the majority of sensors show a high correlation between the Finite Element Method (FEM) and experimental methods, underscoring the model's competence in replicating material behavior, sensor 4 presents a notable discrepancy. This low correlation points to discrepancies that could arise from a variety of factors, including potential experimental errors, variations in material properties not accounted for in the model, or incorrect assumptions in the FEM simulation. Despite this, it's important to emphasize that although the data from sensor 4 displays a significant relative error, the absolute error is very small and does not jeopardize the overall results of the assay. This observation suggests that while the discrepancies indicated by sensor 4 merit further investigation, they do not necessarily detract from the validity of the experimental approach or the predictive accuracy of the FEM. It suggests a reassessment of the assumptions underlying the FEM model or the conditions under which the experimental tests were conducted [8].

The absolute difference and percentage error (Fig. 5c; Fig. 5d) between FEM and experimental tests illustrate the quantitative variations in material responses. These variations, especially the significant percentage errors observed in certain sensors, highlight the need for a more refined adjustment of the FEM model to enhance its accuracy. In line with the work of [9], which discusses the importance of precise adjustments in simulation models to capture material behavior, this analysis reinforces the value of continuous model revisions based on experimental feedback.

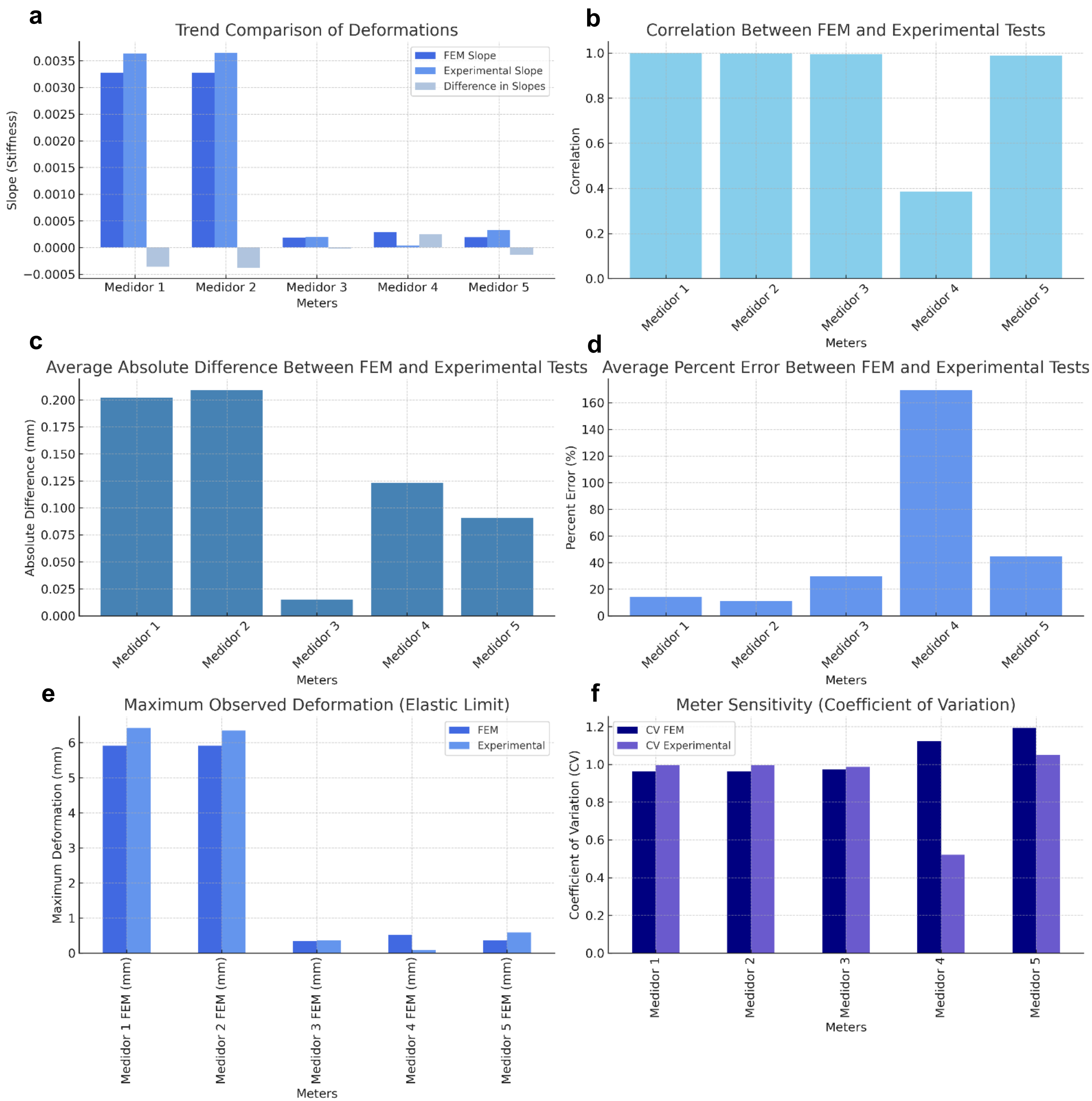

Fig. 5 (a) Trend Comparison of Deformations (b) Correlation Between FEM and Experimental Test (c)Average Absolute Difference Between FEM and Experimental Test (d) Average Percent Error Between FEM and Experimental Test (e) Maximum Observed Deformation (f) Meter Sensitivity.

The observed yield strength (Fig. 5e) in experimental tests, compared to the predictions of the FEM model, provides valuable insight into the materials' capacity to withstand deformations before entering an irreversible plastic regime. This This aspect is crucial for validating the robustness of the FEM model in predicting critical failure points. References such as such as the study by [10] on yield strength analysis in structural materials support the need to integrate these observations into the FEM model calibration.

The sensor's sensitivity (Fig. 5f) highlights the importance of selecting measurement devices that accurately capture subtle variations in material behavior. Identifying this sensitivity is essential for determining the suitability of sensors and models for various tests and materials. Sensors with greater sensitivity are particularly valuable when one wishes to detect subtle variations in material behavior or contexts where materials exhibit highly nonlinear properties [11].

Thus, the integration of FEM and experimental results illustrates the inherent complexity in modeling and experimental testing, highlighting the imperative need for meticulous calibration and validation. This approach ensures the accuracy and reliability of the models used and serves as a stepping stone for advancing scientific knowledge by revealing new research questions and guiding the development of more sophisticated simulation and testing methods. Additionally, through the use of the clamps tested and analyzed in this study, we achieved approximately 40% of the moment effort of the profile, which would correspond to the application of a load of 18000N. This significant outcome highlights the potential of clamp joints to optimize force distribution and withstand substantial loads, reinforcing their applicability in structurally sustainable and efficient engineering projects.

This aspect further underscores the relevance of our comparative analysis, emphasizing how clamp joints can significantly contribute to the advancement of structural engineering. The comprehensive and detailed analysis of the presented graphs meets the need for a deep discussion and provides valuable insights into structural engineering. It emphasizes the importance of an iterative process of refinement and validation, where each observation, whether of agreement or discrepancy, serves as a starting point for deeper investigations.

5. Conclusion

This investigation delved into the applicability and efficacy of demountable clamp joints within steel frameworks, distinguishing itself through the integration of Finite Element Method (FEM) simulations and rigorous experimental testing. The findings corroborate the viability of clamp joints as a sustainable and reversible alternative to conventional joining techniques, such as welding and drilling, due to their capability to facilitate efficient and secure connections without permanent alterations to the material.

Comparative analyses between the outcomes of FEM simulations and experimental results demonstrated a high level of correlation, validating the accuracy of the simulation model utilized to predict structural behavior under various loading scenarios. This research emphasizes the importance of ongoing refinement and validation of simulation models, grounded in detailed observations of discrepancies and parallels between simulated and experimental outcomes.

For future studies, we recommend an exploration into a bracket model and the connection of screws to enhance further the capacity of the joints to absorb and distribute forces. Such investigation could focus on variations in materials, designs, and arrangements of screws, aiming to maximize the efficiency of connections and facilitate even more resilient and adaptable structures.

Implementing clamp joints proposes significant implications for structural engineering, suggesting that adopting such joints can foster more sustainable, efficient, and adaptable construction practices. This work contributes to the existing body of knowledge on clamp joints in steel structures and lays a solid foundation for future inquiries, emphasizing the necessity of an iterative process of simulation model improvement based on experimental validation.

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