

Behaviour and analysis of adaptable beam-to-column joints with long slotted holes

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Abstract

This research addresses the need for circularity in the construction sector by proposing a modular building strategy utilizing adaptable beam-to-column joints with long slotted holes. A "kit of parts" approach is introduced where web cleats with long slotted holes provides horizontal adaptability allowing reclaimed steel members of various dimensions to be reused without the need for recutting. Utilizing non-linear Finite Element (FE) analyses validated against experimental testing, this study investigates the mechanical behaviour of these joints under eccentric shear loading. The investigation identifies two primary failure modes: bolt bearing against the beam web at smaller extensions and a Vierendeel mechanism characterized by plastic hinges at the corners of the slotted holes at maximum extensions. Statistical comparison shows that the current analytical model in EN 1993-1-8:2024 for bearing strength is generally conservative, with a Mean Absolute Percentage Error (MAPE) of 11.91%. Furthermore, a new analytical proposal for predicting Vierendeel failure, based on quadratic interaction between internal forces, demonstrates reasonable predictive accuracy with a MAPE of 10.34%.

Keywords

Steel joints, Adaptability, Reuse, Reclaimed beams, Circularity, Vierendeel action.

1 Introduction

Sustainable development has become an increasing necessity in the construction sector. The industry is one of the primary contributors to global CO₂ emissions; therefore, there is an urgent need to transition from linear production models to a circular approach. However, many challenges remain in implementing the use of reclaimed steel components in practical design. Among these challenges, the need for fully demountable structures is clear, necessitating the use of mechanical fasteners as the primary connection method. Nevertheless, designing for disassembly alone is not sufficient. To address this, within the framework of the RFCS project Connect4C, a two-way strategy is proposed: the use of modular building grids that allow for the standardization of member lengths, combined with adaptable steel connections that can accommodate a variety of member dimensions. By standardizing member lengths within a modular framework, the construction sector can overcome the limited usability of reclaimed steel in new designs due to incompatible dimensions. This approach directly enables circularity by ensuring that deconstructed components can be reintegrated into new projects as a "kit of parts" without the need for energy-intensive recutting.

Consequently, this shift facilitates non-destructive disassembly and creates a predictable secondary market in which reclaimed members are as functionally reliable and interchangeable as newly fabricated ones. To achieve the necessary horizontal adaptability in non-moment-resisting frames, the use of web cleats with long slotted holes is proposed (Figure 1).

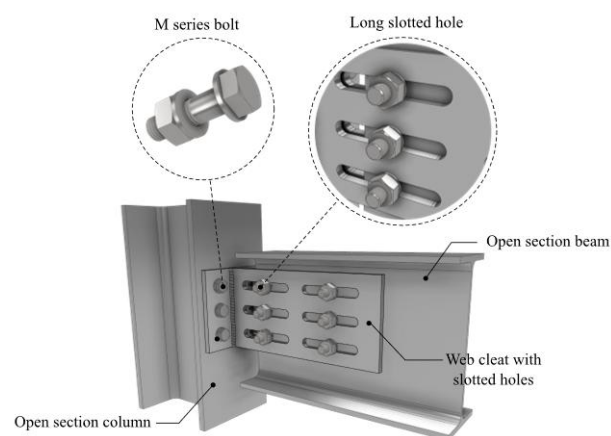


Figure 1 Adaptable web cleat with long slotted holes

With long slotted holes provided in the beam leg of the built-up cleat, different column sizes can be accommodated without the need to change the column axis position or the connection element. This enables the reuse of all steel components and ensures that the same building grid can be maintained across multiple lifecycles of the steel members. In addition, a small, slotted hole is incorporated in the column leg of the cleat, allowing for the use of multiple beam web thicknesses without the need for additional drilling.

The mechanical behaviour of slotted holes has been studied primarily in cover plate joints [1–3], where it has been shown that they exhibit a lower bearing capacity than standard round holes. This finding led to the inclusion of a reduced bearing capacity in EN 1993-1-8:2005 [4], based on the research presented in [5], which proposes a constant reduction factor. In the next generation of European steel standards, EN 1993-1-8:2024 [6], this reduction is instead expressed as a function of end distances, hole diameters, and slot lengths. While assessing the strength of individual slotted holes against bolt bearing is critical, it is equally important to evaluate their behaviour considering multi-bolt joints under eccentric shear loading, as occurs when they are applied to full-scale beam-to-column joints such as the one considered in this study. To address this issue and assess the behaviour of eccentrically loaded beam-to-column bolted connections with long slotted holes, this paper presents a comprehensive parametric finite element (FE) study. The primary objective is to investigate potential failure modes and to evaluate the accuracy of existing design methodologies in predicting the capacity of these joints, ultimately proposing optimized design rules when applicable.

2 Numerical model

An advanced numerical model was developed to investigate the behaviour of the joint. Nonlinear finite element (FE) analyses were performed using the commercial FE software package ABAQUS. An implicit solver was adopted, and the joint was modelled using three-dimensional solid finite elements, as shown in Figure 2.

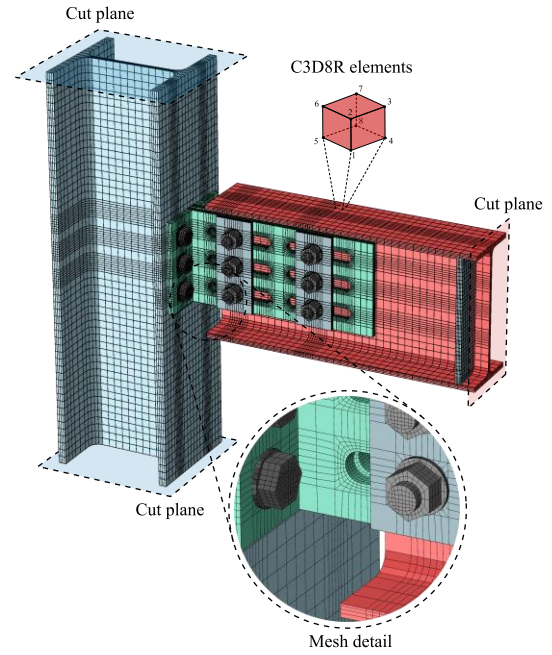


Figure 2 Finite element mesh

Material nonlinearity was considered through the definition of the plastic behaviour of the steel components. A quad-linear constitutive relationship was adopted [7]. A displacement-controlled analysis was performed, and the pre-loaded bolts were modelled by applying a tensile load to the inner mid-surface of the bolt shank. The numerical model was validated against a previous experimental test conducted at the University of Luxembourg (Figure 3).

2.1 Parametric study

A parametric study was conducted considering the joint subjected to shear. The boundary conditions shown in Figure 4 were adopted to assess the shear strength of the eccentrically loaded joint. To this end, a vertical load was assumed to act at a distance of 675 mm from the beam end. As a result, the connection and the supported mem-

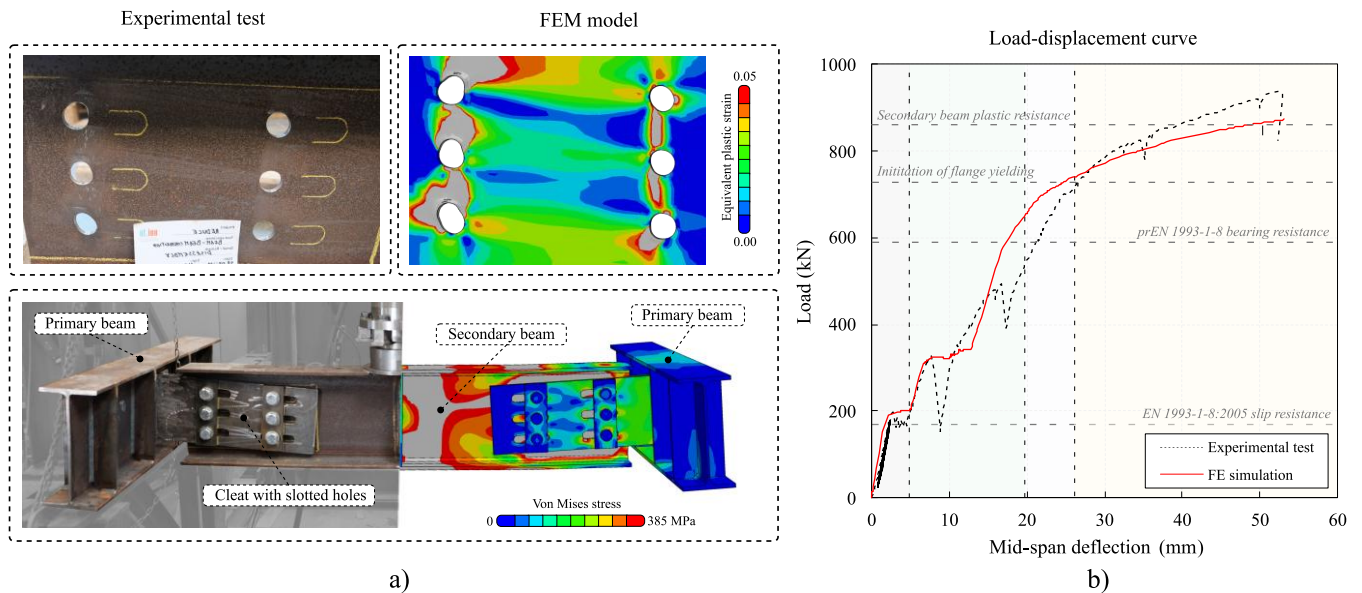


Figure 3 Numerical model validation

ber experienced a constant shear force and a linear bending moment distribution.

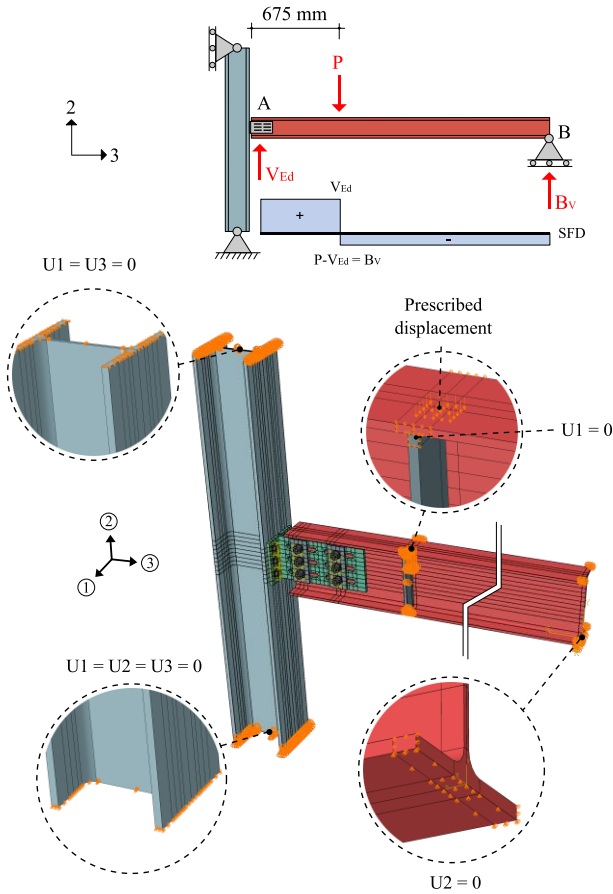


Figure 4 Boundary conditions

Based on these FE models, the effects of several parameters were assessed, including the material strength of the beam, cleat, and bolts; the dimensions of the supported member; cleat thickness; slotted hole dimensions; as well as bolt diameter and preload level. Initially, the position of the bolt within the slotted hole and its effect on the failure mode and shear strength of the joint were investigated. To this end, five possible bolt positions along the slotted hole were considered (Figure 5). Subsequently, two distinct parametric studies were carried out. These parametric studies correspond to the two decisive failure modes identified in the first step.

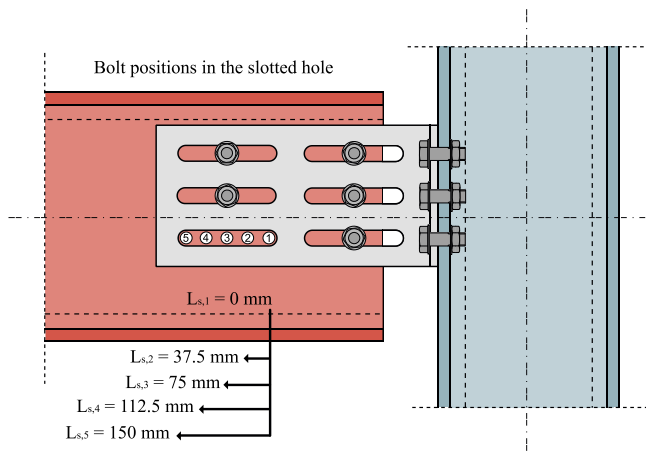


Figure 5 Assessment of bolt position

Each parametric study consisted of 216 analyses of the connection for two distinct bolt positions within the slotted hole, corresponding to small extension ($L_{s,2}$, see Figure 5). and maximum extension ($L_{s,5}$, see Figure 5).

3 Results and discussion

The initial assessment of the joint behaviour as a function of the bolt position along the slotted hole revealed that, when the bolt is located towards the end of the slotted length, the transfer of shear forces across the openings promotes local yielding, leading to the formation of plastic hinges at the corners of the slotted holes.

This behaviour is similar to the Vierendeel mechanism observed in beams with web openings [8–10]. When the bolts are positioned at minimum extension, and considering that high-strength steel is used for the cleats, the beam web becomes the weakest component. In this configuration, the beam web is responsible for carrying the entire shear force transferred through the bolts to the two web cleats. Consequently, the governing failure mode is bolt bearing against the beam web holes.

This behaviour is illustrated in Figure 6, which shows that the bolt position has a significant influence on the shear strength of the joint. For slot lengths (L_s) ranging from 0 to 75 mm, failure was governed by bearing of the beam web, whereas for L_s equal to 112.5 mm and 150 mm, failure was governed by the Vierendeel mechanism. Although the first three bolt positions exhibited the same failure mode, significant differences in shear capacity were observed. These differences are attributed to the increasing eccentricity between the applied shear force and the bolt group centreline as the bolt position varies along the slotted hole. Figure 6 also indicates the point at which the bearing-induced failure occurred, as well as the point at which the Vierendeel failure mechanism was attained. The method to define the failure points for each mode is described in more detail in the remainder of this paper.

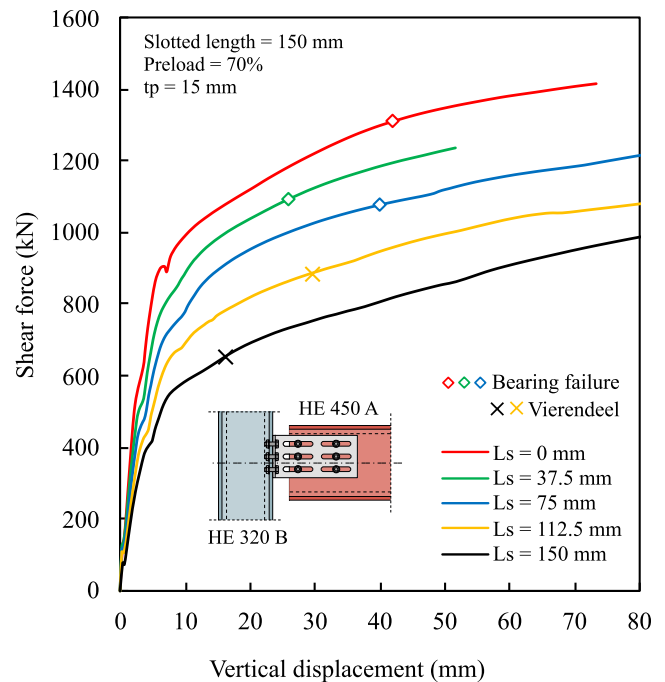


Figure 6 Effect of the bolt position on the shear strength

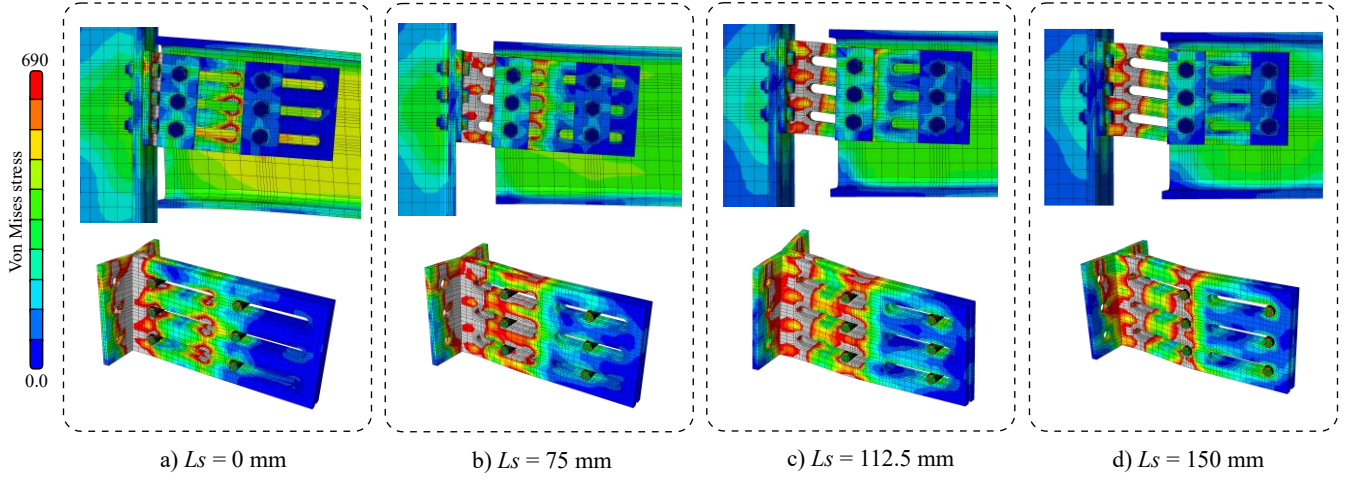


Figure 7 Stress field of web cleats according to bolt position

Figure 7 illustrates the yielding pattern in the web cleats for different bolt positions along the slotted hole. It is evident that the bolt position alters the stress distribution. For $L_s = 112.5$ mm and $L_s = 150$ mm, the transfer of shear across the opening induces an additional local bending moment, which leads to yielding and the formation of plastic hinges at the corners of the slotted holes. This additional bending moment is commonly referred to as the Vierendeel bending moment. The lever arm associated with this mechanism increases with the distance of the bolt from the left corner of the opening, with the most critical condition occurring at the maximum extension. In this case, the shear strength of the joint is inversely proportional to the slotted hole length.

3.1 Bearing strength

The bearing failure of the beam web plate occurs at the smallest extensions of the slotted hole cleat. This phenomenon is characterized by significant deformation of the beam web holes, as shown in Figure 8. The analytical approach adopted for the design is based on determining the maximum compressive stress that can be sustained by the web hole due to the contact between the hole wall and the bolt shank.

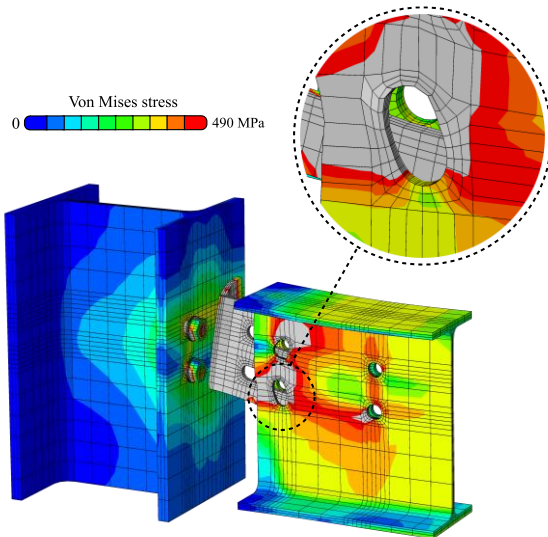


Figure 8 Bearing failure of the beam web holes

This contact induces a concentration of very high forces over a small area, thereby resulting in significant stress levels at the holes. EN 1993-1-8:2024 limits the maximum compressive stress based on the relationship between the hole size and its distance from the plate edges (Equations 1 to 4). In the best-case scenario, when the distance to the plate edge is sufficiently large, the maximum compressive stress can reach up to three times the ultimate strength of the plate.

$$F_{b,Rd} = \frac{k_m \alpha_b f_u d t}{\gamma_{M2}} \quad (1)$$

$$\alpha_b = \min\left(\frac{e_1}{d_0}; 3 \frac{f_{ub}}{f_u}; 3\right) \text{ for end bolts} \quad (2)$$

$$\alpha_b = \min\left(\frac{p_1}{d_0} - \frac{1}{2}; 3 \frac{f_{ub}}{f_u}; 3\right) \text{ for inner bolts} \quad (3)$$

$$k_m = 0.9 \text{ for steel grades equal or higher than S460} \\ k_m = 1 \text{ for steel grades up to S460} \quad (4)$$

To account for how the bolt force distribution translates into the shear force in the joint, Equations 5 to 8 can be used. The Equation 1, which is given in Annex C of EN 1993-1-8:2024, describes the shear strength of a full-scale joint with two vertical rows of bolts subjected to bearing.

$$V_{Rd} = \frac{n}{\sqrt{\left(\frac{1 + \alpha n}{F_{b,ver,Rd}}\right)^2 + \left(\frac{\beta n}{F_{b,hor,Rd}}\right)^2}} \quad (5)$$

For vertical lines of bolts:

$$\alpha = \frac{z p_2}{2I} \quad (6)$$

$$\beta = \frac{z p_1}{2I} (n_1 - 1) \quad (7)$$

$$I = \frac{n_1}{2} p_2^2 + \frac{1}{6} n_1 (n_1^2 - 1) p_1^2 \quad (8)$$

However, assessing the agreement between the bearing strength design and the FE simulation results is not straightforward, due to the difficulty in identifying the failure point in the FE model. The strategy adopted in this

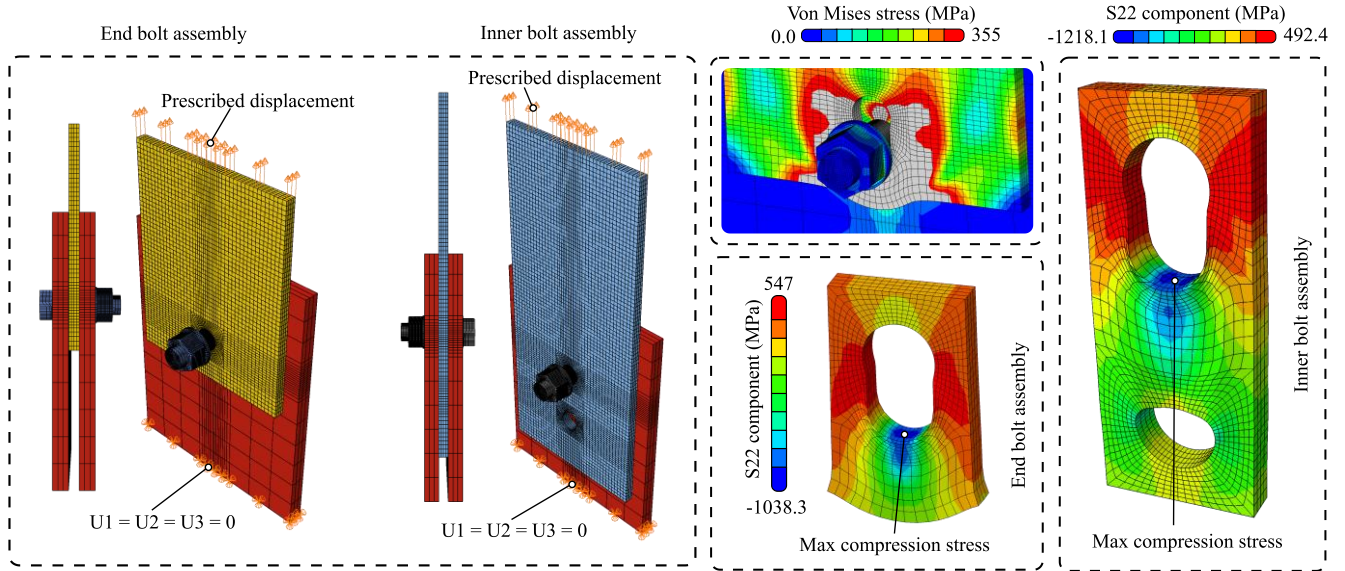


Figure 9 Modelling of plate in bearing component for estimating bearing strength

paper was to first estimate the shear force that the beam web plate can resist by considering a single concentrically applied force. Based on this approach, the maximum compressive bearing stress of the plate at the component level was evaluated (Figure 9). This was achieved through FE simulations of the plate component in bearing, considering both the internal and edge bolts. Under the loading and boundary conditions used in this study, the internal bolt represents the vertical bearing resistance of the joint, while the edge bolt represents its horizontal bearing resistance. After estimating the maximum compressive bearing strength of both cases, the interaction between the horizontal and vertical plate bearing resistances was assessed using the criterion given in Equation 9.

$$\left(\frac{F_{b,hor,Ed}}{F_{b,hor,Rd}}\right)^2 + \left(\frac{F_{b,ver,Ed}}{F_{b,ver,Rd}}\right)^2 = 1 \quad (9)$$

The comparison between the shear strength obtained with FE modelling and with the analytical model from prEN1993—8 is shown in Figure 10. The comparison demonstrates a strong linear correlation between the analytical predictions and the numerical simulations over a broad range of shear strengths related to bearing phenomena. As shown in the figure, the majority of the data points reside below the 45-degree line of equality, indicating that the analytical model is generally conservative. Quantitatively, the model exhibits a reasonable degree of accuracy and consistency, evidenced by an average FEM/analytical ratio of 1.14 and a relatively low Coefficient of Variation (COV) of 7.91%. Furthermore, the Mean Absolute Percentage Error (MAPE) was calculated at 11.91%, with the superimposed error histogram confirming that the peak error frequency for most samples remains within a narrow, acceptable range.

One important aspect to be highlighted is that 3 different levels of preload were considered in the study: snug-tight, 35% and 70% of the load that leads to the ultimate strength to be attained in the bolt shank. As the analytical prescription from prEN1993—8 does not account for the frictional share of load transfer, the magnitude of average error between the analytical equations and the FE results

from the full-scale joint is correlated with the magnitude of preload.

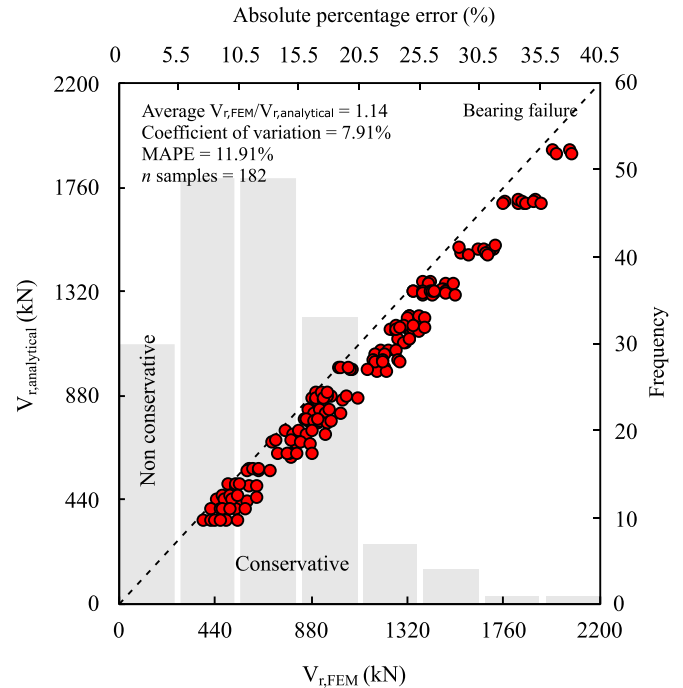


Figure 10 Bearing failure: assessment of EN1993-1-8:2024

3.2 Vierendeel Strength

The formation of plastic hinges at the corners of the slotted holes, caused by the transfer of shear forces across the opening, leads to the so-called Vierendeel mechanism failure mode of the joint, particularly when the maximum extension of the web cleat is considered. This phenomenon is directly related to the length of the slotted hole, which acts as a lever arm for the local shear force acting at the hole corners. As a result, additional local bending develops, known as the Vierendeel bending moment. This mechanism is typical of beams with web openings, especially those with elongated openings. Design approaches in standards and research literature generally involve checking the strength of individual parts of the cross-section against the local internal forces that arise. For beams, this

is typically performed by verifying the strength of the top and bottom tee sections at the centreline [11,12] of the opening. In this paper, a similar strategy is proposed, in which the cleat is divided into blocks responsible for carrying the local internal forces that arise at the critical cross-section (Figure 11).

It is well established that multiple local internal forces co-exist at the local section, namely normal force, shear force, and Vierendeel bending [8]. Although Vierendeel bending largely governs the behaviour, several authors have suggested that the interaction between the internal forces at the critical cross-section should be considered [10–12]. In line with this approach, this paper proposes a quadratic interaction between internal forces (Equation 10), with the normal force accounted for through the verification of the bending strength of the cleat section. As reported in the literature [13], for circular and elongated circular openings, the critical section resisting the induced Vierendeel bending is radial and oriented at an angle of approximately 25°. At this section, the bending resistance may be taken as about 17% higher than that of a rectangular section oriented at 0°.

$$\left(\frac{V_{Ed}}{V_{Rd}}\right)^2 + \left(\frac{M_{Ed}}{M_{Rd}}\right)^2 + \left(\frac{M_{V,Ed}}{M_{V,Rd}}\right)^2 \leq 1 \quad (10)$$

The shear resistance V_{Rd} is taken as the plastic shear strength of the cleat section. Similarly, the bending resistance M_{Rd} is defined as the plastic bending resistance of the cleat section at the centreline of the slotted hole. The Vierendeel bending resistance $M_{V,Rd}$, however, is considered as the sum of the bending resistances of the critical cross-sections, oriented at an angle of 25°, which are subjected to the moment induced by shear force transfer (Equation 11) considering the effective length l_{eff} .

$$M_{V,Ed} = V_{Ed} l_{eff} \quad (11)$$

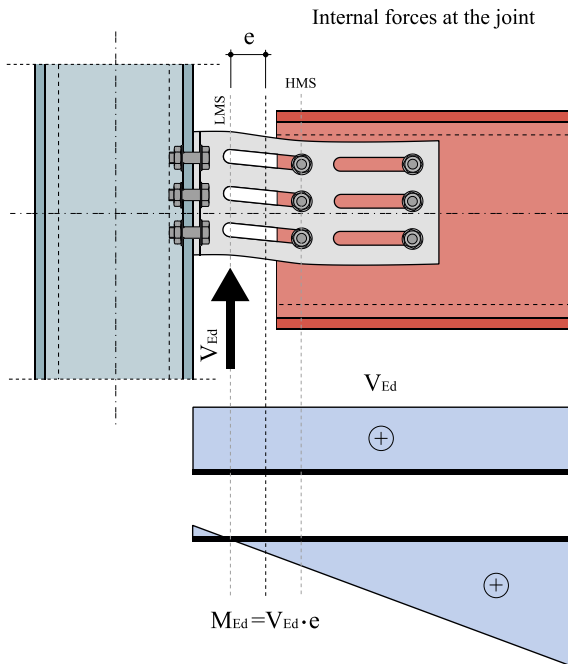


Figure 11 Internal forces at the slotted opening.

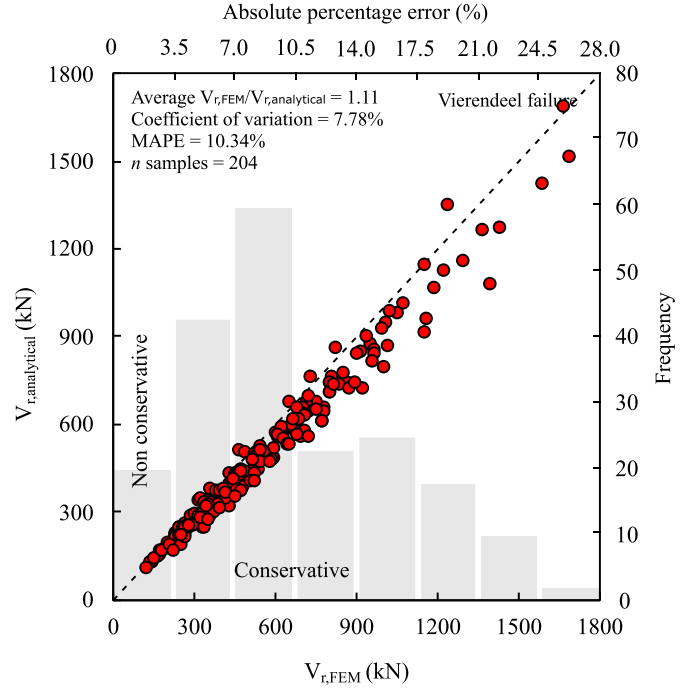
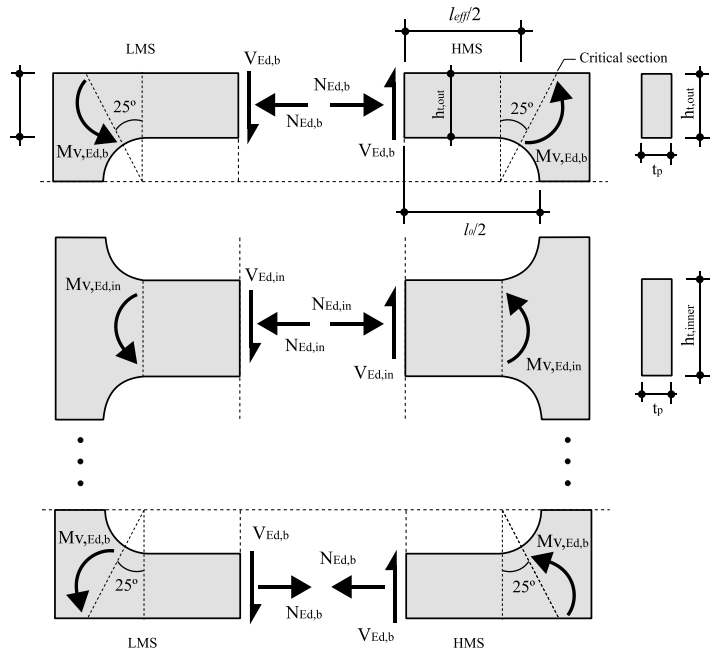


Figure 12 Vierendeel failure design model results

When this method was applied and compared with the FE simulation results, the outcomes shown in Figure 12 were obtained. The provided scatter plot illustrates the correlation between the shear capacities obtained from finite element modelling and those predicted by the analytical model for 204 samples focusing on Vierendeel failure. The data points exhibit a strong linear trend closely aligned with the 45-degree dashed equality line, indicating good predictive accuracy. Statistically, the analytical model demonstrates a slight tendency toward under-prediction, as evidenced by an average ratio between FEM and analytical proposal of 1.11 and the majority of data points falling within the "Conservative" region. The Mean Absolute



Internal forces at the blocks

Percentage Error (MAPE) is calculated at 10.34%, complemented by a relatively low coefficient of variation of 7.78%, which confirms the consistency of the analytical approach. Furthermore, the superimposed histogram of absolute percentage errors indicates that the highest frequency of errors occurs in the lower range (approximately 3.5% to 10.5%), suggesting that the analytical model remains reasonable across a broad spectrum of load magnitudes.

4 Conclusions

This study presents the development and assessment of adaptable beam-to-column joints incorporating long slotted holes, specifically designed to facilitate steel reuse by accommodating variations in member dimensions within modular structural grids. Through detailed numerical investigations, it is demonstrated that the structural performance of the joint is governed by two distinct failure mechanisms. The following conclusions are drawn from the study.

- At minimum bolt extensions, failure is controlled by beam web in bearing, whereas at maximum bolt extensions the response is dominated by a Vierendeel mechanism, characterized by the formation of local plastic hinges in the connected members.
- A comparative evaluation between finite element results and analytical predictions indicates that the current EN 1993-1-8:2024 design provisions for bearing resistance are generally adequate and conservative, yielding an average FEM-to-analytical resistance ratio of 1.14.
- A quadratic interaction model, based on previous research on beams with web openings is proposed to estimate the Vierendeel bending strength of the joint, serving as a preliminary yet robust design approach.
- The proposed approach demonstrates satisfactory predictive accuracy and consistency, with a mean absolute percentage error (MAPE) of 10.34% and a coefficient of variation (COV) of 7.78%.

The findings establish a preliminary framework for the design and implementation of adaptable beam-to-column connections, particularly suited for circular and reusable steel structures, which will be refined with results of a forthcoming experimental campaign within the Connect4C project.

Acknowledgments

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