

Full paper

Innovative column splice for reusability: an analytical design method for complex loading

Arnaud Neutelers¹ | Maxime Vermeylen¹ | Laurent Duchêne¹ | Jean-François Demonceau¹**Correspondence**

Ir. Arnaud Neutelers
University of Liege
Faculty of Applied Sciences,
ArGEnCo Department
Quartier Polytech 1, Allée de la
découverte, 9, B52/3
4000 Liège, Belgium
Email: arnaud.neutelers@uliege.be

¹ University of Liège, Liège,
Belgium

**Abstract**

The construction sector is still identified as part of the most polluting industrial sectors, even if significant progresses in terms of recycling have been achieved. So, to reach the carbon neutrality by 2050 as stipulated in the Paris agreement, the construction methods and solutions need to be optimized, targeting a maximal reusability of the structural elements. Within this context, Connect4C, a RFCS project was initiated with the objective of developing demountable, adaptable and reusable connecting solutions for the most common joint typologies.

The present paper focuses on the column splice joint typology. First, a description of the proposed innovative column splice solution is provided, highlighting the main properties improving the reusability of structural steel members. Then, the developed design analytical method in agreement with the Eurocode design philosophy and allowing for the characterization of the column splice mechanical properties and is presented. The method is afterwards applied to the column splice under investigation to predict its resistance under complex loading conditions including both axial loads and biaxial bending. Comparisons of the analytical model predictions with Abaqus finite element models are performed as a preliminary validation of the developed method before the performance of the experimental tests planned within the Connect4C project. Lastly, insights regarding the impact of the axial load on the initial bending stiffness of the column splice are given.

Keywords

Column splice, circular construction, steel joints, reusability, adaptability, combined loading

1 Introduction

Recently, design of buildings has increasingly been driven by ecological concerns. First on a voluntary basis, the design for sustainability is progressively implemented on the European market through the Green Deal [1] targeting a carbon neutrality for 2050. To support the industry in this transition, many RFCS funded projects investigated solutions reducing building carbon footprint. Among the contemplated solutions, ensuring the reusability of steel members through appropriate joints detailing is rather effective [2]. Henceforth, the Connect4C RFCS European project [3-5] has been initiated with the objective of extending this philosophy by developing innovative solutions of moment-resisting joint [6], simple joint [7-8] and column splices [9-10]. This paper focuses on the latter typology as part of this project.

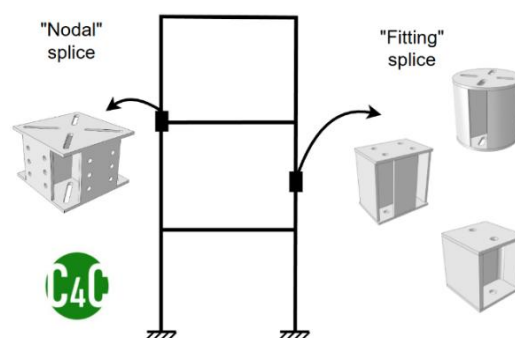


Figure 1 Connect4C splice configurations

As shown in Figure 1, two different configurations have been developed for the column splices. When the splice is located at the level of a floor [9], a solution with endplate allowing the splice to act also as a component for the joints

at the beam extremities is proposed, maximizing the mechanical efficiency of the solution and providing a maximum of flexibility in terms of geometrical adaptability (to connect for instance columns with different dimensions). In particular, this adaptability is provided through the use of long slotted holes in the column splice horizontal plates (Figure 1) offering flexibility for the positioning of the bolts connecting the column extremities to the column splice. This solution is peculiarly convenient in case of tubular columns due to the accessible vertical flat surfaces provided by the splice end-plates allowing for demountable bolted connections at the beam extremities. The dimensions of the column splice end-plates can be adjusted to fit with different beam dimensions, respecting the structural grid as proposed within the CONNECT4C project [4].

If the splice is located between floors [10], then beam connections are no longer required while constraints on the splice dimensions appear to limit the aesthetic impact of the solution. In particular, the splice should fit as close as possible with the dimensions of the connected columns. While for the previous splice solution, the column splice dimensions could extend the ones of the connected columns, so offering bigger lever arms for the column splice connections, the dimension constraints mentioned above impose to locate the bolts within the column cross-section outer perimeter, so limiting the lever arm which can be mobilized for the column splice connection. Thus, the mechanical efficiency of the present solution is more limited than the column slide solution located at the level of a floor. However, with an adequate location of the columns splices within the structure, the bending moments developing at the level of the column splice between two floors should be more limited than the ones appearing at the level of column splices located at the level of a floor.

Targeting an optimization of the column splice dimensions, an advanced design models has been developed to characterize the mechanical properties of the column splices subjected to axial forces and biaxial bending moments. The latter is presented in the next section.

2 Analytical models for MN interactions in joints

2.1 Resistance

In practice, such considerations are often neglected due to their high complexity. In EN1993-1-8:2024 [11], simplified models are proposed to account for the MN interaction but the latter do not rely on a strong scientific background and have been proved to be overconservative or unsafe, depending on the applied MN loading [12]. To overcome these weaknesses, more recent models have been developed based on the well-known component method concept [13]. The most general one has been first proposed by Cerfontaine [14-15] and aims at predicting the plastic MN interaction resisting curve for bolted steel connections. This scope has later been extended to steel-concrete composite connections by Demonceau at room temperature [15], but also at elevated temperatures [16]. In addition, this model has been implemented in a beam finite element within the homemade FEM software FINELG [17]. Besides, this methodology has already been applied and validated against the proposed splice configurations [9] (cf Figure 1) and extended to interactions with combined biaxial

bending moments [10]. For both concision and simplicity's sake, the full analytical method is not presented herein; only a summary of the key information is provided hereafter.

For the developed splice solutions, brittle failure modes as well as bolt group effects are avoided through appropriate connection detailing. As a first step, the method requires to identify all the zones that can transfer either tension (i.e. the bolts cross section) or compression (through contact diffusive area) in the connection. These zones should then be discretized in joint rows to be analytically characterized [9]. Afterwards begin an iterative process requiring to assume a position of the plastic neutral axis (PNA) determining which joint rows are activated or not. Thus, the static scheme is fixed, and the joint resistances can be computed through the application of the static theorem. These steps should be repeated for several positions of the PNA until the entire MN interaction resisting curve is drawn. This entire process is shown in Figure 2. As can be observed in Figure 2d, the application of an axial load to a joint can significantly decrease but also increase the bending resistance of the joint.

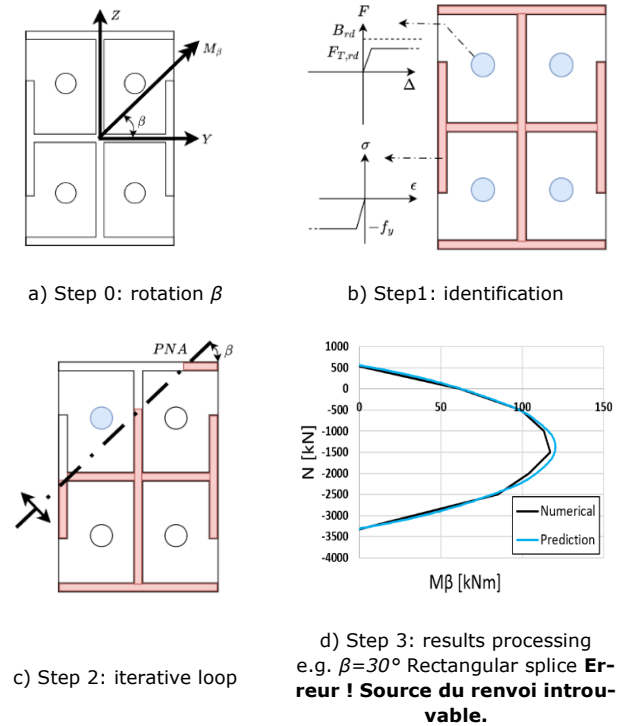


Figure 2 Methodology for plastic MN interaction

2.2 Stiffness and stability

The MN interaction at the level of a joint is not only affecting its resistance but also its stiffness. In particular, the actual bending stiffness can be increased by the presence of an axial load. Knowing that the presence of a column splice may have significant impact on the column buckling as shown in [18-20], accounting for benefit from an increased bending stiffness due to the presence of axial loads could allow for an optimization of the column design. Nevertheless, despite the identification of this improvement, limited research has been conducted on this topic up to now. In particular, some authors provided easy-to-deem criteria to neglect the splice influence [19], other proposed improved spring models [17] or energy based

method, [21]. However, the complexity of these models requires numerical support and are not suited for daily joint design. Besides, none of the models can predict the stiffness of connection without structural analysis but rather predict the full joint response for given sequence of load inputs. Accordingly, further investigations are required on this topic. Within the present paper, a preliminary study aiming at investigating the possibility of extending the analytical model briefly summarized in the previous section to predict the evolution of the column splice stiffness as a function of the applied axial force is investigated. For sake of validation, a numerical model has been built as briefly described in the following section.

3 Numerical modelling

The numerical model built using Abaqus is illustrated in Figure 3. Elastic – perfectly plastic S355 material law has been implemented in the splice component while the base plates implemented to apply the loads (in grey on Figure 3) are assumed to be fully rigid. EN14399 M20 10.9 HR bolts have been used to ensure ductile yielding of the splice endplate at failure. Interaction between the several parts is modelled with a “hard” normal contact while a 0.3 friction coefficient is used for tangential behavior.

Regarding the boundary conditions, all degrees of freedom are blocked excepted along the splice axis where a pair of imposed axial loads of opposite direction are applied during the first step of the loading sequence. During the second step, the axial loads are maintained whilst rotation along the Y axis is unlocked at the supports to apply a pair of opposite bending until failure of the connection is observed. C3D8R cubic elements with reduced integration are used over the thickness of each plate to ensure convergence of the results. Simulations are conducted with a dynamic implicit scheme accounting for geometrical and material non-linearities.

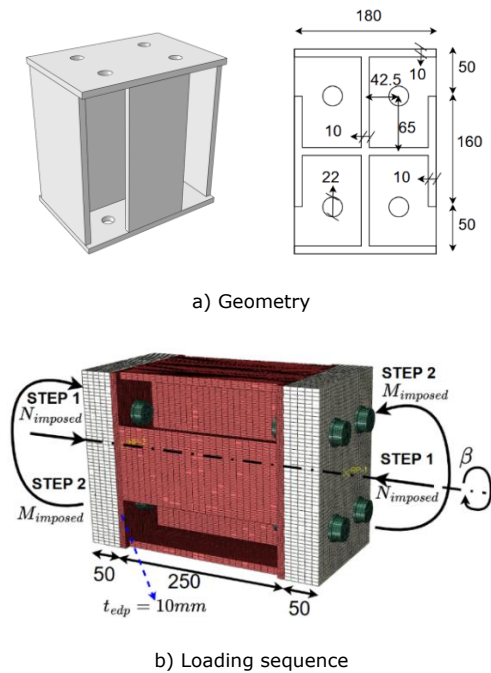


Figure 3 Abaqus numerical model

Lastly, this model aims at reproducing exactly the assumptions made in the analytical model (see next section).

Thus, the proposed methodology can be validated against the numerical results ensuring proper comparison. In other words, both in the numerical model and in the analytical developments, it is assumed that the properties of the tension rows (resistance and stiffness) are known while further investigation and characterization are still required.

4 Analytical model for stiffness with $M_y + N$

4.1 Pure bending

As a first step for predicting the splice stiffness, only pure bending M_y is herein considered. Besides, as for the resistance model, material laws are assumed to be elastic – perfectly plastic.

According to EN1993-1-8:2024 [11] recommendation, the initial stiffness of splice can be computed under pure bending through an equivalent spring model. Hence, both the equivalent position $z_{eq,T}$ and the equivalent stiffness $k_{eq,T}$ of the tension row can be respectively computed as follows:

$$z_{eq,T} = \frac{\sum k_i z_i^2}{\sum k_i z_i} \quad (1)$$

$$k_{eq,T} = \sum k_i z_i / z_{eq,T} \quad (2)$$

Where z_i and k_i are the vertical distance between row i and the flange center of compression and the stiffness of i^{th} row respectively. As the objective of the performed investigation is to validate the proposed assembly procedure, the stiffness of the bolt rows in tension has been numerically determined for sake of accuracy and is equal to 410 kN/mm for the example considered in this paper. This stiffness of 410 kN/mm accounts for the components (i) endplate in bending, (ii) bolt in tension and (iii) half of the splice in elongation. For the component in compression, the splice shortening stiffness $k_{eq,C}$ is computed as follows:

$$k_{eq,C} = EA_c / L/2 \quad (3)$$

with A_c the area in compression, E the Young modulus (210.000 MPa) and L the splice length (250 mm).

Lastly, the joint stiffness can be assessed by assembling the equivalent rows:

$$S_{j,ini} = \frac{E z_{eq,T}^2}{\left(\frac{1}{k_{eq,C}} + \frac{1}{k_{eq,T}} \right)} \quad (4)$$

Nevertheless, the scope of this prediction is limited since only valid in absence of axial load and until two thirds of the plastic bending resistance $M_{pl,rd}$ of the joint [11]; [11] allows to extrapolate the evolution of the stiffness of the joint up to $M_{pl,rd}$ knowing $S_{j,ini}$. While the scope covered by Eq.(4) is rather limited, it is important to highlight that the stiffness remains constant over the range $[0; 2M_{pl,rd}/3]$ (with $N=0$). Starting from this observation, the postulate that “it exists ranges over which stiffness is constant”, can be made as the basis of the proposed methodology.

In addition, the plastic MN interaction curves as described

in Section 2.1 can be considered as the condition expressing a complete loss of stiffness (i.e. $S_{j,ini} = 0$) in the connection since an elastic-perfectly plastic behavior is assumed. Consequently, outside and along the plastic MN interaction curve, the stiffness of the connection is nulled while it is not the case inside the curve. In the following subsections, other ranges of constant stiffness are identified and detailed.

4.2 Column splice in compression

A rather straightforward zone that can be identified and predicted consists of the connection being in full compression in the elastic domain. In such configuration, the compression load is transferred by direct contact between the plates. Consequently, the section contributing to both stiffness and resistance of the connection is the complete splice cross-section. The bending stiffness of the latter can be predicted using elastic beam theory:

$$S_{j,full\ section} = EI/L/2 \quad (5)$$

with I the inertia of the splice cross-section.

Regarding the boundaries limiting the scope of application of Eq.(5) (i.e. on which this stiffness is constant), two conditions should be verified for any pair of M and N applied. The first one requires each fiber of the connection to be under compression (see Eq.(6)) to guarantee the activation of the complete splice cross-section. Similarly, the second condition aims at avoiding nonlinear behavior by excess of compression as reflected by Eq.(7). Henceforth, the following conditions should be satisfied at the external fibers:

$$\frac{N}{A} + \frac{My}{I} = 0 \quad (6)$$

$$\frac{N}{A} + \frac{My}{I} = -f_y \quad (7)$$

with A the splice area, f_y the yield strength and y half of the splice height (for symmetric section).

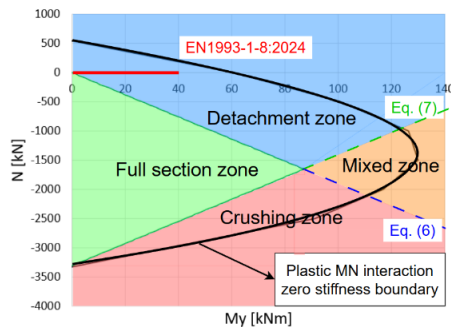


Figure 4 Identification of main behavior zones

The so-obtained results can be graphically illustrated in Figure 4. On this graph, different zones can be reported: the EN1993-1-8:2024 [11] prediction (red line), the zero stiffness plastic MN interaction curve (black curve) and the zone in which the splice cross-section is fully activated (green area), delimited by Eqs. (6) & (7). The physical meaning of this pair of equations can be highlighted as follows in Figure 4. Eq. (6) expresses the initiation of contact loss at the extreme fibers. Thus, beyond this condition

(i.e. in blue in Figure 4), detachment between the column end-plate and the column splice occurs and the splice cross-section is partially under compression. On the other hand, Eq. (7) transcribes the initiation of yielding in the extreme fibers. Consequently, further increasing loads (i.e. going into red area in Figure 4) leads to propagation of yielding and initiation of crushing. Lastly, both areas may overlap in case of high loading conditions. In such configuration, both phenomena above described, i.e. the yielding propagation and detachment, occur simultaneously in a zone that can be qualified as mixed.

4.3 Initiation of detachment and crushing

Whilst zones implying yielding by excess of compression are less relevant since impairing the reusability of the connection, the detachment zone despite its strong non-linear behavior does not necessarily implies plasticity, especially at initiation of detachment when the first bolt row is not yet activated (see Figure 5a). In this configuration, the resisting cross-section of the connection is only made of the area under compression. Only a reduced area A' contributes to the loading transfer and should be considered in the connection characterization. The reduced section geometry can be fixed according to the position where detachment is initiated (i.e. where the stress is equal to zero). Besides, as a boundary condition, the outermost fiber in compression is assumed to be yielded as shown in Figure 5a. Hence, the dotted area does not contribute to stiffness or resistance. Since this load transfer mechanism also exclusively implies compression by contact as in previous section, then the stiffness can be computed similarly to Eq. (5), considering geometrical properties of the area A' :

$$S_{j,partial\ section} = EI'/L/2 \quad (8)$$

Where I' is the inertia of the reduced cross-section.

While the crushed response seems completely different at first glance, it is in fact similar to the initiation of detachment. From the stiffness perspective, there is no difference between a detached fiber and a yielded one (see red area in Figure 5b) since both fibers exhibit a zero stiffness when an elastic-perfectly plastic behavior law is assumed. Henceforth, Eq. (8) is also suited for predicting crushed response. Boundary conditions should nonetheless be adapted by imposing detachment (i.e. zero stress) on an outermost fiber whilst the position of the axis delimiting the crushed zone can be arbitrarily chosen as shown on Figure 5b.

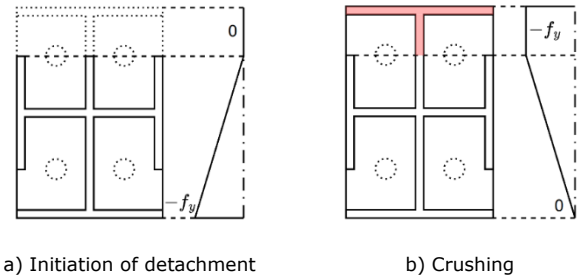


Figure 5 Static schemes of identical stiffnesses for initiation of detachment and crushing

In Figure 6 is represented an updated version of Figure 4

where boundary of the detachment zone without bolt row activation is identified. This boundary corresponds to the configuration when the detachment axis reaches the first bolt row (cf Figure 5a). Besides, the equivalent boundary for the (cf Figure 5b) crushing zone has also been illustrated on Figure 6.

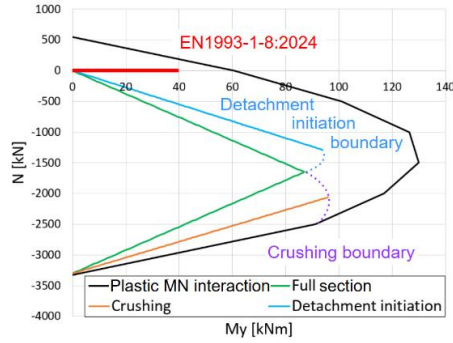


Figure 6 Identification of partial detachment and crushing zones

4.4 Detachment with bolt row activation

As a next step, the detached zone with one bolt row activated can be characterized. As for previous configurations, boundary conditions should be defined to obtain a static scheme from which stiffness can be derived. As in the previous section, the position where detachment is initiated (i.e. zero stress) can be chosen between the bolt rows. Moreover, the stress at the outermost fiber in compression should not exceed f_y . Yet, an additional condition implying a non-yielding ($F_{el} = 2F_{pl}/3$ [11]) of the bolt row should also be considered. However, only two boundary conditions are required to uniquely define a static scheme. Henceforth, the third condition, unused for the static scheme, should be checked afterward to ensure the validity of the computation. While further investigations are still required to accurately predict the stiffness within this zone, its boundary can already be assessed.

As shown in Figure 7, the stiffness boundary obtained for this zone with one bolt row activation significantly increases the area of the MN interaction diagram where the response of the connection remains fully in the elastic domain.

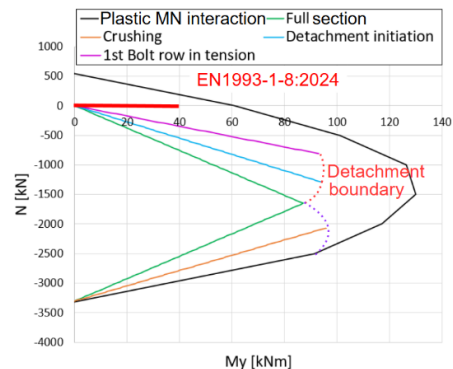


Figure 7 Identification of detachment zone with bolt row activation

4.5 Concept of reusability zone

Finally, since the purpose of the Connect4C splices is to address reusability issues, it is fundamental to be able to identify for which pairs of M_y and N the connection is free

from plasticity. Except for crushing zone, all responses above characterized are bounded by apparition of yielding in either the bolt row or an outermost fiber. Henceforth, the envelope delimited by these limit cases can be defined as the elastic domain of the connection or, in other words, the zone in which reusability is ensured (see the reusability zone as depicted in Figure 8). Consequently, an appropriate design of the connection suited for reusability should have all its design load combinations included within this zone for SLS. Regarding ULS, plastic redistribution should be allowed as per EN1993-1-8:2024 [11] and the plastic MN curve should be used for design.

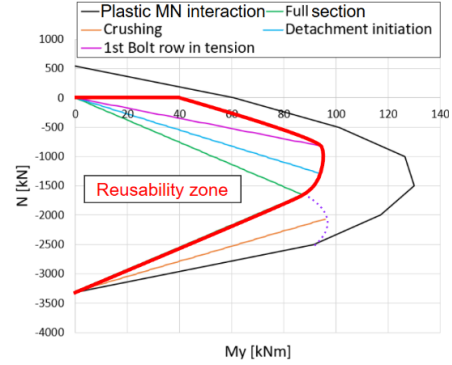


Figure 8 Identification of the reusability zone

5 Results

Lastly, results detailed in Table 1 can be obtained by applying the methodology presented in Section 4 to the geometry of Figure 3a. As a reminder, tension row properties ($k_T = 410$ kN/mm and $F_{pl} = 259.76$ kN) are issued from Abaqus to assess the proposed model accuracy in isolation. Hence, despite a slight overestimation of the full section model, results can be seen as satisfactory. Nevertheless, further studies are still required to characterize the remaining zones, account for bolt group effects and, last but not least, extend this method for combined biaxial bending loading conditions.

Table 1

Zone	Prediction			Abaqus
	N [kN]	M [kNm]	S_j [kNm/mrad]	S_j [kNm/mrad]
Pure bending Eq. (4)	0	< 40	13.12	13.08
Full contact Eq. (5)	-500	26.37	107.14	86
	-1000	52.75	107.14	86
Detachment initiation Eq. (8)	-500	36.56	78.3	65.83
	-1000	73.12	78.3	70.09

6 Conclusions and perspectives

As shown in previous sections, satisfying accuracy was obtained by comparing the analytical predictions to the numerical ones for the prediction of the initial stiffness of joints subjected to MN. Nevertheless, as for the resistance model, extension of the model presented in Section 4 to

combined biaxial bending moment is contemplated. Hence, a consistent full Eurocode based MN interaction characterization joint methodology valid for both resistance and stiffness will be made available. The latter should then be validated against the results of the experimental campaign to be conducted in the framework of Connect4C.

Acknowledgements

This scientific publication is carried out with a financial grant of the Research Program of the Research Fund for Coal and Steel and supported by the Wallonia-Brussels Federation within the framework of a FRIA grant for the first author.

References

- [1] Global Alliance for Buildings and Construction; International Energy Agency and the United Nations Environment Program (2019) *Global status report for buildings and construction: Towards a zero-emission, efficient and resilient buildings and construction sector*.
- [2] Sansom, M.; Girao, A.; Lawson, R. M.; et al. (2020) *Reuse and demountability using steel structures and the circular economy (REDUCE)*. Final Report Project, no 710040.
- [3] Connect4C (2023) *High-strength steel connections for circular construction*. no 101112300, Website: <https://connect4c.eu/>
- [4] Larena, A. B.; Sanz, G. G.; Alves, T.; et al. (2025) *High-Strength Steel connections for circular construction*. Structures and Architecture, CRC Press, pp. 286-293.
- [5] Alves, T.; Larena, A. B.; Ljubinkovic, F.; Conde, J.; Da Silva, L. S. (2025) *Connect4C system: case study*. Proceedings of XV Conference on Steel and Composite Construction.
- [6] Jankovic, N.; Ljubinkovic, F.; Conde, J.; Da Silva, L. S. (2025) *Adaptable and reusable double-sided beam-to-beam steel joint*. Proceedings of XV Conference on Steel and Composite Construction.
- [7] Silva de Carvalho, A.; Bogdan, T.; Demonceau, J.-F.; Ljubinkovic, F.; Kozma, A.; Da Silva, L. S.; Odenbreit, C. (2025) *Parametric Finite Element Study of Pre-loaded Joints with Long Slotted Holes*. Proceedings of The International Colloquium on Stability and Ductility of Steel Structures.
- [8] Silva de Carvalho, A.; Bogdan, T.; Odenbreit, C. (2025) *Mechanical behavior of adaptable steel joints with long slotted holes*. Proceedings of XV Conference on Steel and Composite Construction.
- [9] Neutelers, A.; Duchêne, L.; Conde, J. C.; Da Silva, L. S.; ... & Demonceau, J. F. (2025). *Innovative Column Splice for Circular Steel Construction*. Proceedings of The International Colloquium on Stability and Ductility of Steel Structures.
- [10] Neutelers, A.; Vermeulen, M.; Duchêne, L.; Demonceau, J.-F. (2025) *Characterisation of innovative steel splice connections under combined loading*. Proceedings of XV Conference on Steel and Composite Construction.
- [11] EN 1993-1-8 (2024). *Eurocode 3: Design of steel structures – Part 1-8: Design of joints*. Brussels.
- [12] Demonceau, J.-F. ; Golea, T. ; Jaspart, J.- P ; et al. (2021) *D3-1 : Design Recommendations against Progressive Collapse in Steel and Steel-Concrete Buildings*.
- [13] Jaspart, J.-P.; Weynand, K. (2016) *Design of steel joints and composite structures*. Ernst & Sohn.
- [14] Cerfontaine, F. (2004) *Etude de l'interaction entre moment de flexion et effort normal dans les assemblages boulonnés* [PhD thesis]. University of Liege.
- [15] Demonceau, J.-F.; Cerfontaine, F.; Jaspart, J.-P. (2019) *Resistance of steel and composite connections under combined axial force and bending including group effects: Analytical procedures and comparison with laboratory tests*. Journal of Constructional Steel Research, Vol. 160, pp. 320-331.
- [16] Haremza, C.; Santiago, A.; Demonceau, J.-F.; et al. (2016) *Composite joints under MN at elevated temperatures*. Journal of Constructional Steel Research, Vol. 124, pp. 173-186.
- [17] Golea, T.; Corman, A.; Mathieu, J.; et al. (2023) *An innovative mechanical model for structural steel joints*. Engineering Structures, Vol. 277, pp. 115459.
- [18] Snijder, H. H.; Hoenderkamp, J. C. D. (2008) *Influence of end plate splices on the load carrying capacity of columns*. Journal of Constructional Steel Research, Vol. 64, No. 7, pp. 806-822.
- [19] Simao, P. D.; Girao, A.; Bijlaard, F. SK. (2012) *Influence of splices on the buckling of columns*. International Journal of Non-Linear Mechanics, Vol 47, No. 7, pp. 806-822.
- [20] Girao, A.; Simao, P. D.; Bijlaard, F. SK. (2010) *Stability design criteria for steel column splices*. Journal of Constructional Steel Research, Vol. 66, No. 10, pp. 1261-1277.
- [21] Da Silva, L. S.; Girao, A. (2001) *An analytical evaluation of the response of steel joints under bending and axial force*. Computers & Structures, Vol. 79, No. 8, pp. 873-881.