



# CHARACTERISATION OF INNOVATIVE STEEL SPLICE CONNECTIONS UNDER COMBINED LOADING

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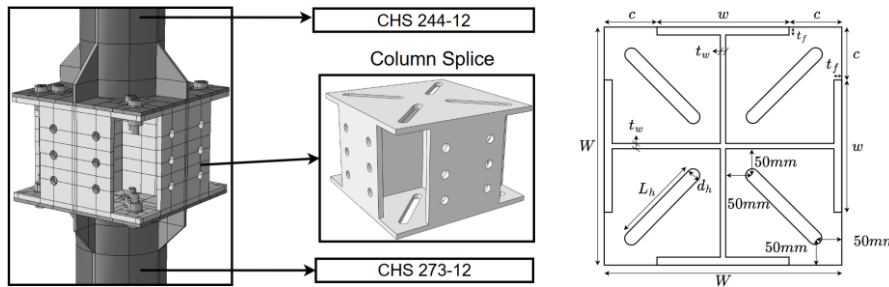
**Abstract:** Within the framework of Connect4C, a European RFCS project, innovative joint solutions are developed to enhance the reusability of structural steel elements. Among the covered joint typologies, the present paper focuses on the latest developments related to the innovative column splice solutions. The latter are first presented. Afterwards, the method allowing for the characterization of the column splices under combined loading, namely combined bending ( $M_y + M_z$ ) and axial load  $N$ , is described. Numerical simulations of the splices are then performed and compared with analytical predictions to validate the proposed approach. Finally, effects of combined loadings on the initial bending stiffness of the column splices are discussed.

## 1. Introduction

Despite an intensive recycling strategy, further actions should be taken by the steel industry to reach the carbon neutrality targeted by the Green Deal in 2050 [1]. One of the possible identified strategies is to promote the reusability of structural steel elements. However, although possible in practice, the reuse of structural steel elements is still limited due to technical constraints such as the lack of adaptability at the joint level or the need to limit remanent deformations which may appear when plasticity develops. Connect4C [2], a European project funded by the Research Fund for Coal and Steel (Grant number 101112300), aims at tackling these issues by developing innovative demountable and adaptable joint solutions. The present paper focuses on the research efforts aiming at developing an innovative column splice concept and developing a characterization model when such joints are subjected to complex loading cases. In particular, in Section 2, the Connect4C column splice solution is detailed. Then, the latter is mechanically characterized in Section 3 through the use of the component method and in Section 4 through the use of numerical simulations performed with Abaqus. In Section 5, both predictions are compared and discussed. Finally, the influence of the loading condition on the initial bending stiffness of the investigated column splice is addressed in Section 6.

## 2. Connect4C column splice solutions

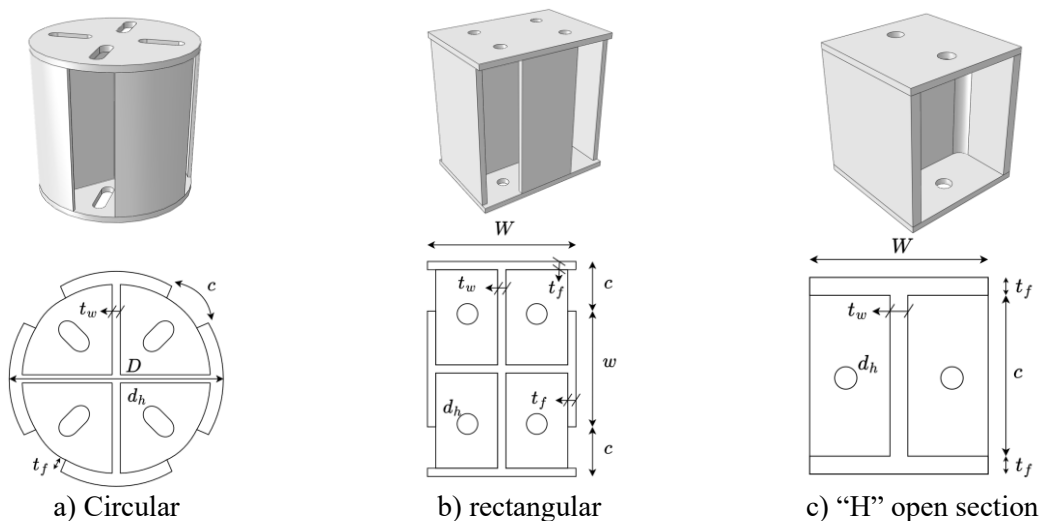
A first Connect4C column splice solution has been developed as presented in **Fig. 1**, more details are available in [3]. This splice demonstrates a high level of adaptability, allowing for the connection of various column cross-section shapes (double-T profiles, rectangular tubes and circular tubes), a change of column cross-section on each side of the column splice and the connection of beam members while complying with the adopted Connect4C structural grid [4]. However, this solution is deemed not aesthetic thus implicitly constraining its location within the floor’s depth.



**Fig. 1:** Connect4C “nodal” square splice [3]

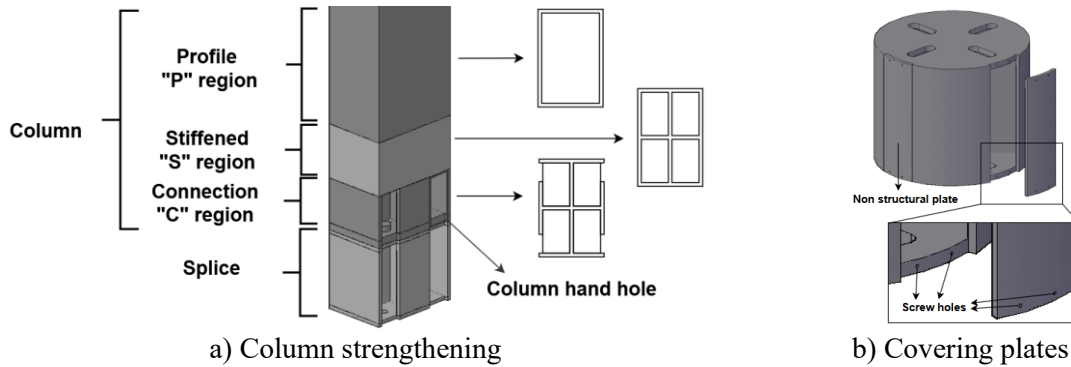
This drawback significantly limits the splice’s scope of application. Thus, an alternative has been proposed, using the same conceptual philosophy as described in the present paper.

If the positioning of the column splice at mid-height of the floor is contemplated, it is required to have a better fit of the splice with the dimensions of the columns to obtain the expected aesthetic. So, adapting the splice outer geometry as illustrated in **Fig. 2** is rather straightforward while conserving the splice’s advantages, namely the vertical adaptability, the access for tightening the bolts, a contact connection to efficiently transfer compression loads, ... However, the fitting constraint imposes the bolts to be located within the tube, so impairing their tightening. As a consequence, hand holes identical to the splice should be cut in the columns. Moreover, to counterbalance the loss of bearing capacity induced by the hand holes, to improve the connection efficiency and to limit local yielding in the connected column for sake of their reusability, stiffeners should be welded within the tube cross-section as depicted in **Fig. 3**. It should be noted that columns with open sections are not concerned by the above-mentioned issue despite having weaker resistance and lower initial stiffness, especially along the weak axis in respect of the rectangular splice.



**Fig. 2:** Connect4C “fitting” splices

Lastly, in order to limit the aesthetic impact of both hand holes and splice's openings, cover plates can be used to enclose the section. However, to achieve this, each endplate should be notched between their flanges and have threaded screw holes over their thickness as shown in **Fig. 3**.



**Fig. 3:** Splice & covering solution

### 3. Characterizing the splice under combined loading

In structural systems, such column splices may be subjected to axial forces and bending moments in both principal directions. To characterize a joint, the component method [5] is recognized as one of the most appropriate analytical methods and is recommended in EN1993-1-8 as design method. However, although this method can cover a wide range of joint configurations and loading conditions, the latter has been mainly developed to cover joints under pure bending as reflected in the normative codes [6]. The present section will highlight how this method can be extended to load cases including axial load and bending in order to allow the characterization of the column splices.

#### 3.1 Axial load and monoaxial bending

Barely covered in the literature [7]-[9], the Cerfontaine model [10], [11] provides an analytical method based on the component method for characterizing steel joints under combined  $M-N$ . Initially developed to design steel beam-to-column connections, the procedure was then improved and extended to composite joints by Demonceau [12]. The latter more general and accurate version was applied to the “nodal” square splice (**Fig. 1**) and successfully validated against numerical simulations in [3].

The previously mentioned design methodology relies on the sole assumption that all the components activated at yielding exhibit a ductile behavior allowing for plastic redistribution within the connection. The method first requires to characterize the connection both under pure tension and compression. In compression, the resistance corresponds to the resistance of the connected cross-section (see **Fig. 4b** grey shaded area) while, in tension, the resistance under pure tension is conditioned by the plastic mechanism, function of both geometry and resistance, developing in the connection plate. Indeed, the column splice has been designed in such a way that the connection plate is the weak component as a ductile failure mode is targeted. Accordingly, the force passing through each bolt  $F_T$  (shaded grey area in **Fig. 4a**) should be smaller than the bolt resistance  $B_{rd}$  as highlighted in **Fig. 4c**.

The second step implies assuming a position of the Plastic Neutral Axis (PNA) thus determining which regions of the connection are activated in compression and in tension. Owing to

the latter information, equilibriums can afterward be computed to assess the corresponding couple of  $N$  and  $M_y$  causing failure. Drawing the entire interaction curve requires the consideration of several PNA positions and assessing the equilibriums for each of these positions.

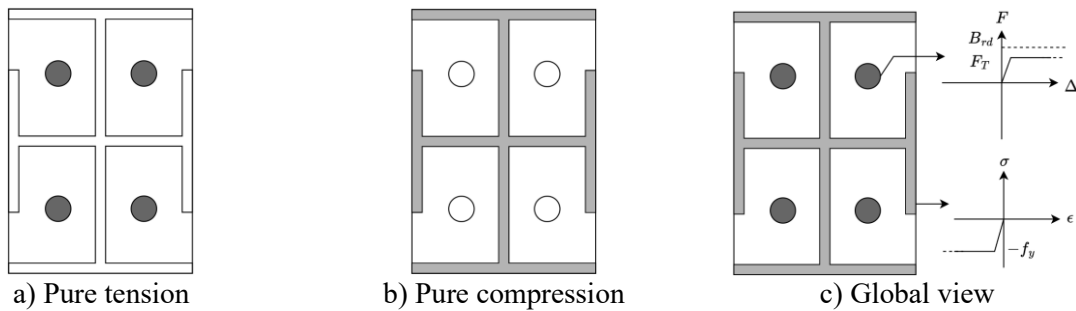


Fig. 4: Connection resisting cross section

### 3.2 Extension to axial load and biaxial bending

As previously mentioned, the above-described method was initially developed for characterizing beam-to-column connections. In such assemblies, transverse bending is often negligible and the consideration of biaxial bending was thus not necessary. Nevertheless, typical column bases and splices in moment-resisting frames sustain such complex loadings and should be designed accordingly by determining the entire  $N - M_y - M_z$  interaction volume (see Fig. 5), in other words, the collection of all combinations of  $N - M_y - M_z$  associated to a failure of the splice.

It should be noted that the method addressed in Section 3.1 is applicable to any geometry and provides the  $(N + M_y)$  resisting point based on the knowledge of the PNA position. Therefore, independently of the section rotation  $\alpha$ , in other words, change of coordinate system as illustrated in Fig. 5b,  $N$  and  $M_\alpha$  resisting points for each position of the PNA, and, more globally,  $N + M_\alpha$  resisting curves can be assessed. Once the entire interaction curve  $M_\alpha + N$  computed within the cylindrical coordinate axes  $(M_\alpha; \alpha; N)$  is available, the latter can be expressed back within cartesian coordinate axes for practical use as illustrated hereafter.

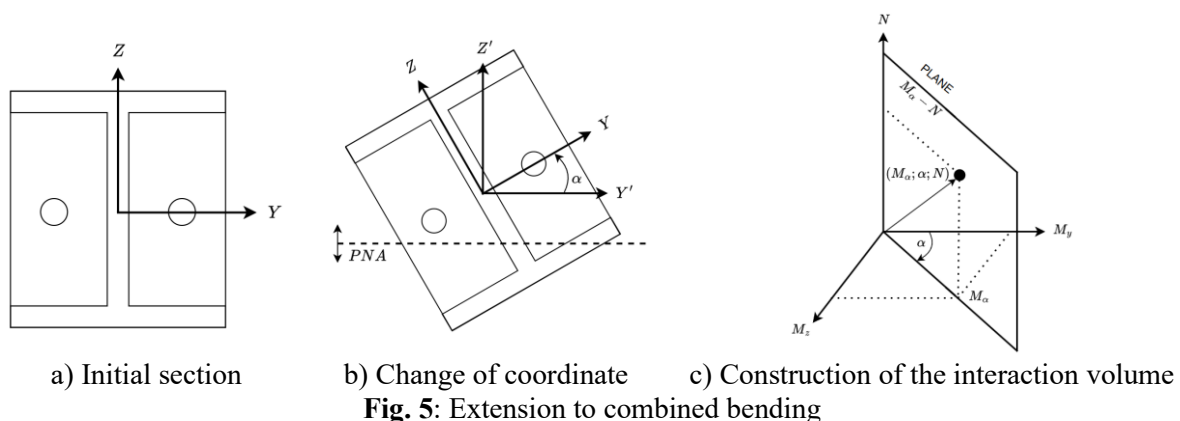


Fig. 5: Extension to combined bending

## 4. Numerical simulations

Whilst an experimental campaign is already scheduled within the Connect4C project to validate in real conditions the developed numerical and analytical models, preliminary numerical mod-

els of the splice connections have been produced using Abaqus to identify the scope of application of the method, investigate some modeling assumptions and give some insight into the splice's mechanical performance and stiffnesses. Closest configurations are column bases bolted to concrete foundations and are currently not covered by the method.

#### 4.1 Modelling assumptions

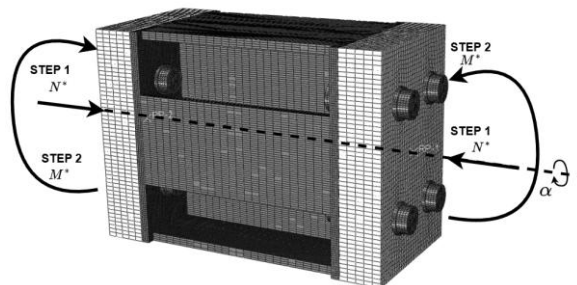
Interaction  $N - M_y - M_z$  resisting volumes were produced from Abaqus for the nodal splice (splice N°1 – see **Table 1**) and the fit splices (splices N°2 to 4) illustrated in **Fig. 1** and **Fig. 2** respectively. Geometries are reported in **Table 1**. The specimens are bolted to 50mm thick elastic ( $E = 210\text{GPa}$ ) foundations. On the other hand, all the other material laws are assumed to be nominal elastic-perfectly plastic behavior laws.

**Table 1:** Numerical model properties

N°	Splices	$t_f$ [mm]	$t_{edp}$ [mm]	$H$ [mm]	$c$ [mm]	$t_w$ [mm]	$W$ or $D$ [mm]	$f_y$ [MPa]	Bolt position(s) (Y, Z) from center	Bolt center
1	Square [3]	15	15	300	100	10	450	355	(±100; ±100) (±150; ±150)	M24 10.9
2	Circular	6	10	300	72	10	274	355	(±53; ±53)	M20 10.9
3	Rectan- gular	10	10	250	65	10	180x260	355	(±42.5; ±65)	M20 10.9
4	H open section	15	10	200	170	9	200	355	(±55; 0)	M24 10.9

NB :  $H$  is the height of the splice whilst  $t_{edp}$  is the end plate thickness (already accounted in  $H$ )

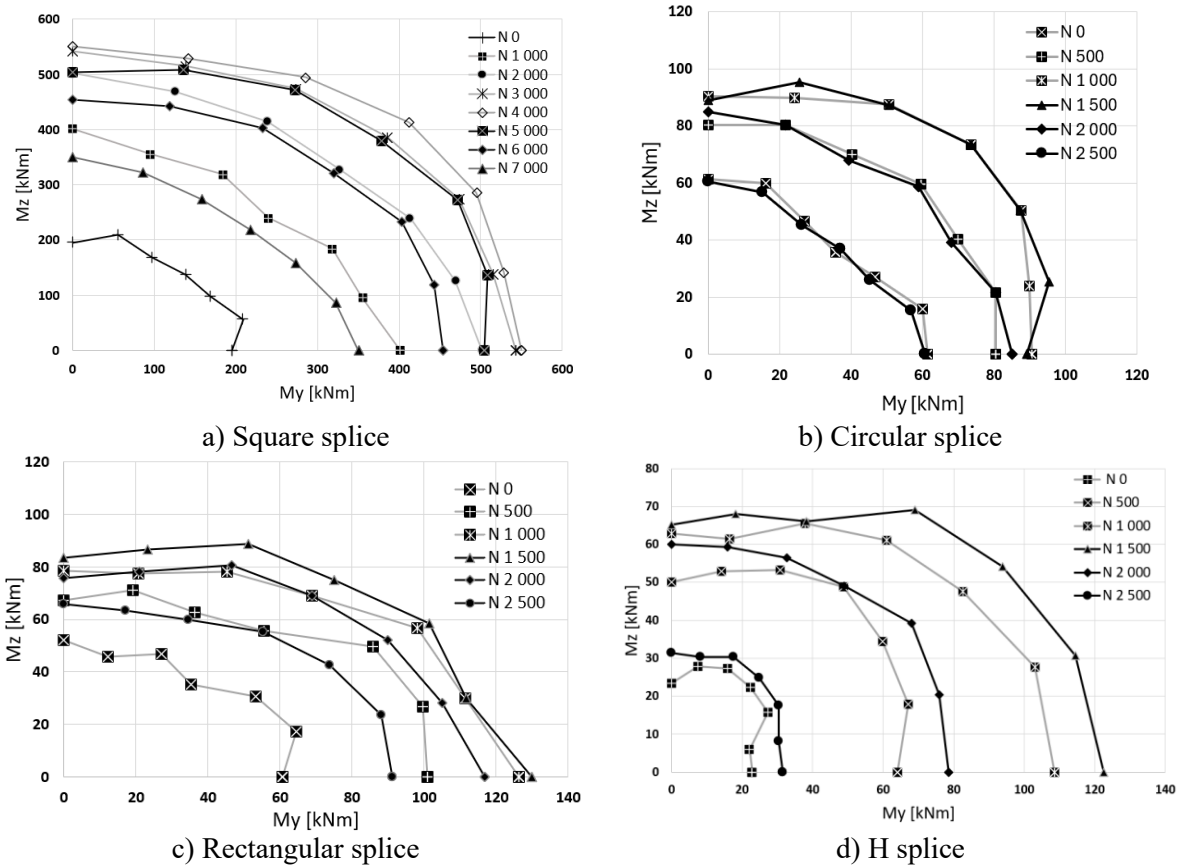
Interactions between the different parts of the model are considered through hard normal contact and a friction coefficient of 0.3. Both boundary conditions and loadings are applied to the model on reference points rigidly tight to the foundations outer face. The quasi-static loading is applied in two dynamic implicit analysis steps accounting for the geometrical and material non linearities. The first one consists of applying a pair of opposite axial loads up to a fixed value whilst the second step requires to increase the pair of opposite bending moments along the PNA until failure is reached. Besides, all the other degrees of freedom are blocked, and the overall model is rotated by an angle  $\alpha$  when testing another bending ratio as illustrated in **Fig. 6**. Regarding the finite element used, C3D8R cubic element with reduced integration are selected for each part. Also, a sensitivity study was conducted in order to identify the suitable number of elements, i.e. at least 4 elements over the thickness, to be used to ensure the accuracy of the results while keeping reasonable computation time. The above-described numerical procedure is similar to the one defined in [3] and used for modeling the square splice.



**Fig. 6:** Numerical model

### 4.2 Results

The so-produced numerical results are illustrated in **Fig. 7** in the  $M_y - M_z$  interaction plan for several values of axial loads. In particular, since each splice has at least two axes of symmetry, simulations to only cover one quarter of the interaction curves were conducted. Reported plastic resistance points on the graphs are determined according to the Eurocode [6] definition, i.e. as the linear extrapolation intersection of both elastic and hardening branches.



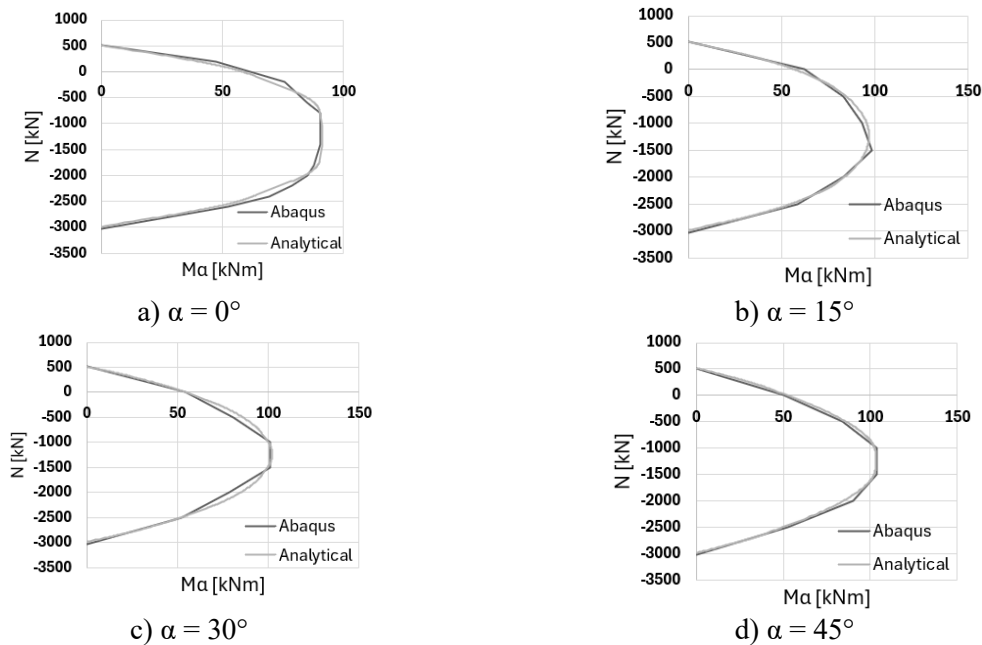
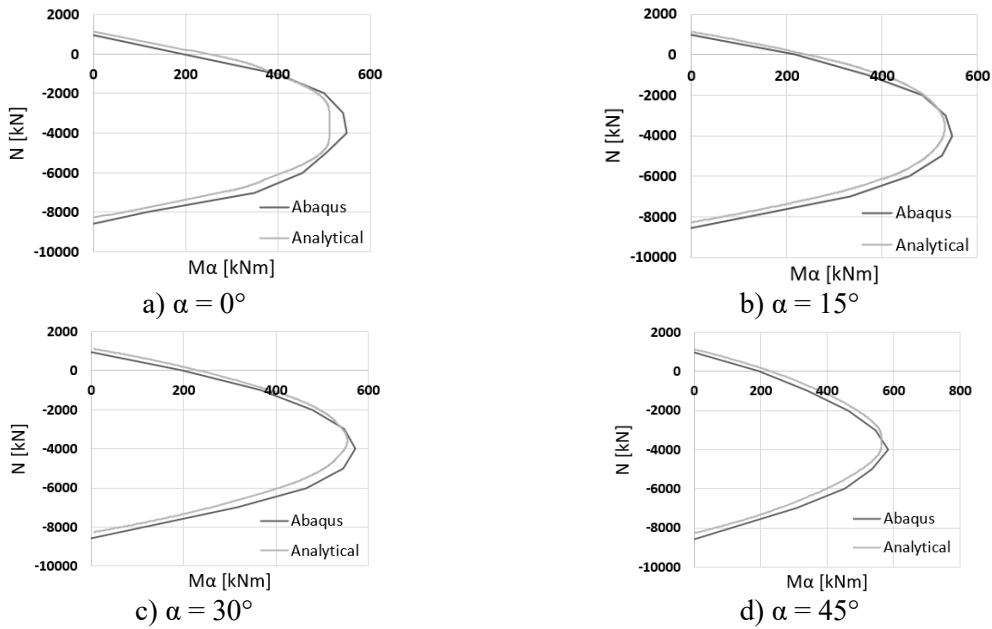
**Fig. 7:** Numerical  $M_y + M_z + N$  interaction curves –  $N$  in [kN]

A major outcome from **Fig. 7**, already highlighted in [3], is the significant increase of bending bearing capacity induced by the presence of compression axial load. For each connection, the bending resistance is averagely doubled for building typical gravity loads when compared to the bending resistance in absence of axial load. Therefore, significant optimization could be achieved by accounting for the  $M-N$  interaction when designing column splices and, more globally, structural joints subjected to such loading scenario. In particular, it can be observed in **Fig. 7d** that a significant resistance to bending up to 120kNm can be achieved for a connection that is usually considered as a hinge and used as such for column bases. However, in concordance to the typical idealization, foundations are not designed to withstand such bending loads. These considerations emphasize the need for more accurate joint characterization and verification.

### 5. Comparison & discussions

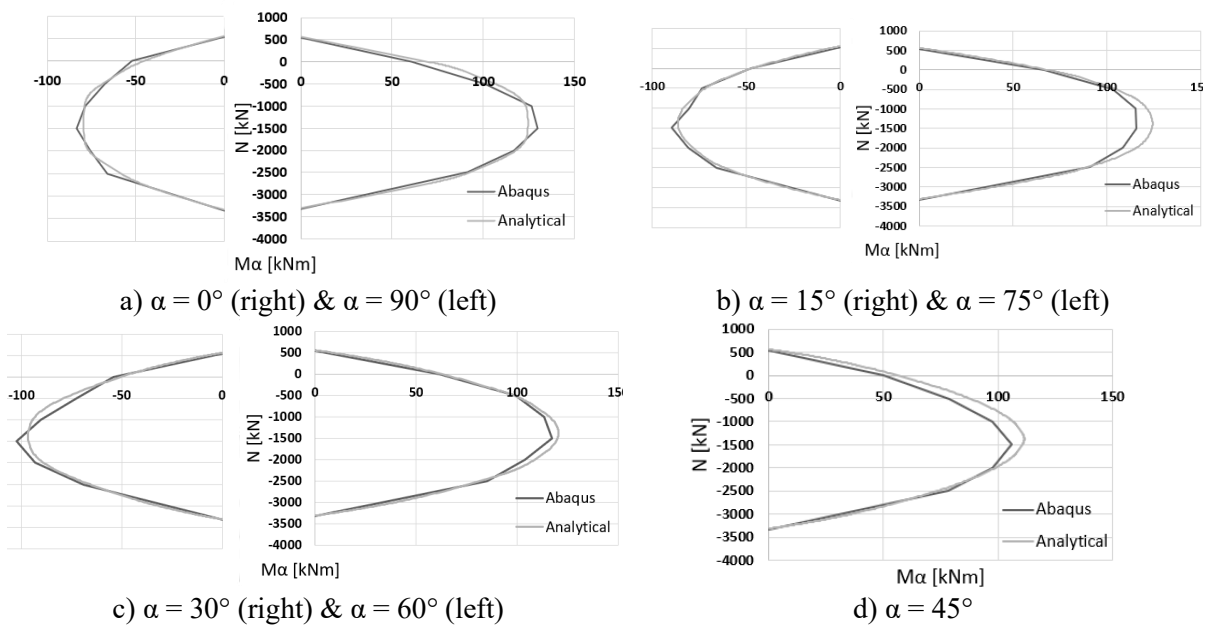
Analytical predictions using the assembly procedure described in section 3 are provided in **Fig. 8** to **Fig. 11** for the various splice configurations and compared against the numerical results. Whilst overall satisfactory accuracy is obtained, minor differences can be observed, identifying

possibilities for improvement of the model. In particular, regarding the square splice in **Fig. 8** characterized using a complete analytical procedure considering the component characterization provided in [3], conservativeness can be highlighted with a slight underestimation of the peak bending resistance due to the adopted modelling assumption regarding the redistribution of the tensile load between the bolt rows as discussed in [3].

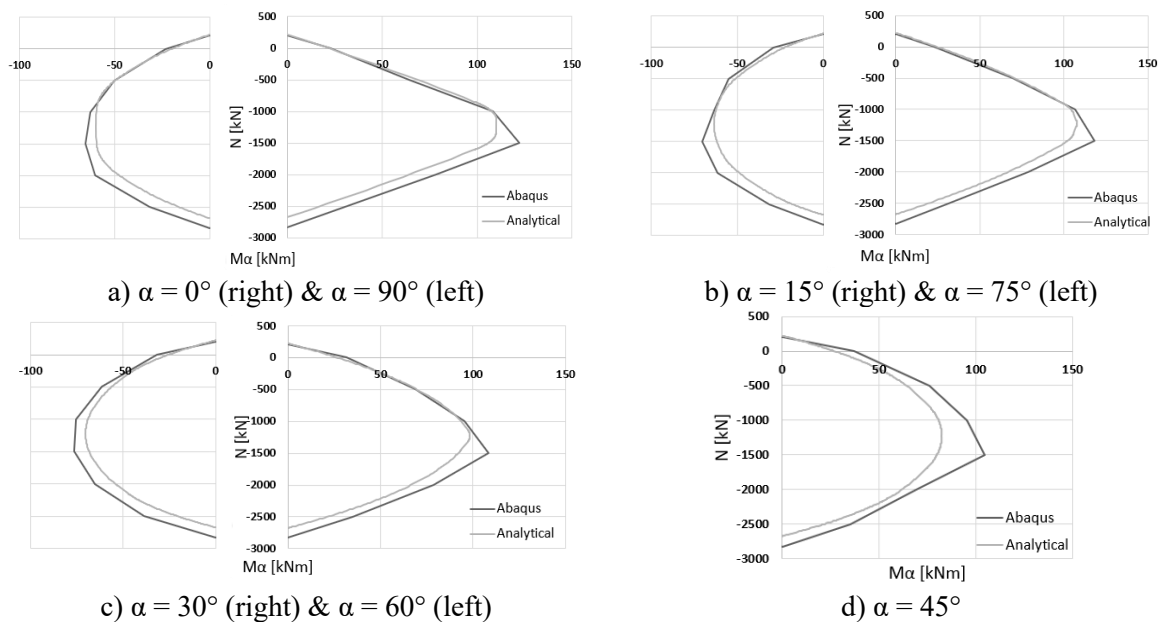


For the other joint configuration, as no formulas are yet available for the characterization of the component “plate in bending” for the specific splice configurations considered herein, the tensile resistance  $F_T$  of each bolt zone was extracted from the numerical model loaded under pure tension as the objective of the present study is to validate the assembly procedure described in Section 3. As a perspective, analytical formula to predict  $F_T$  should be developed, which

constitutes one of the objectives of the PhD thesis of the first author. Whilst high accuracy can be observed for the circular splice as shown in **Fig. 9**, differences can be observed for the rectangular splice (see **Fig. 10**). This difference may be explained by the fact that, in the analytical model, it is assumed that the full plastic mechanism around the bolt in tension is developed as soon as the bolt is in the tension zone while, in practice, the development and shape of the latter could be affected by a location and the inclination of the PNA close to the considered bolt. So, considering a full  $F_T$  in the bending equilibrium instead of a reduced one reflecting both influences of the location and inclination of the PNA leads to an overestimation of the plastic bending resistance. This observation constitutes also a perspective to the presented study. It should be noted that highly stiffened configurations, such as the circular splice, are less sensitive to the above-mentioned effect in comparison to more flexible endplate (i.e. the rectangular splice). Lastly, results depicted in **Fig. 11** show safe predictions coming from the analytical model.



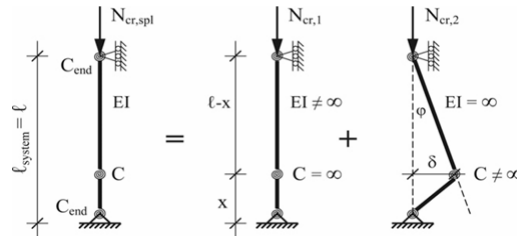
**Fig. 10:** Rectangular splice validation



**Fig. 11:** H splice validation

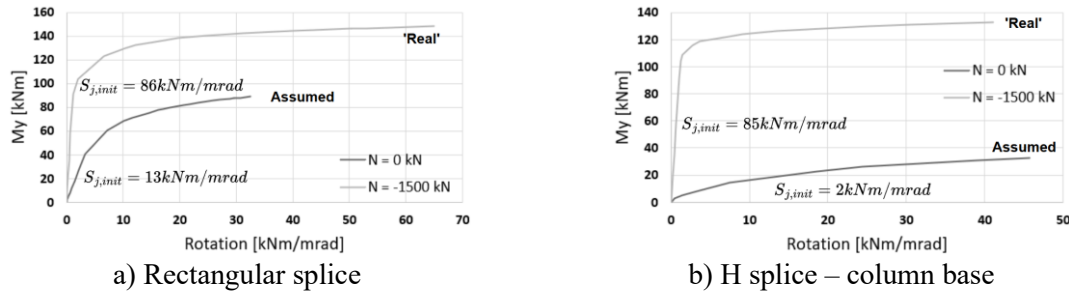
## 6. Stiffness insights

Thanks to the numerical investigations conducted, few insights and considerations regarding the impact of the axial load on the bending stiffness of the column splice can be raised. Whilst several authors [13], [14] & [15] investigated the effect of the column splice bending stiffness on the overall structural stability (see **Fig. 12**), none proposed analytical formulas to predict the stiffness of the connection, taking into account for the effect of the axial load.



**Fig. 12:** Splice effect on column stability [15]

However, as highlighted in **Fig. 13** presenting bending vs rotation curves extracted from some of the preformed numerical simulations, the axial load may have a significant impact on the initial stiffness of the connection, inducing an increase of the initial bending stiffness of the splice. Accordingly, the consideration of the latter effect could have a positive impact on the column stability check. This constitutes a last perspective to the presented study.



**Fig. 13:** Influence of the axial load on the initial bending stiffness ( $\alpha = 0^\circ$ )

## 7. Conclusions

Within the present paper, the analytical and numerical characterization of innovative demountable and reusable column splices developed in the framework of the Connect4C project has been presented. In particular, the accuracy of the proposed analytical model has been investigated and discussed. Even if this preliminary study demonstrates a high potential of the proposed model, some perspectives for further developments to improve its accuracy and field of application have been identified:

- The resistance of the plate in bending component should be analytically characterized considering the specific configuration met in the proposed splice solutions;
- In particular, the influence of the PNA location on the development of the plastic mechanism in the plate in bending component should be studied;
- Further investigations are required to predict the bending stiffness of the splices accounting for the presence of axial load.

Finally, the developed method should be finally validated against experimental tests planned in the coming year.

## Acknowledgments

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