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Faculty of Mechanical Engineering

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Comparative analysis of the analytical and numerical models for different types of beam-to-column connection

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Abstract *In steel structures, beam-to-column connections play a crucial role in forming stable spatial structure by linking structural elements set in orthogonal directions. As one of the critical load-bearing components, the connection significantly affects the overall structural stability. This paper presents a comparative analysis of analytical and numerical results for the most commonly used beam-to-column connections: web cleat, partial depth end-plate and fin-plate, in accordance with relevant standards and regulations. Analytical calculations include the determination of ultimate load-bearing capacity and stiffness of the connections, while a numerical model based on finite element method is developed to analyze the behavior of the connections under loading. The results of the analysis provide insight into discrepancies between analytical and numerical methods, confirming the reliability of calculation models and their applicability in structural design. The developed model reduces the need for expensive and complex experimental testing, enabling the determination of key characteristics for various connection types. The obtained results can be used for element design and global structural analysis, following standardized protocols.*

Keywords *beam-to-column connection, analysis, finite element method*

1. INTRODUCTION

Joints are key elements in steel structures, ensuring their stability and structural integrity. The primary function of joints is to securely connect two or more elements, with the choice of joint depending on mechanical requirements, production and assembly costs, and application specifics. Joints used in steel structures include bolted, welded and riveted connections. The mechanical properties of joints directly affect on the global behavior of the structure, including its strength, stiffness and stability.

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Proper dimensioning of joints is crucial for efficient load transfer, ensuring stiffness or flexibility in line with design requirements. To achieve optimal performance, it is necessary to design joints in accordance with relevant standards, such as Eurocode 3 1993–1–8: 2005 [1], which define criteria for the calculation and verification of the load-bearing capacity of steel joints. Precise analytical calculations based on these standards enable reliable dimensioning of structures and ensure their safety during operation.

Bolted joints play a key role in the various steel construction, as they enable efficient load transfer and system stability. They are widely used due to their cost-effectiveness, ease of installation, and disassembly, but they have lower load-bearing capacity compared to welded joints. The most common application of these joints is the connection of steel profiles that form the basis of the load-bearing structure of the steel construction. In addition, bolted connections are used to connect various components, such as additional plates and reinforcements. This ensures the stability of the system.

Numerous studies address the issue of self–loosening of bolted connections and their impact on the stability of the structure, particularly in dynamically loaded systems such as bridges, overhead cranes and automated storage systems. Pirdayr et al. [2] investigated the effect of bolt loosening on the vibrational characteristics of plates with bolted joints through experimental tests and numerical analysis using the finite element method. Zhengyi et al. [3] developed and validated a numerical model to analyze the moment–rotation characteristics of web–cleat joints, examining the impact of parameters such as the number of bolts, spacing and angle thickness to improve the assessment of their stiffness and maximum bending moment before failure. Hawxwell and Tsavdaridis [4] experimentally investigated three types of joints – eccentric end–plate, fin–plate and partial depth end–plate, analyzing their rotational stiffness and load–bearing capacity. Research by Chen et al. [5] analyzed the cyclic behavior of a connection with fillet welds in joints for steel frames with moment–resistant columns, showing that this joint reduces the risk of brittle fracture and enables the formation of a plastic zone. These investigations confirm the importance of detailed analysis of these joints to enhance their performance and longevity during operation.

The field of bolted beam–to–column joints in steel structures has been extensively researched and is well–documented in numerous studies. It is also specifically addressed in Eurocode 3 (EN 1993–1–8). However, there remains a strong need for comprehensive comparative analyses between analytical and numerical methods. They help to understand better how joints behave under real loads, improve design methods, and make engineering solutions more reliable and efficient.

The goal of this research is to conduct a comparative analysis of analytical and numerical methods for assessing the load–bearing capacity and stiffness of beam–to–column connections in steel structures. The focus is on joints that are most often applied in practice, analyzing the deviation between theoretical calculations and numerical analysis based on the finite element method (FEM).

The obtained results contribute to the optimization of calculation models, reducing the need for experimental testing and providing more accurate determination of key joint characteristics in accordance with relevant standards. This type of comparative analysis plays a significant role in product development in the early stages of design.

2. DEFINITION OF JOINTS

The aim of this paper is to provide a comparative analysis of the analytical and numerical data obtained by calculating the most commonly used types of connections in the steel constructions.

2.1 Types of connection

The most commonly used beam–to–column connections, shown on Figure 1 are:

- web cleat (WC),
- partial depth end–plate (PDEP) and
- fin–plate (FP).

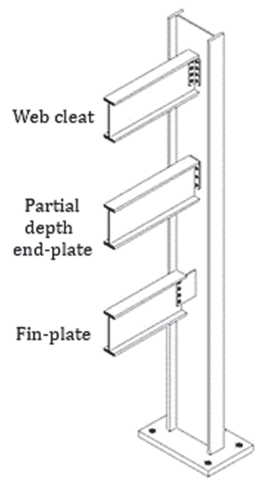

Fig. 1. Beam–to–column connections

The key parameters which are affecting on dimensioning of bolted joints in these structures include contact pressure between connected elements and shear forces acting within the joint. Optimization of these connections involve analyzing load distribution, interaction between joints and load–bearing elements, and assessing their reliability during exploitation.

2.1.1 Web cleat

The WC is a type of connection consisting of two angle brackets, typically attached to the web of the beam, as it is shown on Figure 2. This connection doesn't require welding and allows minimal adjustments during assembly using non–preloaded bolts. However, there are certain limitations, such as reduced flexibility in adjusting the skew of the beam and difficulties in connecting to shallow depth columns.

Fig. 2. Web cleat connection

Additionally, this connection has a lower load–bearing capacity. The rotational capacity of the connection primarily depends on the deformation of the angle brackets, while the effect of slip between the connected parts is smaller. To minimize rotational resistance, it is recommended to reduce the thickness of the angle brackets and increase the spacing between bolts. The connection moment is small and can be neglected in analytical analysis.

2.1.2 Partial depth end–plate

PDEP connections are a simple and widely used solution for beam–to–column connection in steel structures. The end plate, which can cover the entire cross–section height or only a part of it, is welded to the supported beam, while the connection to the column is achieved using bolts, as it is shown on Figure 3. These connections allow a certain degree of rotation, enabling the structure to accommodate deformations.

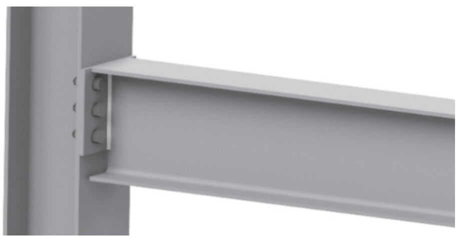

Fig. 3. Partial depth end–plate connection

In these connections, welding is performed on the beam web. A key aspect of their design is the optimization of weld dimensions to minimize deformations and prevent material damage. The plate dimensions, bolt arrangement, and steel selection are defined to ensure adequate load–bearing capacity and joint stability.

2.1.3 Fin–plate

The FP connection, shown on Figure 4, comprises a steel plate welded to the column, while the beam is connected using bolts. This type of connection is widely utilized due to its ease of assembly and the elimination of complications associated with shared bolts in double–sided connections. The rotational capacity of fin–plate joints arise from: deformation of the plate and/or beam holes, out–of–plane bending of the plate and shear deformation of bolts. Additional deformations may occur due to bolt slippage. However, this effect is typically limited as the majority of bolts rely on the edges of the holes from the outset.

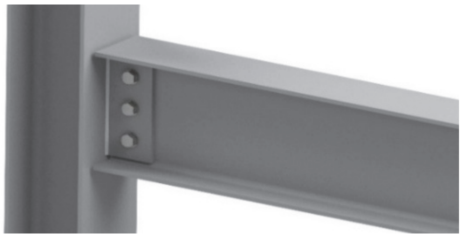

Fig. 4. Fin–plate connection

The analysis of bolts in this connection must ensure that none of the components – the plate or the bolt, exceed their resistance capacities. Failure to do so may result in joint loosening and localized damage [6].

2.2 Analysis of analytical models

The analytical calculation for considered connections will be calculated in VC Master software [7]. As material is used standard structural steel S275 with a yield strength of 275 MPa according to EC3–1–1: 3.2.3 (T.3.1) [1]. The connection transfers a shear force of $V_{Ed} = 200\ kN$.

A comparative analysis will be conducted for the following basic elements for all connections:

- standard profile HEA 200 for the column,
- standard profile IPE 300 for the beam and

- bolts M20, grade 8.8, as the connecting elements, with $f_{yb} = 640$ MPa, following EC3–1–8: 3.1.1 (T.3.1) [1].

The specific fastening elements, such as plates, will vary depending on the type of connection.

When designing steel connections according to EC3 [1], certain requirements related to geometry, bolt, weld and plate resistance must be met. These criteria are detailed below, aiming to ensure a reliable load transfer within the connection and prevent failure of any of its components.

2.2.1 Geometrical Requirements

For each connection, the minimum and maximum spacing requirements for hole distances and edge clearances must be satisfied in accordance with EC3–1–8: 3.5 (T.3.3) [1]. The minimum hole distance from the plate or profile edges prevents local plastic deformation and material tearing, while the minimum spacing between bolts prevents stress zone overlap and ensures an even load distribution. The maximum spacing between bolts and plate edges ensures that the plate does not deform and prevents local bending between bolts. All three connections meet the minimum and maximum spacing requirements.

2.2.2 Bolt resistance

Within the bolt resistance assessment, two key checks are considered – bolt shear capacity, which ensures that the bolts can withstand shear forces without failure, and bearing resistance, which verifies that the contact pressure between the bolts and the connected elements remains within permissible limits to prevent local plastic deformation.

- Bolt shear capacity

Bolts must be checked for shear by comparing the design shear force per bolt $F_{v,Ed}$ with the bolt shear resistance $F_{v,Rd}$, following equation:

$$\frac{F_{v,Ed}}{F_{v,Rd}} < 1 \qquad (2.2.2.1)$$

The design shear force per bolt is calculated as the quotient of the total shear force and the number of bolts contributing to load transfer, while the bolt shear resistance is defined according to EC3–1–8: 3.6.1 (T.3.4) [1]. For WC this ratio is 0,37, for PDEP 0,28 and for FP 0,83. The FP connection has the most critical shear utilization ratio, but remains within the permissible limits.

- Bearing resistance check

The bearing resistance of bolts $F_{b,Rd}$ is compared with calculated bearing force per bolt $F_{b,Ed}$, following equation:

$$\frac{F_{b,Ed}}{F_{b,Rd}} < 1 \qquad (2.2.2.2)$$

The design bearing resistance of a bolt is defined in EC3–1–8: 3.6.1 (T.3.4) [1], while the bearing force per bolt is determined as the total shear force divided by the number of bolts participating in load transfer, taking into account the load distribution and any eccentricity of the load. For WC this ratio is 0,54, for PDEP 0,29 and for FP 0,99. The FP connection is at the bearing resistance limit, indicating the potential for local plastic deformation. This value is critical, and an increase in bolt edge distance or plate thickness is recommended.

2.2.3 Plate resistance

The plate resistance assessment includes two key checks: plate shear resistance, which ensures that the plate can withstand shear forces without failure, and plate bending resistance, which verifies that the plate can resist bending moments within safe limits.

- Shear resistance

The plate shear resistance $V_{c,Rd}$ must be greater than the applied shear force V_{Ed}, as it is given in EC3–1–1: 6.2.6 (6.17) [1]:

$$\frac{V_{Ed}}{V_{c,Rd}} < 1 \qquad (2.2.3.1)$$

For PDEP this ratio is 0,97, while for the FP it is 0,75. The WC does not involve a supporting plate, and therefore, no plate shear resistance is considered for this connection. All connections are safe in terms of shear, except for PDEP, where the utilization ratio is close to the resistance limit, suggesting that increasing the plate thickness would be advisable.

- Bending resistance

The bending moment in the plate $M_{y,Ed}$ is determined as the result of the applied external loads and their eccentricities, and it is compared with its bending resistance $M_{y,c,Rd}$, following EC3–1–1: 6.2.5 (6.12) [1]:

$$\frac{M_{y,Ed}}{M_{y,c,Rd}} < 1 \qquad (2.2.3.2)$$

Plate bending is negligible for WC and PDEP connections, except for FP, which is 0,47. Even if plate bending occurs, it remains within safe limits.

2.2.4 Block shear check

The block shear check evaluates the potential for simultaneous bolt failure and plate deformation. It is defined as ratio of applied shear force V_{Ed} and resistance on block shear $V_{eff,2,Rd}$, which is defined in EC3–1–8: 3.10.2 (3) [1], and given with equation:

$$\frac{V_{Ed}}{V_{eff,2,Rd}} < 1 \qquad (2.2.4.1)$$

This ratio is 0,40 for WC and 0,39 for FP. In the PDEP connection, a block shear check is not required because the force is not transmitted directly through the body of the end plate, as it acts as an intermediate element. This geometry does not allow for the formation of a characteristic block shear failure path.

2.2.5 Weld check

The weld capacity must exceed the calculated stress. Comparing with other connections, only the WC has no welds. The final weld verification is performed by comparing the design stress in the weld $\sigma_{w,Ed}$ with its shear resistance $f_{w,Rd}$, ensuring that the condition from EC3–1–8: 4.5.3.2 [1], shown with following equation is satisfied.

$$\frac{\sigma_{w,Ed}}{f_{w,Rd}} < 1 \qquad (2.2.5.1)$$

For the PDEP this ratio is 0,53, while for the FP is 0,33. Both welded connections have sufficient safety reserves.
Dependence of load resistance defined above for every type of considered connection is shown on Figure 5. Where an empty line exists, it represents a zero value [6, 7].

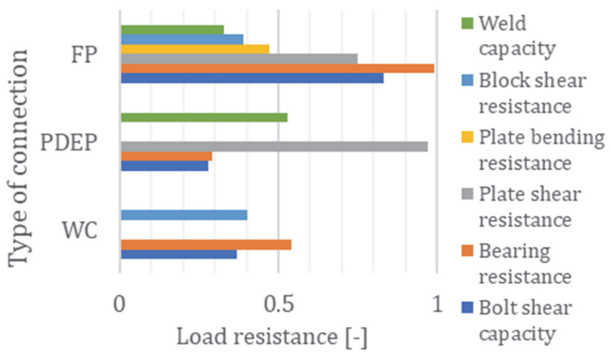

Fig. 5. Dependence of connections on load resistance

2.3 Analysis of numerical models

As mentioned, the numerical model for the FEM analysis was developed in Autodesk Inventor 2025 [8]. The objective is to evaluate displacements, contact pressure and safety factors for each connection to determine the optimal variant.
FEM analysis allows discretization of a complex structure into smaller, simpler elements, called finite elements. Each element is assigned with material properties, boundary conditions and loading conditions that replicate the physical environment. The software then solves a system of equations to determine the response of the structure. Key features are:

- Geometry and mesh – define geometry of a part, and then convert it into a mesh of smaller elements; finer mesh provides more accurate results, but requires more computational resources;
- Material properties and boundary conditions – material properties such as elasticity and density can be assigned, as well as boundary conditions, including fixed elements and applied loads;
- Types of analyses – supports analyses such as static and modal, but in this case is used static analysis, to evaluate displacements, contact pressures and safety factors;
- Post–processing results – after analysis, results are visualized through stress and displacement distributions, helping to identify critical points in the design.

FEM allows design and material optimization, and ensures the safety of components, making product development more efficient.

3. DISCUSSION OF ANALYTICAL APROACH

As all connections have been designed according to EC3 standards, the safety checks have been successfully met. Although all connections are satisfied, there are opportunities for optimization. For the WC connection, reducing the weight can be achieved by optimizing the length of the angle profiles or the number of bolts, while for the PDEP, increasing the thickness of the faceplate or adjusting the bolt spacing could improve the bearing capacity of the stiffener plate. For the FP connection, increasing the edge distance of the bolts or the plate thickness could improve the bearing capacity for bearing stress.

Analytical results of the aforementioned connections are given in Table 1. It is important to note that optimization was not performed in this analysis, as the focus was on the comparative analysis of these connections, in order to ensure comparability with the same input parameters.

Table 1. Analytical results of beam–to–column connections [7]

	Characteristics	**WC**	**PDEP**	**FP**
Geometrical characteristics	Plate [mm]	L90×9×250	□230×200×10	□260×110×10
	Bolts [pcs]	6	6	3
	Weld type, a[mm]	/	Fillet weld, 4	Fillet weld, 5
Hole/edge spacing	Min. spacing requirements	<1	<1	<1
	Max. spacing requirements	<1	<1	<1
Bolts	Shear check	0,37<1	0,28<1	0,83<1
	Bearing check	0,54<1	0,29<1	0,99<1
Plate	Shear check	/	0,97<1	0,75<1
	Bending check	/	/	0,47<1
Block shear failure	Plate	0,40<1	/	0,39<1
Weld	Weld check	/	0,53<1	0,33<1

4. DISCUSSION OF NUMERICAL RESULTS

To complement the analytical approach and validate the structural behavior of the connections, a FE model was developed, and the following conditions were applied:

- a shear force of 200 kN was applied along the Z–axis on the bolted connections;
- the column was fixed at its base, while the bolts were modeled using *pin constraint* conditions to accurately simulate their force transfer function.

The numerical analysis results will be compared with analytical calculations based on EC3 [1] to verify the model's accuracy and identify potential critical points. The aim was to thoroughly investigate and compare the summarized results of the analyzed connections presented in Table 2, in order to assess the stability of the bolted connection under the applied load.

Table 2. Summarized results [8]

	WC	**PDEP**	**FP**
Total displacement [mm]	0,026375	0,023866	0,01473
Safety factor [−]	1,98149	3,41241	1,07034
Maximum total contact pressure [MPa]	107,974	116,006	262,18

Due to its critical performance indicators, such as the lowest safety factor and the highest contact pressure, the FP has been identified as the most vulnerable connection. Therefore, the following numerical results and visualizations focus entirely on the FP in order to provide a more detailed insight into its structural behavior and identify the exact areas of potential weakness. The highest displacement was observed in WC, exceeding the values recorded for PDEP and FP, shown on Figure 6.

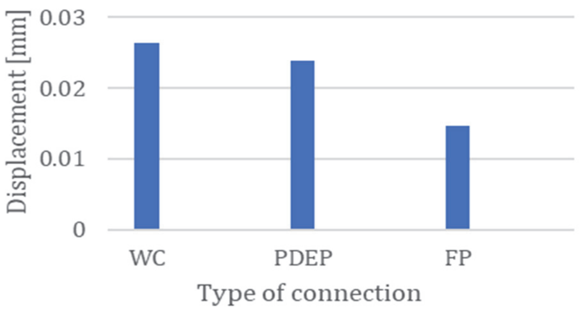

Fig. 6. Dependence of connections on displacement

This clearly indicates lower stiffness and a greater tendency for deformation under the applied load in the WC. Based on these results, the PDEP demonstrates optimal performance, whereas the WC may require additional reinforcement or deformation control measures. The lowest recorded safety factor was found in the FP, indicating a stress values close to the allowable limits, as illustrated on Figure 7.

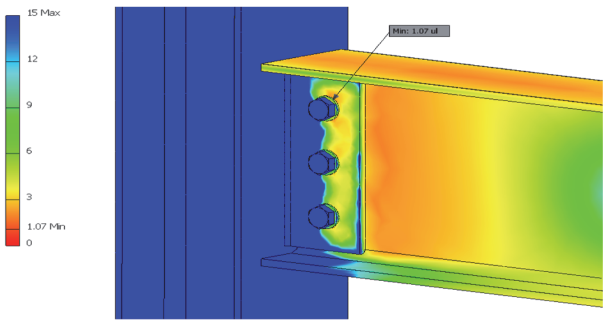

Fig. 7. Place of minimal value of safety factor for FP

This suggests that the FP joint operates near its maximum capacity, and further checks or design modifications may be required in practice. The WC shows a slightly higher reserve, while the PDEP stands out as the most reliable, with the highest minimum value. Therefore, the PDEP provides the best safety reserve, while the FP joint exhibits the lowest resistance in critical areas.

Analysis of the maximum contact pressure and its distribution across the joints reveals significant variations in stress concentration. The critical location of contact pressure is presented in Figure 8.

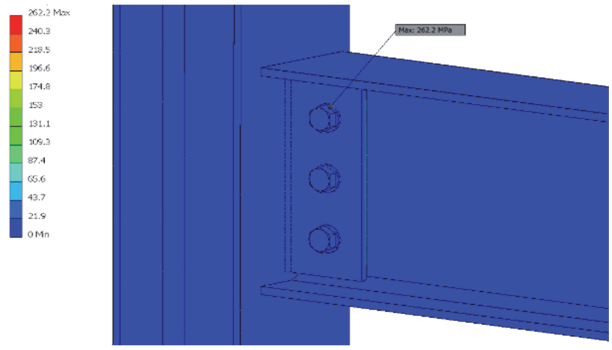

Fig. 8. Place of maximum contact pressure for FP

The FP joint indicates high stress concentrations at specific points, indicating potential zones of plastic deformation or local failure. In contrast, the WC and PDEP joints exhibit lower values, suggesting a more uniform stress distribution. The maximum contact pressure is observed at the washer–to–plate interface, particularly around the edge of the hole nearest to the applied load.

5. CONCLUSION

The analysis of beam–to–column connections in steel structures confirm that all connections meet the requirements defined by Eurocode 3 [1]. However, they exhibit varying degrees of utilization in terms of shear, bearing, block shear failure and weld resistance. This analysis assists in selecting the optimal joint based on specific design requirements.

Based on the obtained results, WC connection represents a simple solution with moderate stress levels, suitable for light to medium loading requirements. PDEP demonstrates a uniform and generally favorable stress distribution, making this connection a good option for the optimal solution. However, the fabrication process, which includes welding, can introduce additional labor and material costs compared to the simpler bolted WC connection. In the FP connection, contact forces in the bolt holes cause high local stresses, with values close to the allowable limit. Although this connection provides high stiffness, it results in significantly increased stress and may require additional control and reinforcement in the joint zone.

A comparison of the numerical results obtained by FEM revealed a high degree of agreement. This confirms the reliability of numerical models for engineering practice. It also highlights the relevance of software tools for preliminary

design and optimization of connections reducing the need for complex experimental testing. For a comparison of these three connections, it can be concluded that the WC exhibits the highest resistance parameters in the analyzed aspects.
Further research should focus on expanding the analysis by including additional variants of connections and profile types, as well as different loading combinations. Special attention could be given to the effects of long–term loading and material fatigue, using innovative materials and bolt or plate shapes to increase the load–bearing capacity and extend the resistance of connections. Additionally, it would be desirable to develop a parametric model that enables rapid assessment of connection behavior when input parameters change, thereby contributing to the optimization of the structure in the early stages of structural design.

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