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# Parametric Finite Element Study of Preloaded Joints with Long Slotted Holes

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**Abstract**

This study investigates the mechanical behaviour of preloaded beam-to-beam joints incorporating long slotted holes, which can be used to provide horizontal adaptability for the joint in the context of steel reuse. Finite element analyses, validated against experimental results, were performed to evaluate the impact of parameters such as plate thickness, bolt preload, bolt diameter, and bolt number on joint shear and slip performance. Results reveal that increasing bolt preload levels from 30% to 70% leads to a marked improvement in slip resistance and a modest increase in overall shear capacity. Force–displacement curves show that higher preload delays the onset of slip and enhances initial stiffness due to improved frictional engagement at the interfaces. Bolt slip was monitored at the individual bolt level and was found to initiate at significantly higher loads when greater preload was applied. The findings emphasize the critical role of preload in controlling interface behaviour and improving connection performance, particularly in the early stages of loading. In the shear resistance, number of rows and bolt diameter had a stronger influence, though gains diminished beyond M24 due to the adverse effects of larger clearance holes on bearing resistance.

**Keywords**

Slotted holes, Circular construction, Preloaded bolts, Finite element analysis

# 1 Introduction

The construction industry is increasingly urged to adopt sustainable methods that lessen environmental impact while ensuring durability and efficiency. This push stems from the need to replace conventional linear processes with circular models focused on recycling and reusing materials. By prioritizing modification and reuse over replacement, structural elements can be repurposed with minimal waste, extending their life cycle and conserving valuable resources. These systems are intentionally engineered for disassembly rather than demolition, making it easier to recover and reintegrate components into new projects. This approach significantly reduces embodied carbon, and minimizes the overall environmental footprint of the built environment.

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In circular steel construction, joints play a crucial role in enabling reuse and adaptability. Unlike traditional welded or permanent connections, demountable joints are specifically designed for easy disassembly. This allows structural elements like beams and columns to be removed without damage, making them suitable for reuse in new configurations or projects. Without these types of joints, recovering and reusing steel member is difficult, limiting the potential for circularity. By incorporating adaptable connections, buildings can be more easily modified, extended, or dismantled, supporting a sustainable construction cycle and maximizing material lifespan. One effective strategy to enhance both adaptability and demountability in circular steel construction is the use of slotted holes in bolted connections. These slotted openings allow for flexible bolt positioning, accommodating greater tolerances and enabling components to be adjusted or repositioned without the need for precise alignment. This adaptability is key in circular design, where structures may need to be reconfigured over time. Moreover, since bolted connections are inherently demountable, slotted-hole joints not only support easy assembly and adjustment but also allow for full disassembly without damaging the components. This makes it possible to recover and reuse structural members in future projects, aligning perfectly with the goals of circularity by reducing waste, preserving embodied carbon, and extending the lifecycle of materials.

Research into slotted holes in cleat connections began in the late 20th century. Man et al. [1] investigated how short slotted holes affect the strength and performance of beam-to-column shear connections. Through full-scale testing, they identified key failure modes and highlighted the importance of plate washers in maintaining shear capacity. Plate bearing is a preferred failure mode in shear-loaded joints due to its ductility. Foundational models from the 1980s have been refined and studied by several researchers. Može and Beg [2] studied single and double-bolt connections made from mild and high-strength steel, identifying failure modes such as bearing, splitting, and net section failure. Their work showed that EN 1993-1-8:2005 was overly conservative in predicting bearing resistance. They proposed a revised model focusing on end distance and bolt spacing, which aligned better with experimental data. Subsequent studies validated this approach, especially for large end distances, and highlighted the role of friction [3]. The bearing of slotted holes is also a focus of research since the early 2000s. Wald et al. [4] examined slotted holes perpendicular to the load direction and found that, while longer slots presents reduced bearing resistance, the impact on short, slotted holes was less pronounced. Cavène et al. [5] used Digital Image Correlation and LVDTs to analyze stiffness in bolted connections with slotted holes, developing an analytical model considering flexural and bearing effects.

While the performance of connections with short and medium slotted holes has been extensively investigated, the behaviour of joints incorporating long slotted holes remains comparatively underexplored. In such connections, slip resistance plays a critical role in preventing bolt slippage and the subsequent development of bearing deformations. Given the importance of both shear and slip resistance in ensuring joint performance, this study employs a validated, advanced numerical model to analyse the shear behaviour of preloaded beam-to-beam connections with long slotted holes. A comprehensive parametric study is conducted, examining the effects of supported member configuration, bolt diameter, preload level, and number of bolts on the joint response.

## 2 Numerical modelling

The numerical simulations were carried out using Abaqus® finite element software with solid elements. A dynamic implicit solver was employed under quasi-static conditions. Bolt preload was simulated by

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applying a temperature gradient along the bolt shank. The plates were modeled using a quadri-linear material behavior [6], while the bolts followed an elasto-plastic material model incorporating linear strain hardening. Surface-to-surface contact with a friction coefficient of 0.2 was considered. In order to assess the validity of the numerical model, comparison with experimental results was performed, as described in the next section.

## 2.1 Validation study

As part of the RFCS REDUCE European project [7], an experimental test was conducted at the University of Luxembourg to investigate a beam-to-beam joint with slotted holes (Figure 1). The test involved a three-beam assembly (with IPE 360 as supported and supporting member), where the beams were connected using web cleats with long slotted holes on the beam legs. The assembly was loaded at mid-span, and both deflections and joint rotations were recorded throughout the test. Significant elongation of the beam web bolt holes was observed, primarily resulting from localized bearing deformation. This deformation initiated following bolt slippage and progressed as the internal moment demand increased, continuing until the plastic moment capacity of the beam section was attained.

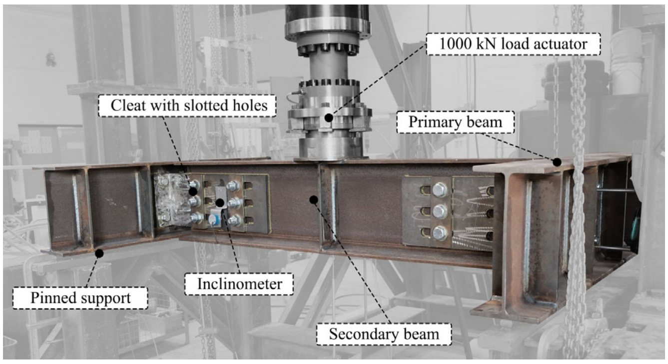


**Figure 1** Experimental test used as a reference for FE model validation

To simulate the test and assess the validity of the FEM model, a structured mesh was utilized, as illustrated in Figure 2, with 32 elements arranged around each bolt hole. The global element size was set to 20 mm, and three elements were defined through the plate thickness of each part.

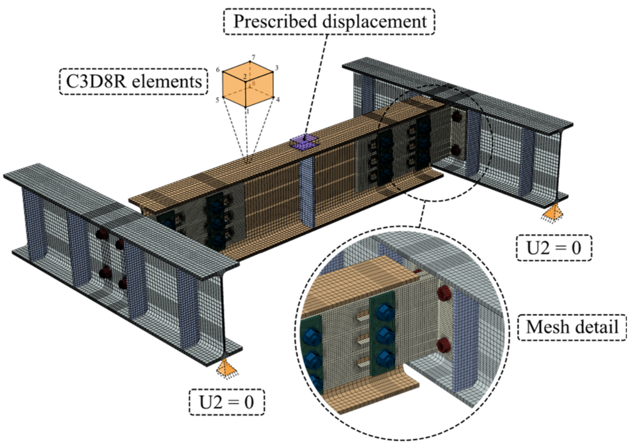


**Figure 2** FE mesh of the experimental test simulation

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The results of the validation study are presented in Figure 3. A very good agreement was observed between the experimental test and the advanced numerical model, with the finite element simulation effectively capturing the behaviours seen during the test. This includes the overall deformation (Figure 3a) and the load-displacement curve (Figure 3b). Since the connection was preloaded before the test started, slip was largely prevented up to a certain point, and this phenomenon was accurately captured by the FE model. The first bolt slippage occurred at 170 kN, which was precisely represented by the FE simulation. As shown in Figure 3c, the first bolt line began to slip simultaneously at this load. From this point, up to the end of the slip, the bolt in the first row and first line experienced a tensile force of 129.31 kN. With a friction coefficient of 0.2 and the presence of two shear planes in the joint, friction was responsible for transferring 51.72 kN. This translated into a shear force of 86.3 kN on the joint, which occurred at a mid-span load of 172.6 kN. Additional slips were observed in the experimental test and in the simulation. After the initial slip of bolts 1 to 3, slippage was observed on bolts 6, 4 and 5, in this sequence. After bolt slippage, all holes exhibited bearing deformations, and significant elongation was observed in both test and FEM. The analytical determination of bearing resistance according to EN 1993-1-8:2005 indicates a bearing capacity of 600 kN. The test was executed up to beam failure due to plastic bending capacity being achieved at a load of 824 kN. As all these points were accurately represented by the FE model, the validation was considered successful.

## 2.2 Parametric study

The parametric study was conducted in a similar way as the experimental test. However, as the major point in the joint design is its shear resistance the loading was slightly modified. On the parametric study, two concentrated loads are used to promote higher shear forces at the joints, as depicted in Figure 4.

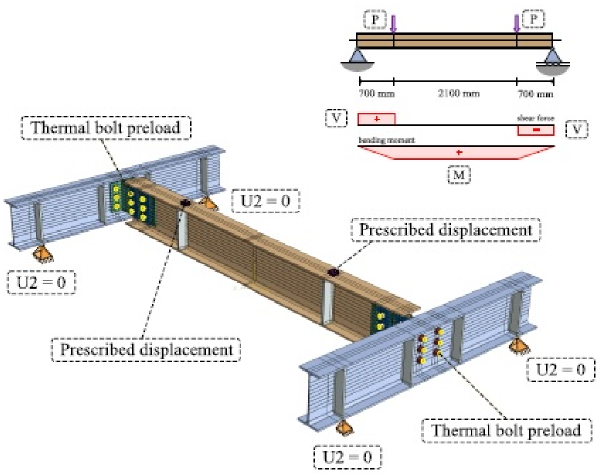


**Figure 4** FEM for the parametric study: loads and boundary conditions

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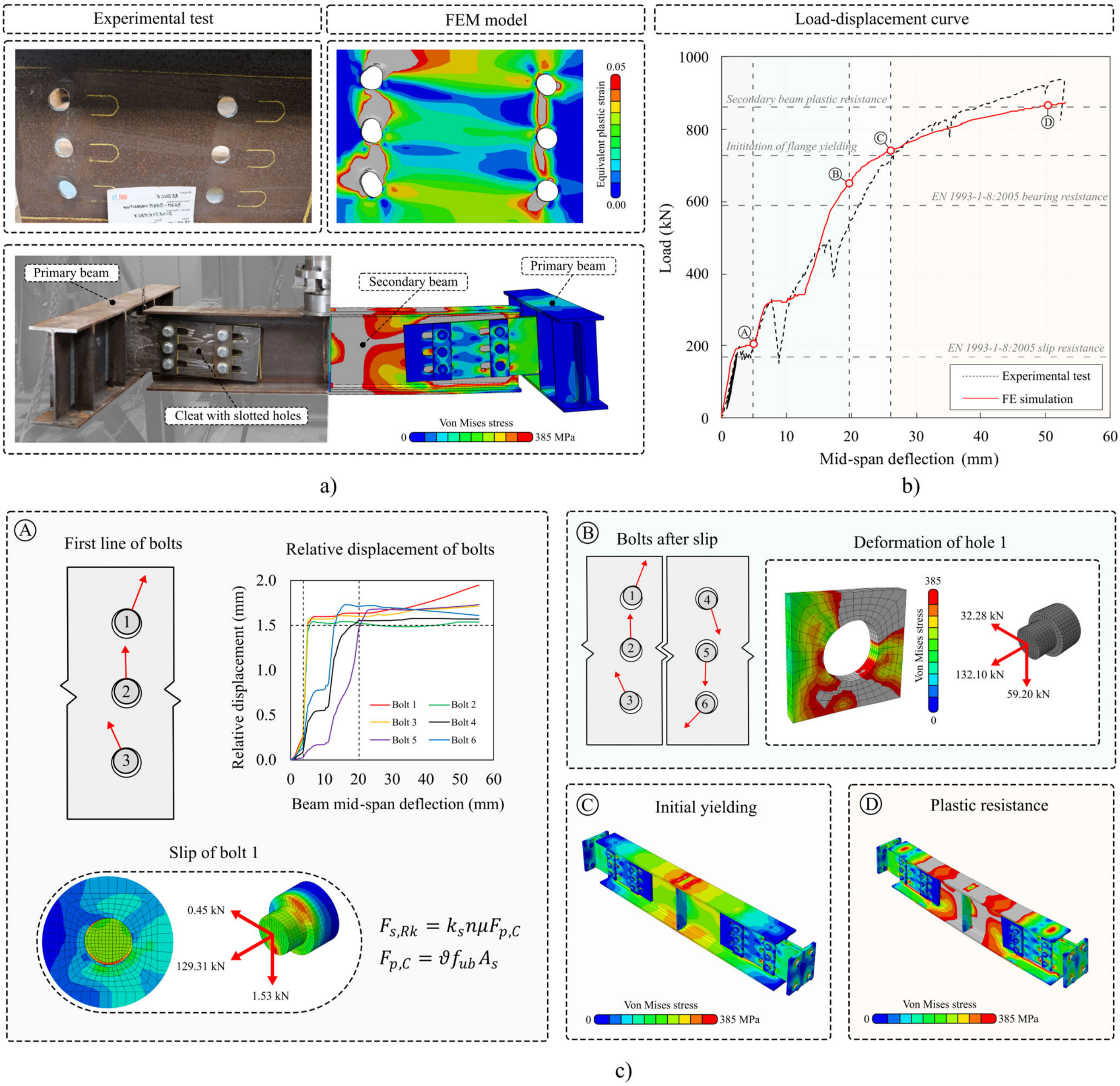


**Figure 3** Results for the validation study. a) Deformed shape. b) Load-displacement curve. c) Details of observed model response during the FE analysis

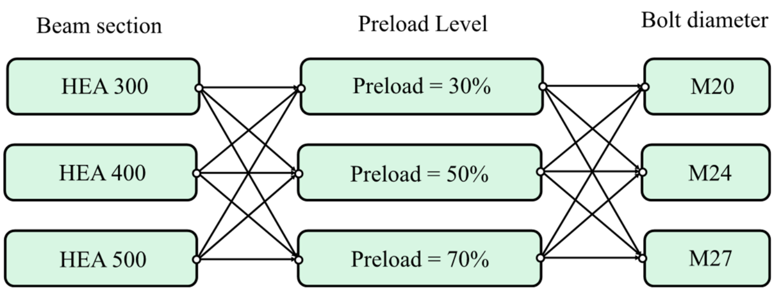


**Figure 5** Parametric study information flowchart

The concentrated load P near the joint will promote a shear force V = P on the connection. Displacements at load introduction points and vertical reaction forces are measured to build shear force-displacement

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curves. For the analyses, 3 beam sections were considered, with different preload levels, and bolt diameters, as shown on Figure 5. It is highlighted that the number of bolt rows is a function of the beam considered, being taken as 1, 2 and 3 rows for HEA 300, 400 and 500, respectively.

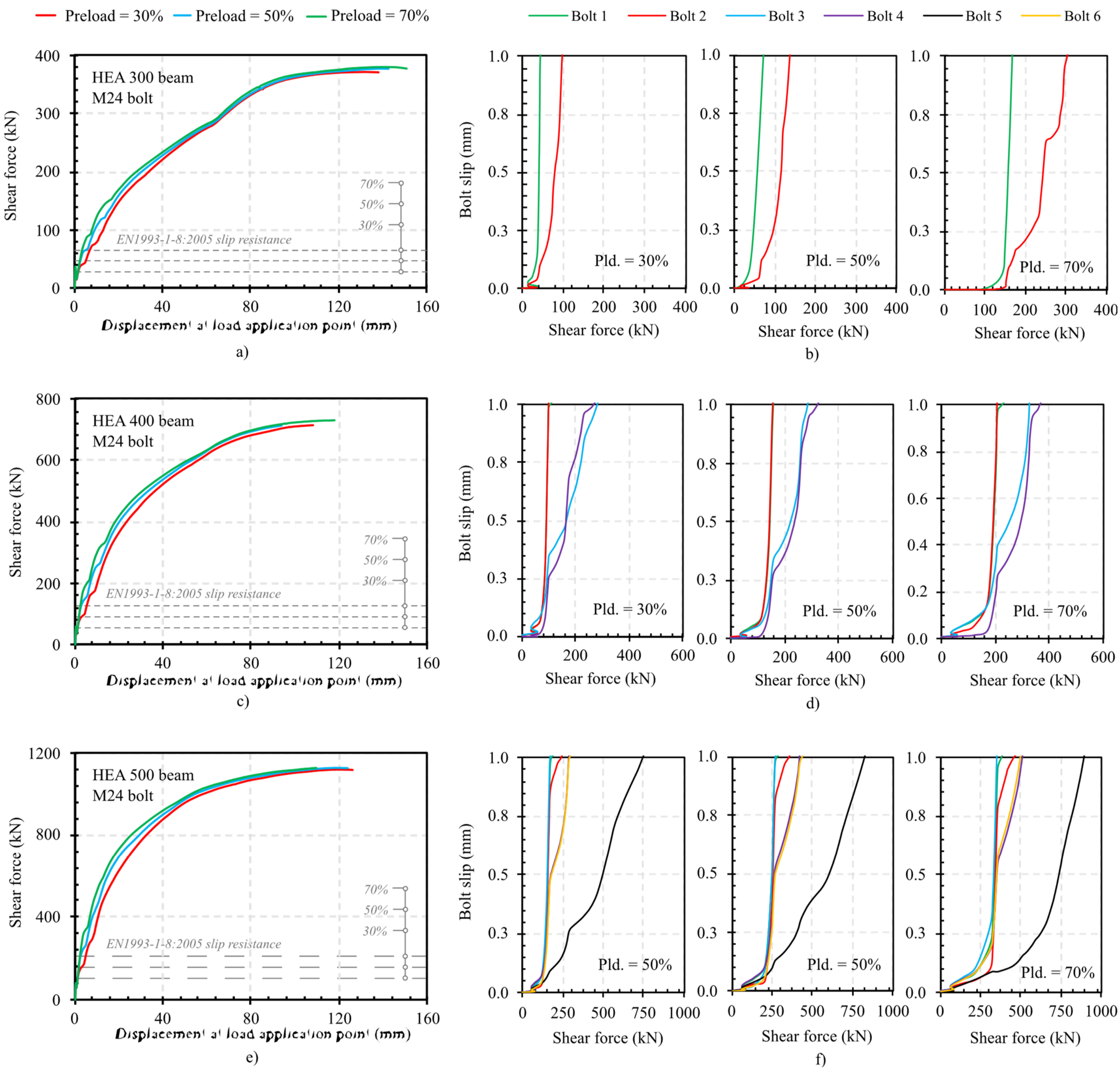


**Figure 6** Shear force vs. displacement curves and bolt slip behaviour. a) HEA 300 - shear vs. displacement. b) HEA 300 – bolt slip behaviour. c) HEA 400 – shear vs. displacement. d) HEA 400 – bolt slip behaviour. e) HEA 500 – shear vs. displacement. f) HEA 500 – bolt slip behaviour

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# 3 Results and discussion

In Figure 6 it is shown the shear performance of three different steel beam configurations, HEA 300, HEA 400, and HEA 500, under varying bolt preload levels of 30%, 50%, and 70%. Figures 6a, c, and e illustrate the global shear force–displacement response, while the subplots (Figures 6b, d, and f) depict bolt slip as a function of applied shear force, highlighting the critical thresholds at which slip initiates for each preload condition. The numbering of the bolts follows the same logic as the one shown in Figure 3c.

A consistent trend is observed across all analyzed beam sections: increasing the preload level improves slightly the shear capacity of the bolted connection and significantly improves the slip resistance of the joint, since the onset of the first slip, characterized by a noticeable change in the slope of the force-displacement curve, occurs at higher shear forces with increasing preload levels. In all cases, the beams with 70% preload not only sustain higher peak loads but also demonstrate delayed onset of bolt slip. The effect is particularly noticeable in the initial stages of loading, where the slope of the force–displacement curve remains steeper for higher preloads, indicating enhanced stiffness due to more effective frictional engagement at the interfaces. For the HEA 300 beam (Figure 6a), the 70% preload condition exhibits a pronounced delay in slip initiation, with bolt slip occurring at approximately 86 kN compared to 34 kN for the 30% preload case. This trend persists with increasing beam size. In the HEA 400 beam (Figure 6b), the slip initiation for the 70% preload occurs at around 168 kN, while for the 30% preload, slip begins near 67 kN. The HEA 500 beam (Figure 6c) shows the most significant loadbearing enhancement: bolts under 70% preload withstand over 280 kN before slip, compared to about 112 kN for the lowest preload case. The subplots reinforce this interpretation by plotting bolt slip against shear force for each preload level. These plots reveal that increased preload shifts the bolt slip curves to the right, indicating that higher clamping forces prevent early slip and maintain joint slippage behavior under greater loads. The slip curves for lower preload levels (e.g., 30%) display earlier and more abrupt increases in displacement, suggesting premature slip and reduced load transfer by friction. It is also highlighted in these curves the sequence of slippage of each bolt of the connection. Moreover, the shape of the bolt slip curves evolves with beam size and preload. Larger beams, with more bolts (HEA 500) displays a more gradual slip transition, especially for the bolts of the second line, reflecting a more distributed and progressive mobilization of the interface.

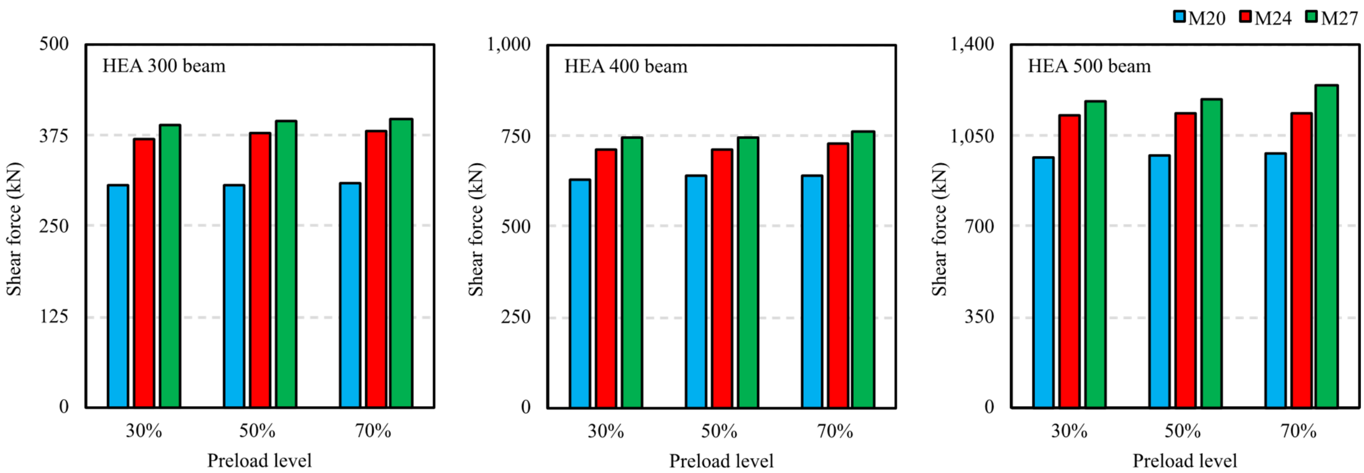


**Figure 7** Comparison between bolt diameter and preload level for all analysed sections

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This behavior reconfirms that preload effectiveness becomes increasingly critical for maintaining the efficient structural behavior in higher-capacity beams, where bolt slip could otherwise compromise load distribution and stiffness, given that these beams are able to withstand significant levels of shear force.

The results presented in Figure 7 indicate that both preload level and bolt diameter influence the shear resistance of the connections across the three beam types (HEA 300, HEA 400, and HEA 500), but to varying degrees. While an increase in preload from 30% to 70% leads to a slight enhancement in shear resistance (the maximum increase observed in the data from this study was of 4.58%, for the HEA 500 beam), the effect is relatively modest, with an average increase of 1.13%. This behaviour can be attributed to the role of preload in bolted connections, where it primarily delays the onset of slip by increasing the frictional resistance between the connected elements, rather than substantially affecting the ultimate shear or bearing capacity of the joint. The observed increase in shear resistance is primarily attributed to the predominant failure mode of the joints, which was bearing failure at the beam web holes. As the bearing mechanism progresses, evidenced by significant elongation of the bolt holes, material flows laterally around the holes. This lateral expansion induces axial forces in the bolts. As the tensile force in the bolts increases, a larger portion of the load is transmitted through friction at the bolt–plate interface rather than through direct shear. This redistribution reduces the shear demand on the bolts and enhances the engagement of the bearing mechanism, thereby contributing to the increased shear resistance. In contrast, changes in bolt diameter have a much more significant impact on the overall shear resistance.

As the bolt diameter increases from M20 to M27, there is a clear and substantial rise in the shear force values for all beam types and preload levels (an increase of up to 22.95% in the shear strength of the joint was observed in in the present study). This is largely due to the larger bearing area provided by the bigger bolts, which reduces stress concentrations around the bolt holes and enhances the joint's ability to resist shear forces without failure. However, larger bolts also result in increased clearance between the bolt and hole. As bolt diameter increases, the corresponding hole size also increases (e.g., 22 mm for M20, 26 mm for M24, and 30 mm for M27), which reduces the bearing resistance. This results in a less efficient transfer of load between bolts and connected elements, limiting the additional benefit of upsizing the bolt beyond M24. Furthermore, larger hole diameters introduce greater initial tolerances and misalignments, which can reduce preload effectiveness in controlling slip. The average increase of shear resistance from M20 bolts to M24 was of 15.26% and from M24 to M27 bolts was of 5.39%.

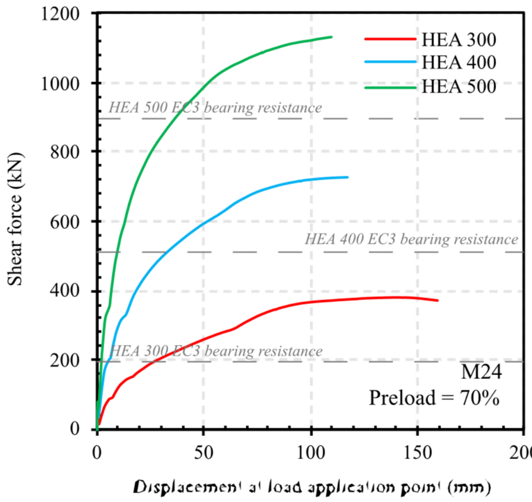


**Figure 8** Shear vs. displacement curves for the analysed beams

Comparing the three beams (Figure 8), it is also observed that the larger HEA 500 beam consistently exhibits higher shear capacities than the smaller HEA 360 and HEA 400 beams, which can be attributed, firstly to the increased number of rows and secondly to its increased cross-sectional dimensions (thickness of the web), offering better load distribution and resistance against bearing deformation.

# 4 Conclusion

This study explored the structural performance of preloaded beam-to-beam connections featuring long slotted holes, with a focus on enhancing reusability and adaptability in steel construction. Through validated finite element simulations, the influence of key parameters, including bolt preload, bolt diameter, and supporting/supported members was thoroughly investigated. The study shows the suitability of connections with long slotted holes and investigates the mechanical performance of these bolted joints, particularly regarding slip and shear resistance. Through advanced numerical simulations, it was found that factors like plate thickness and bolt preload levels are essential in determining the behavior and classification of these connections. The analysis revealed that bearing-type failures were the dominant failure mode. The results demonstrate that bolt preload plays a critical role in delaying the onset of slip and enhancing the overall shear resistance of the joint. Higher preload levels consistently increased initial stiffness and postponed bolt slip, leading to improved connection performance across all analyzed cases. However, the effectiveness of increased bolt diameter showed limiting returns beyond M24, largely due to the corresponding increase in clearance hole size, which adversely affects bearing resistance and promotes premature deformations.

To enhance the practical application of these findings, further research is necessary. This should focus on refining strength models and exploring the interaction between flexural and bearing effects also in the slotted holes, ultimately leading to improved design guidelines that can enhance the safety and efficiency of bolted joints with long slotted holes.

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