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Innovative Column Splice for Circular Steel Construction

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Abstract

In 2023, the RFCS research project CONNECT4C, funded by the European Union, was launched with the goal of reducing greenhouse gas emissions from the steel construction industry. The project aims to achieve this by developing innovative joint solutions that enhance the demountability and reusability of steel structural elements. To cover a wide range of practical scenarios, the project focuses on the most common joint typologies. The present paper will address the column splices.

Several key properties were identified and incorporated into the splice design to meet the project's objectives. In particular, the need for an independent, adaptable, and demountable element acting as a fuse element was highlighted. The goal is to concentrate any damage from potential overloading within this independent element, thereby ensuring the reusability of the connected structural elements. Moreover, the developed splice element, with its adaptability, allows for changes in column cross-sections, facilitates beam connections when required, and accommodates minor vertical geometrical misalignments.

This paper presents the innovative column splice solution and its preliminary characterization through advanced numerical simulations performed with Abaqus.

Keywords

Column splice, circular construction, joints, reusability, adaptability

1 Introduction

The Green Deal voted by the European Union targets Carbon neutrality for all new constructions in 2050. Despite all the progress made in recycling and reducing the material input, reuse of structural steel elements is seldom done in practice. Hence, the RFCS research project Connect4C [1] was funded by the European Union to develop innovative joints to enhance the reusability of steel members. Based on the outcomes of the REDUCE project [2] and the "petite maison" [3,4], key properties were identified to ensure the appropriate joint behaviour for reusability. An independent connecting element is required to act as a fuse, concentrate all the plasticity and protect the other elements against any damage. Moreover, this fuse should be demountable and adaptable to be suitable for different cross-section typologies (i.e. open and tubular cross-sections) to compensate for small geometrical

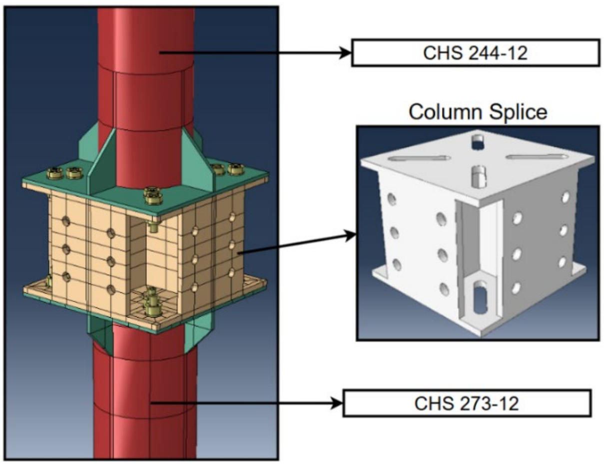


Figure 1 Connect4C column splice

mismatches and change of cross-section dimensions. These considerations were altogether incorporated into the most common joint typologies covered by CONNECT4C's structural system [5]. The present paper focuses on the column splice solution illustrated in Figure 1.

2 Geometry and manufacturing

Initially, bolted cover plates typology was considered due to its widespread use in practice. However, such a connection appeared as inappropriate for reusability due to the local damage at the level of the holes in bearing in the columns. Moreover, this typology is not suited for connecting tubular columns. This leads to the adoption of splices with end-plates. This connection typology is highly efficient due to the load transfer by contact but also tackles the issue of bolt holes' grids misalignment with ease. Indeed, an efficient solution, as demonstrated in [2,3,4], is the use of long slotted holes. The adoption of the latter in the splice's endplates allows for a wide range of geometry for connected members while limiting the constraints on the column's endplate. Drilling new holes along axes inclined at 45°, as depicted in Figure 2, is nonetheless required to ensure the adaptability of the connection.

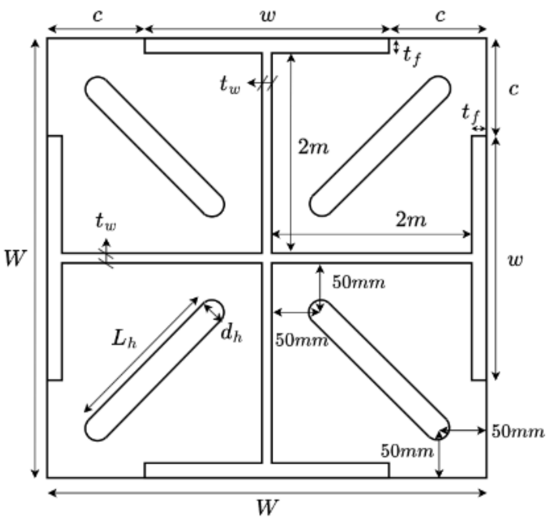


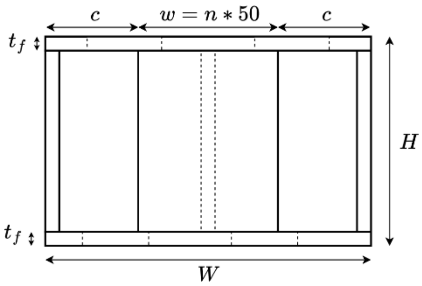
Figure 2 Splice cross section

Similar purposes led to the definition of a cross-shaped section inside the splice. The latter maximizes the contact area in case of connection with tubular columns and so its load-bearing capacity. Moreover, such a cross-sectional shape is well adapted to a moment-resisting frame where a significant bending moment at beam extremities connected to the splice can be expected in both directions. For the sake of simplicity, a doubly symmetric splice is here considered, but other configurations may be contemplated according to the needs. Moreover, sufficient corner openings, length c in Figure 2, are designed to ensure proper access to the bolts for tightening. This distance is set to 100mm and is fixed based on conclusions from the construction of mock-up specimens. The width of the splice can henceforth be assessed as Equation (1) based on the discrete 50mm step grid defined within the framework of Connect4C's structural system [5].

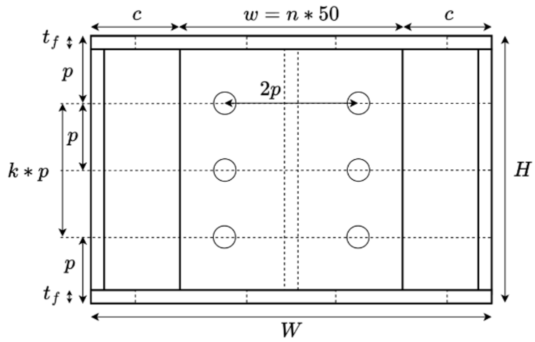
$$W = 2c + w = 2c + 50 * n \tag{1}$$

Where n is a positive integer to be chosen according to the elements to connect. A similar approach is used in Equation (2) to define the height of the splice with k a positive integer and considering a vertical grid of 75mm for the end-plate as required by the Connect4C grid [45]. It should also be noted that H cannot be smaller than 150mm to ensure sufficient space to place and tighten the bolts:

$$H = 150 + k*75. \tag{2}$$



a. Narrow (n < 3) and/or short (k < 2) splices

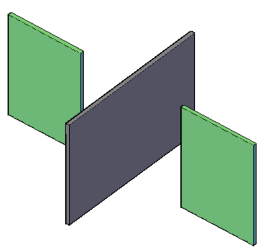


b. Wide (n ≥ 3) and long (k ≥ 2) splices

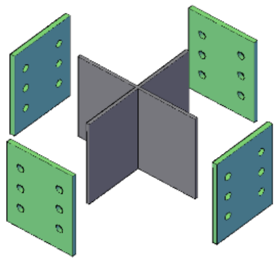
Figure 3 Front view

As suggested in Figure 3b, when the dimensions of the splices are such that the vertical flanges can contain several bolt rows with respect to the defined vertical grid, then beams can easily be connected to the splice as well. Despite constraining the position of the splice to the floor level, this possibility appears convenient when the columns are made of tubular sections. Indeed, on a limited height, the splice offers both ease of connection and efficient load-bearing capacity for open-section profiles to be connected to tubular columns.

Regarding the production of the column splice, a welding procedure was defined and proposed while testing the mock-up specimen. A step-by-step illustration is proposed in Figure 4 and consists of welding the webs and flanges together before adding the endplates. Corner openings provide sufficient space for inserting the welding devices and performing welds.



a. Step 1



b. Step 2

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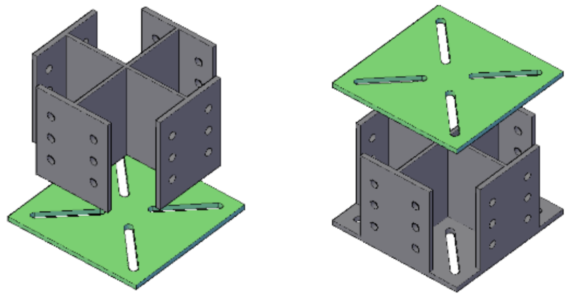


c. Step 3   d. Step 4

Figure 4 Welding procedure

3 Preliminary splice characterisation under MN interaction

Within the splice, two different connections can be identified and characterized. The first one, related to splice-to-beam connection, is already covered by EN1993-1-8 [6,7] and, therefore, is not further considered in this paper. The other one, connecting the splice to the columns, should be properly characterized under the non-negligible MN interaction which may appear. Such characterisation under MN is not appropriately covered by EN1993-1-8, which is why the more advanced and accurate method proposed by Cerfontaine [8,9] is used. Also, the configuration of the upper and lower splice plate is not explicitly covered by EN1993-1-8, so it requires the adaptation of existing characterisation rules to the present configuration. These developments are presented and discussed against numerical results for the upper and lower splice connection plate in the present paper. Characterisation of the column side is also not appropriately covered by the norms under MN interaction and should be done according to the method of Cerfontaine [8,9] or appropriate papers in the case of tubular columns [10].

The Cerfontaine method requires assessing the resistance of each compression and tension row F_C and F_T, respectively. While it is straightforward for the former, the latter needs to be further discussed. The tension rows can be modelled as equivalent T-stubs and their associated effective lengths as recommended in EN1993-1-8 for rows in tension involving plates in bending. In the proposed design, the number of possible shapes of plastic mechanisms in the plate is strongly limited due to the presence of several stiffeners, i.e. the webs and vertical flanges. The shape of the plastic mechanism is assumed to be circular, thus neglecting the small corner opening and the presence of the long-slotted hole as illustrated in Figure 5.

Such a mechanism is covered by the norms [6,7] through Equation (3):

$$F_{rd,EN} = \frac{4m_{pl}}{m} L_{eff} = \frac{4m_{pl}}{m} 2\pi m. \tag{3}$$

Where m_{pl} is the plastic bending moment per unit of length for the end-plate and m is a geometric parameter defined in Figure 2. Equation (3) models the bolts as punctual loads, while it is demonstrated in [11] that assuming a uniformly distributed load below the washers is more accurate for circular patterns. Such a model was already investigated in [12] and led to the following formulation for the prediction of the resistance:

$$F_{rd,T} = \frac{8\pi m_{pl}}{1 - \frac{d_w}{4m}} = \frac{4m_{pl}}{m} \frac{2\pi}{\frac{1}{m} - \frac{d_w}{4}} \tag{4}$$

where d_w is the diameter of the washer, or circle circumscribing the bolt head or nut, as relevant.

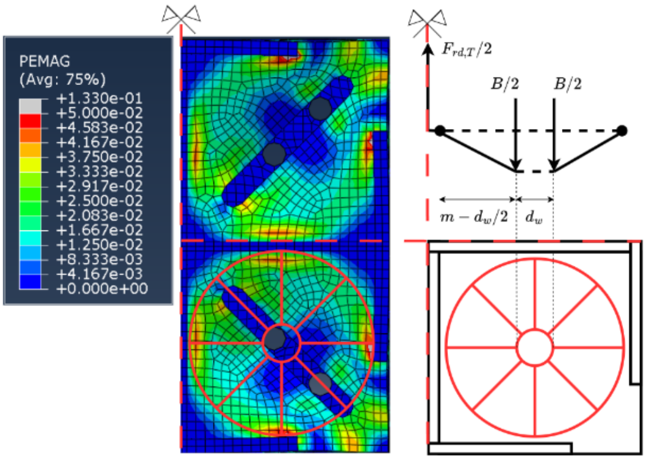


Figure 5 circular plastic mechanism in the splice's slotted connection

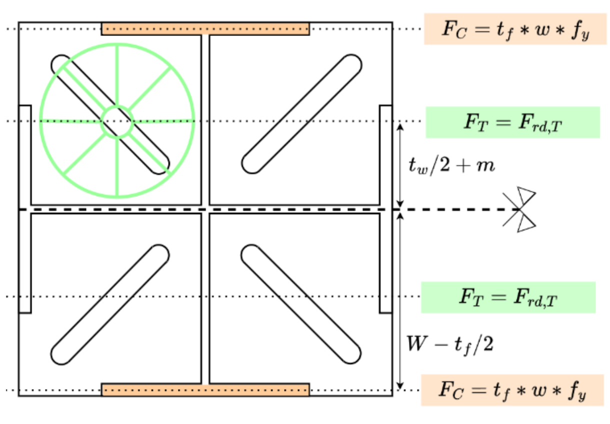
Moreover, to both achieve a safe design and meet Cerfontaine's assumption of a full plastic redistribution between the joint rows [8,9], it is required to check that $B_{t,rd}$, the tension resistance of the n_b bolts, is not exceeded, nor the end-plate punched by the bolt:

$$F_{rd,T} < 0.9\, n_b B_{t,rd}, \tag{5}$$

$$F_{rd,T} < n_b P_{Rd}, \tag{6}$$

where P_{Rd} is the punching shear resistance of the plate. Notice that n_b is the number of bolts in a single bolt row.

Initially, the method proposed in [8,9] neglects the contribution of both webs and stiffeners, thus providing a simple discretisation of the cross section, assuming that only the flanges are transferring compression forces, as illustrated in Figure 6a. However, a more refined discretisation leads to significantly more accurate results, as proved by Demonceau [8, 13]. The latter approach is also considered (Figure 6b), and both approach predictions are compared.



a. Cerfontaine scheme

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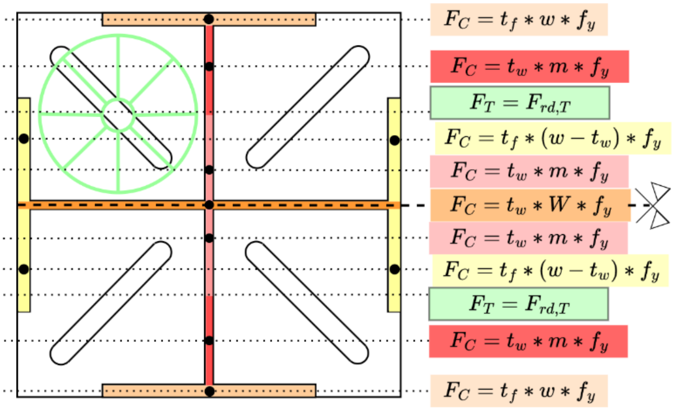
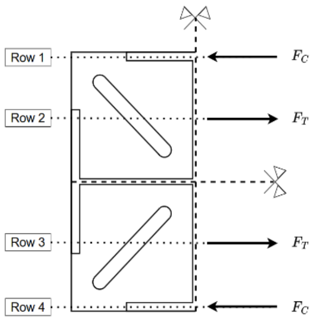


b. Demonceau scheme

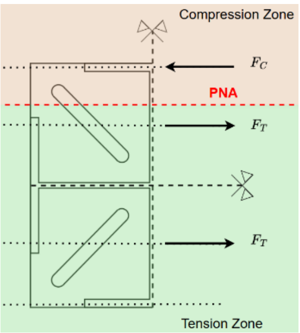
Figure 6 Discretization schemes for MN interaction

Additionally, a third discretization is proposed herein, consisting of considering 1mm thick compression rows to achieve further accuracy.

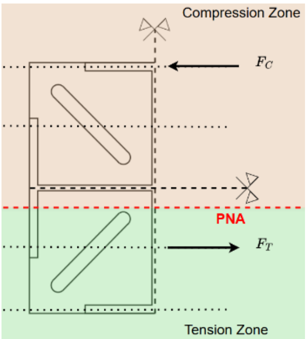
Then, the second step of the method requires assuming a position of the plastic neutral axis (PNA) to identify the activated joint rows. Afterwards, equilibriums can be computed to assess a pair of resisting bending moment and axial force and thus define a point of the interaction curve. This step should be repeated for all the possible positions of the neutral plastic axis. An example is provided hereafter, in Figure 7, for the simple discretization of Figure 6a.



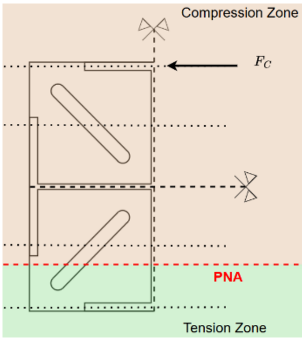
a. Global view



b. PNA between rows 1 & 2



c. PNA between rows 2 & 3



d. PNA between rows 3 & 4

Figure 7 Application of the Cerfontaine method – activated joint row vs position of the PNA

It should be noted that the proposed method does not cover loading cases with bending moments (M_y and M_z) in both directions, thus limiting its range of applications. This is a perspective of development to be addressed in the future by the corresponding author.

Finally, it should be checked that the connection is able to withstand the shear through friction as expressed by Equation (7):

$$V_{rd} = \mu N_{perm} \quad (7)$$

where μ is the coefficient of friction and N_{perm} is the permanent axial load to be transmitted to the splice. Besides, additional contributions neglected in Equation (7) as the bolts' preload and bearing in the holes, can also be considered. This, nonetheless, requires further investigation to ensure a proper characterization.

4 Numerical validation

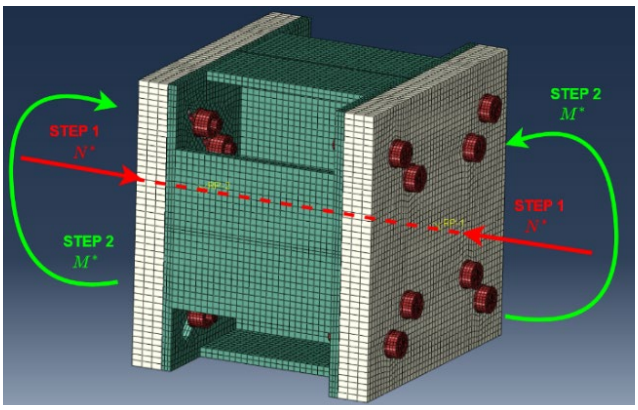
To assess the validity of the above proposed model, an MN interaction curve was generated from the Abaqus Software for a specific geometry of the column splice given in Table 1.

Table 1 Input of the numerical model of Figure 8a

t_f	15	mm	t_w	10	mm
t_{edp}	15	mm	W	450	mm
H	300	mm	f_y	355	MPa
c	100	mm	p	75	mm
Bolts positions		75 & 125		mm from edges	

NB: Flanges' bolt holes are not modeled to avoid parasitic effects

Both sides of the splice are bolted to a 50mm thick S690 plate with 8 M24 10.9 bolts. Each material law was assumed to be elastic-perfectly plastic with nominal properties, while a hard normal contact was used in pair with a 0.3 friction coefficient. Also, simulations were conducted with a two-step implicit dynamic analysis with geometrical non-linearities. The former consists of applying a pair of axial loads of similar magnitude but opposite direction to each support. Then, while maintaining the axial loads, a pair of increasing bending moments was applied on the supports until full yielding of the connection was observed. This loading procedure on the numerical model is illustrated in Figure 8.



a. Static scheme

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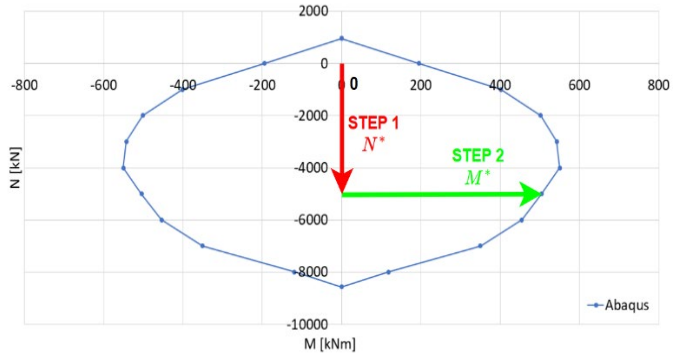


b. Loading steps

Figure 8 Numerical model

Regarding the mesh, solid hexahedral elements with reduced integration (labelled as C3D8R in the software) were used with a minimum of three elements over the thickness of the plates to ensure the quality of the results. The latter are illustrated in Figure 9 with the analytical predictions considering the discretization schemes described in Figure 6.

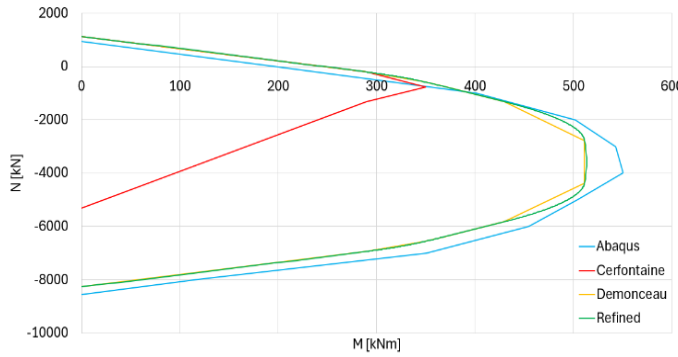
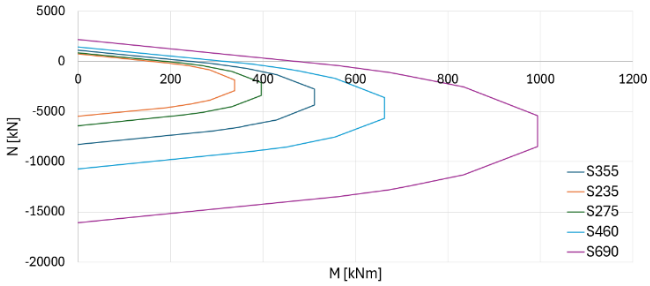


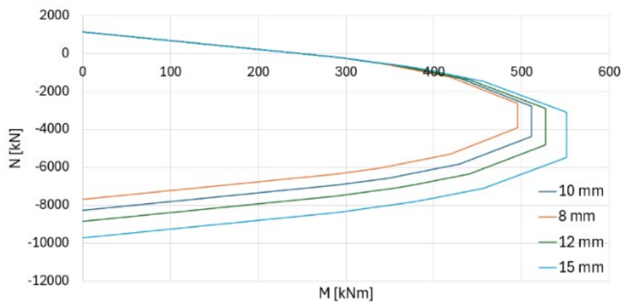
Figure 9 Validation of the discretization schemes

Figure 9 clearly highlights that the discretization scheme proposed by Cerfontaine is too crude for the characterization of the splice's connection. Despite being a rather acceptable assumption for beam-to-column connections, it appears that both contributions of the web and transverse flanges cannot be neglected in splice connections. Contrary to this scheme, the complex one with 1mm thick rows provides accurate and yet conservative predictions. However, the tip of the curve where the bending moment is maximum is not well predicted, meaning further refinement is needed to model the tension rows. Finally, the discretization scheme with an intermediate level of complexity proposed by Demonceau has a level of accuracy close to the complex one whilst using limited computational resources, thus finding a good balance. Therefore, this scheme is used for the following prospective study aiming to identify the range of applications of the column splice. Each parameter is investigated independently of the other and respecting the reference splice's geometry used for the validation (see Table 1).

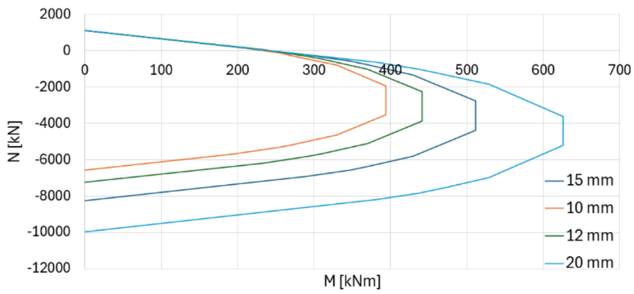
Based on this prospective study, it can be concluded that the proposed design for the column splice is well-suited to a wide range of applications.



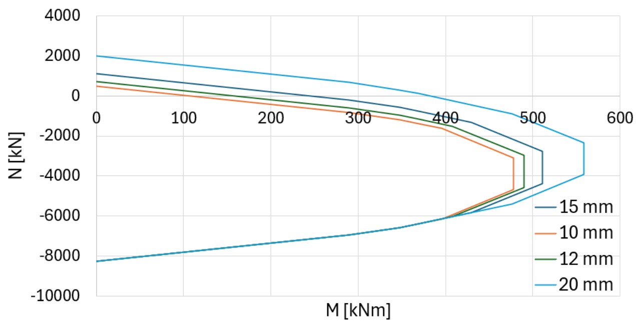
a. Variation of steel grade



b. Variation of web thickness



c. Variation of flange thickness



d. Variation of endplate thickness

Figure 10 Prospective parametrical study

5 Conclusions and perspectives

As concluded in the previous sections, the results obtained through the analytical model proposed with refined discretization schemes are in good agreement with numerical simulations. However, the analytical and numerical models need to be validated against both an extended parametrical study and experimental results to ensure their reliability. Such an experimental campaign will be soon conducted in the framework of Connect4C, aiming to derive full M_y-N-M_z interaction curves and proper design of the column-side connections.

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