

Full paper

Development of new design recommendations for structural steel joints under M-N

Loïc Archambeau¹ | Tudor Golea¹ | Klaus Weynand² | Jean-François Demonceau¹**Correspondence**

Ir. Loïc Archambeau
University of Liège
Faculty of Applied Sciences,
ArGEnCo Department
Quartier Polytech 1, Allée de la
découverte, 9, B52/3
4000 Liège, Belgium
Email: loic.archambeau@uliege.be

¹ University of Liège, Liège,
Belgium

² Feldmann+Weynand GmbH,
Aachen, Germany

Abstract

In steel structures, most of the joints are typically subjected to shear (V) and/or bending (M) forces only, and their behaviour can be fully characterised using the component method as recommended in EN 1993-1-8. However, in some situations, these joints may also be exposed to axial (N) forces. Under such a loading condition, Eurocode 3 currently proposes only a simplified M-N interaction criterion, for which no comprehensive derivation methodology is provided, and whose scientific background is not really founded. Moreover, previous research has already shown that this criterion may also be unsafe or too conservative in certain cases. This paper thus aims to present the main findings of a comprehensive set of analyses, conducted on various joint configurations coming from the literature. These analyses notably include predictions of the joint resistance with an advanced analytical model, a validation of this analytical model using experimental data and comparisons with the prediction from the commercial software COP. Finally, drawn from the outcomes of these analyses, new design recommendations have been formulated to address the identified issues in the European standard.

Keywords

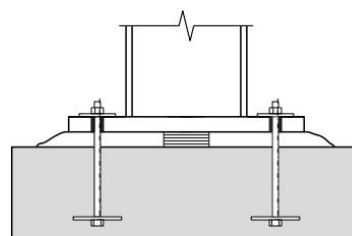
Joints, M-N Interaction, Design recommendations, EN1993-1-8, Component method

1 Introduction

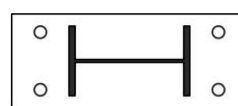
For many years, the characterisation of structural steel joints has been the subject of extensive research and efforts, [1]–[9] among others, aiming at better understanding their behaviour and improving their design. Although joints are typically subjected to shear (**V**) and/or bending (**M**) forces only in most common configurations, they can also face the presence of axial (**N**) forces in connected members. This situation can arise, for example, in moment-resisting column bases (see Figure 1a), in joints at the extremities of pitched roof beams (see Figure 1b), or increasingly in cases where structural robustness must be assessed under various exceptional event scenarios, particularly through the application of the alternative load path method.

Based on the component method, implemented in EN 1993-1-8:2005 [11], it is theoretically possible to characterise any structural steel joint, subjected to any loading conditions, provided that all its active components have been fully identified, characterised, and assembled. However, the assembly procedure currently recommended by the standards is only valid for joints under M, while only unjustified simplified M-N interaction criteria are currently proposed in [11] and [12].

To improve the design method for joints under such a loading condition, F. Cerfontaine developed a universal analytical method [2], which notably allows the derivation of a comprehensive resistance interaction curve for both ductile and non-ductile steel joints under M-N. He also identified several safety concerns associated with the current interaction criterion defined in the standard [11]. Later, this advanced model was extended to steel-concrete composite joints by J.-F. Demonceau [3].



a) Column base [10]



b) Industrial frame [9]

Figure 1 Examples of structural steel joints under M-N

Although the Cerfontaine analytical model can accurately predict the behaviour of structural steel joints under M-N in terms of resistance, its application may remain relatively complex for certain joint configuration, particularly when multiple bolt rows are involved. Therefore, this paper presents three new simplified M-N interaction criteria that have been developed in the framework of a Master thesis carried out at the University of Liège [9] (available in open access). The proposed criteria have been developed targeting an ease of application while effectively addressing the shortcomings of the interaction rules suggested in both the current and forthcoming versions of the European standard.

2 Advanced analytical model

Based on the component method concept and exploiting the static theorem, F. Cerfontaine [2] developed a first complete analytical characterisation procedure for deriving a M-N resistance interaction curve, accounting for group effects and stress interaction phenomena in the column. Through additional developments aimed at evaluating the deformation state of ductile joints at failure, he was also able to extend this model to joints exhibiting non-ductile behaviours. To illustrate and summarise the sequence and nature of the successive steps required to carry out the analytical approach, the flowchart shown in Figure 2 is proposed. Moreover, a detailed description of each step can be found in [9].

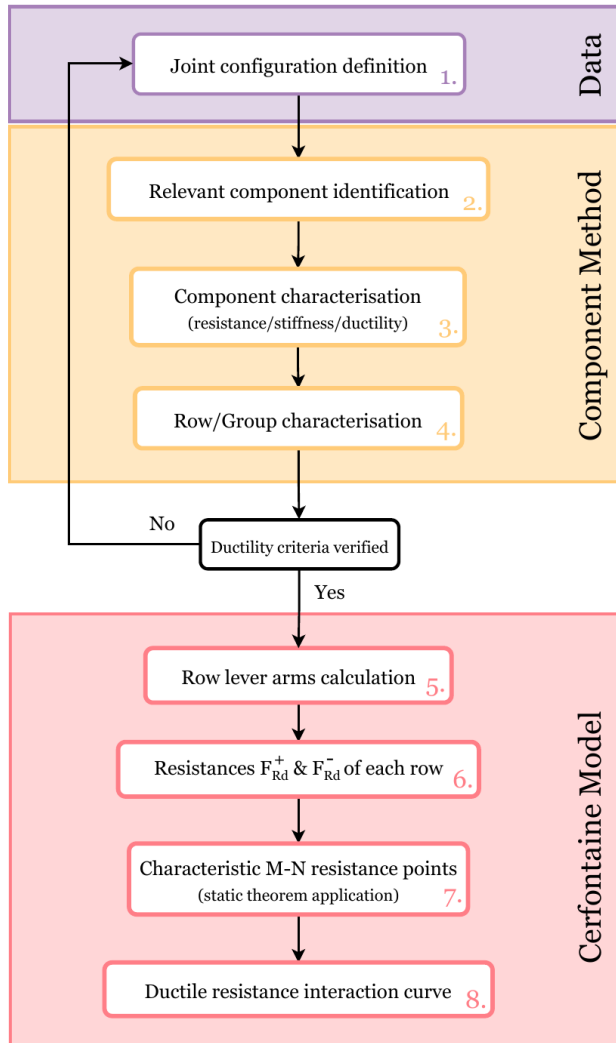


Figure 2 Flowchart of the analytical model for ductile joints [9]

Since the present study focusses primarily on ductile joints, only the calculation steps necessary for designing this type of joint are included in the flowchart. To determine whether a joint can be classified as ductile, two key criteria must be verified: (i) all critical joint components are ductile, and (ii) all welds can be considered as full-strength (see criterion from [13]). The application of this procedure also depends on compliance with the conditions and assumptions associated with the static theorem.

By following this methodology, it is thus possible to obtain, for any ductile joint configuration, a complete ductile resistance interaction curve consisting of $2n+2$ points connected by straight lines (see Figure 4), where n represents the total number of rows (compression & tension) forming the joint. Finally, based on the graphical representation of this M-N interaction curve, it is possible to determine whether any pair of forces M_{Ed} & N_{Ed} applied to the joint will lead or not to its failure. Indeed, if the point of coordinates $(M_{Ed}; N_{Ed})$ is located within or on the interaction curve, then the joint can withstand these loads, regardless of the loading cycle followed by the joint up to this point.

2.1 Application examples

The advanced analytical model developed by F. Cerfontaine has been applied on different joint configurations found in the literature. In total, nine different beam-to-column joint configurations were analysed: six coming from the European project FAILNOMORE [13], two experimentally tested at the University of Coimbra as part of L.R.O. de Lima's PhD thesis [14], and one introduced by F. Cerfontaine in his PhD thesis [2]. For each joint, a technical drawing together with the corresponding geometrical and mechanical properties can be found in [9]. More information on the joints that were experimentally tested can also be found in [14]-[16].

To facilitate the implementation of the entire methodology summarized in Figure 2, Python scripts have been fully developed for the various treated joint configurations. Indeed, introducing in entry the geometrical and mechanical requested data of the joint configuration to be studied, these codes allow to compute the entire ductile resistance interaction curve of this joint. All these scripts can be accessed and downloaded through a link provided in [9].

The Figure 4 shows three distinct ductile resistance interaction curves corresponding to three joint configurations from the FAILNOMORE project [13]. The main difference between the three joints lies in the column and beam profiles being connected, as well as the total number of rows n in these joints. Indeed, the joint configurations A1, B1 and C2 (see Figure 3) present two, three, and five bolt rows respectively, in addition to the two compression rows, each positioned at mid-thickness of the beam flanges.

Each of the nine studied joint configurations was analysed twice: (i) first using the Python scripts developed as part of this study, and (ii) second with the commercial software COP [17], developed by the design office Feldmann + Weyand GmbH in collaboration with the University of Liège, and within which the advanced analytical model proposed by F. Cerfontaine was recently implemented.

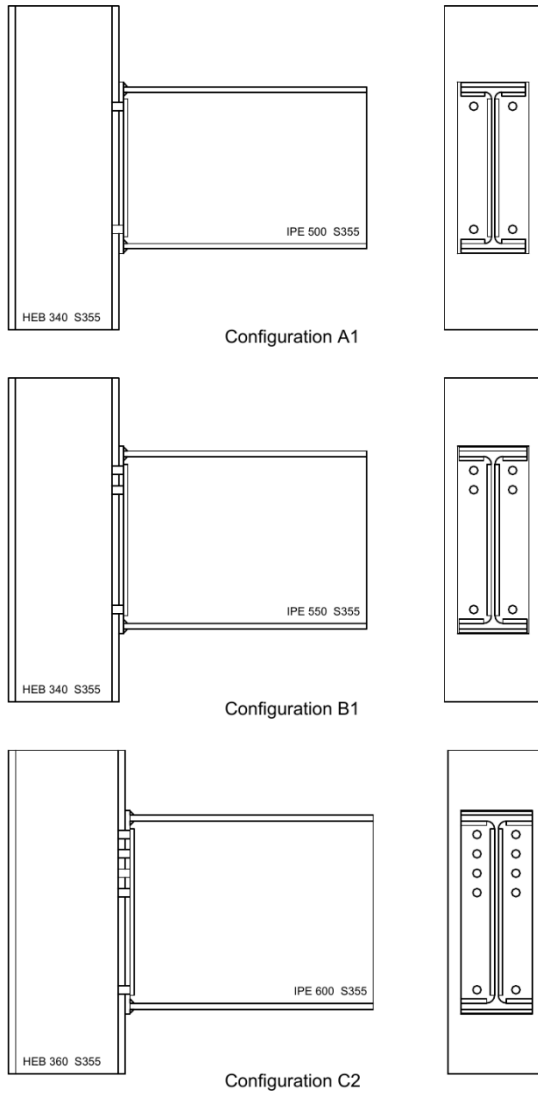


Figure 3 FAILNOMORE joint configurations A1, B1 & C2

2.2 Model validation

First, the ductile resistance interaction curves of the six FAILNOMORE joint configurations obtained using the analytical model were compared with those extracted from the

COP software [17]. Thanks to this validation and the ease of use of COP, the latter was used to perform a parametric study to investigate the influence of key parameters on the joint response under M-N. The results of this parametric study are provided in [9].

The analytical curves were also compared with the results of the experimental campaign conducted at the University of Coimbra [14]-[16]. From a general perspective, the analytical curves tend to accurately predict the M-N resistance of the two tested joints. However, it should be noted that, for some experimental points, the model appears to estimate a higher joint resistance capacity than what was measured experimentally, which may indicate that the Cerfontaine model could occasionally be unsafe. Although this conclusion may appear problematic, it should be put in perspective, particularly regarding the significant variability of the mechanical and geometrical properties measured on the tested specimens, as well as certain assumptions made due to missing information on some parameters. It is also worth noting that, in the past, the Cerfontaine model has already been compared with the results from other experimental campaigns, notably with tests performed on steel and steel-composite joints, as well as steel-composite joints under elevated temperatures, showing a very good accuracy of the Cerfontaine model. Further details on these comparisons and the associated tests can be found in [18]-[19].

Finally, it should be noted that a second Master thesis [20], conducted at the University of Coimbra, carried out finite element numerical analyses of the flush end-plate joint configuration presented in the PhD thesis of L.R.O. de Lima [14]. The so-obtained numerical results are in line with the Cerfontaine model predictions, so also exhibiting same level of differences between the numerical results and the experimental ones. This issue is still under investigation when writing the present paper.

3 Standards M-N interaction criteria

The M-N interaction criteria included in the present (EN 1993-1-8:2005) and forthcoming (EN 1993-1-8:2024) versions of the standards (see Figure 5) follow the same

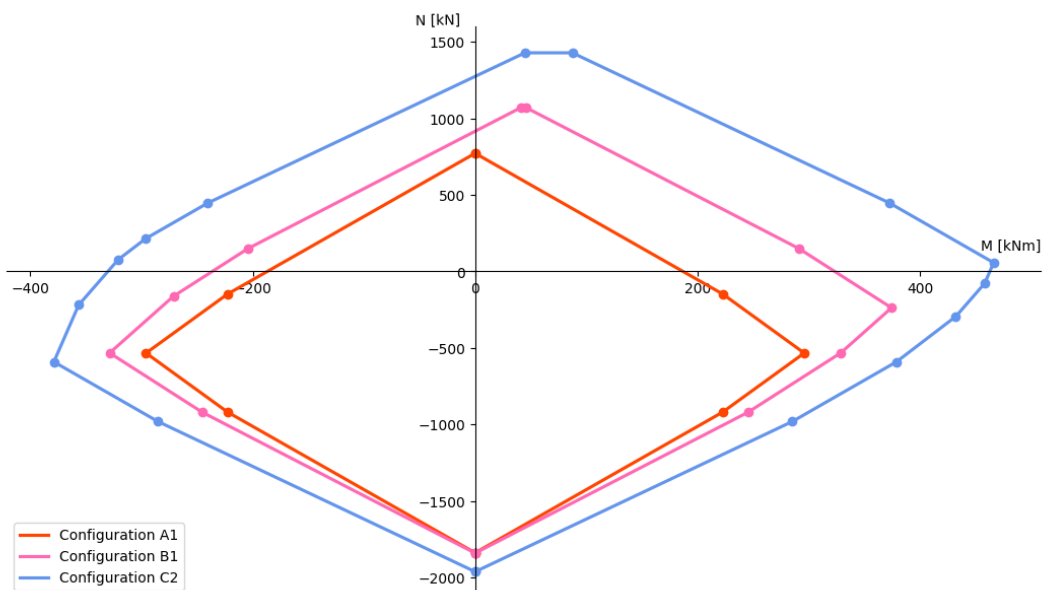


Figure 4 Ductile resistance interaction curves of three different joint configurations from the FAILNOMORE project [13]

methodological approach but differ in the values they employ. Indeed, the core assumption consists in considering that the joint can sustain its resistances under pure bending, and thus not being subjected to M-N interaction, until reaching defined axial force values. Beyond these threshold values, a linear interaction criterion linking the pure bending resistances to the pure axial resistances of the joints is assumed. The main difference between the two versions of the standard therefore lies in the definition of the axial force values below which the M-N interaction can be neglected. In EN 1993-1-8:2005, this value is set to 5% of the axial design plastic resistance of the beam cross-section, while, in EN 1993-1-8:2024, this value is fixed to 5% of the axial design plastic resistances of the joint, assuming no applied moment.

At this stage, some remarks can already be made regarding these M-N interaction criteria. In fact, although both approaches require the calculation of the pure axial resistances (under tension and compression) of the joint to plot the criteria, none of the standards currently provides a procedure to compute these resistances. However, computing these resistances is not obvious, except in cases where the joint is symmetrical and its tension or compression resistance equals the sum of the corresponding row resistances.

For the criterion from EN 1993-1-8:2005 [11], the axial design plastic resistance of the beam cross-section, used to determine the threshold values, can be easily calculated. However, it should be emphasized that there is no direct link between the axial resistance of the beam cross-section and the response of the joint under M-N, which makes this criterion irrelevant.

Nevertheless, the most important observation regarding these two M-N interaction criteria remains the insecure regions, which are clearly visible on Figure 5. This lack of safety was already previously highlighted in [2] and [18]. It can indeed be noted that, in certain regions of the graph, the standards criteria predict higher joint resistances than those indicated by the ductile resistance interaction curve

predicted with the advanced Cerfontaine model.

Although, in most joint configurations, such as the one shown in Figure 5, the insecure regions appear only on one side of the horizontal axis, they can also be observed on both sides depending on the considered joint configuration, which influences the shape of the ductile resistance interaction curve, as illustrated in Figure 6.

Finally, it should also be emphasised that, in certain other regions of the graphs, the standard criteria can sometimes be too conservative when compared to the ductile resistance interaction curves. Even if this is on the safe side in terms of resistance, these large unexploited areas prevent the full exploitation of the joint resistance capacity. Revising these criteria could therefore lead to more effective optimisation of the joint during the design phase, from both structural and economic perspectives.

4 Proposed new M-N interaction criteria

Three new M-N interaction criteria have been developed in [9] with a view to a potential future inclusion in the European standard. The establishment of these new criteria was dictated by two main guidelines. First, offer a simplified alternative to the derivation of the complete ductile resistance interaction curve of the joint. The idea was indeed to shorten the calculation procedure of the Cerfontaine model so that, even when the joint configuration to design becomes highly complex, the computations could still be carried out quickly, and potentially even through hand computations. Second, address the various issues identified in the current M-N interaction criteria proposed in the standards, summarised in the previous section.

To ensure the reliability of these new criteria, their application should be restricted to joints that satisfy the two ductility requirements outlined in Section 2, which are also required for deriving ductile resistance interaction curves. All the equations needed to derive the three criteria, along with several application examples, are provided in [9].

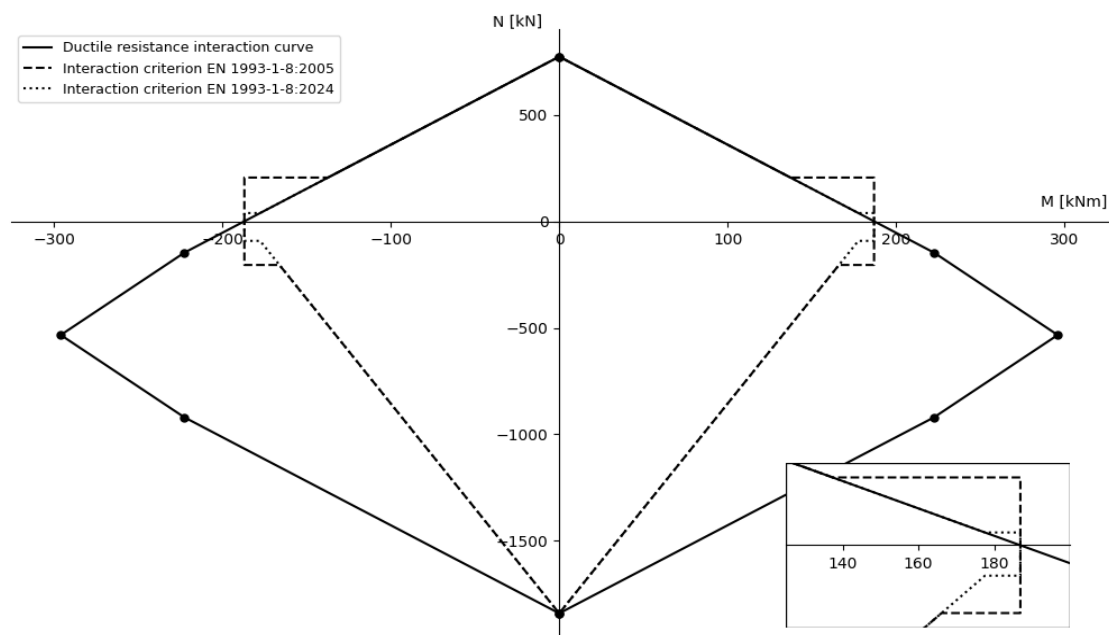


Figure 5 Comparison of the analytical curve with the M-N interaction criteria proposed in both versions of the European standard [9]

4.1 Six-point interaction criterion

To derive this new M-N interaction criterion, it is first necessary to determine the lever arms and resistance values for each row of the joint. These correspond to calculation steps 2 through 6 in the flowchart (see Figure 2). Once all the required data have been obtained, the six characteristic points of the new criterion can be determined. These six points correspond to the six peak points of the full ductile resistance interaction curve of the joint. Finally, the obtained points must be connected in pairs with straight lines to form the outline of the M-N interaction criterion (see Figure 6).

The simplicity of deriving this criterion is likely its greatest advantage, as it requires only six easily computable points to be plotted. As visible on Figure 6, this new M-N interaction criterion is completely inscribed in the ductile resistance interaction curve, thereby ensuring the safe design of the joint. It also enables the capture of a significantly larger portion of the area compared to the two criteria from the standards, improving the use of the full resistance capacity of the joint. However, this criterion does not include "non-interaction" ranges, which could potentially be a drawback for some engineers. Also, this criterion does not pass through the two pure bending resistances, as computed through the component method.

4.2 Eight-point interaction criterion

To enhance the portion of the ductile resistance interaction curve captured by the criterion, while recreating a consistency with the current standard criteria, this second new M-N interaction criterion proposes adding the two pure bending resistances of the joint to the six characteristic points already defined for the previous criterion. The coordinates of these two additional points can be simply derived based on the assembly procedure described in Section 6.2.7.2 of EN 1993-1-8:2005 [11].

4.3 Eight-point criterion with "non-interaction" thresholds

The purpose of this last M-N interaction criterion is to meet the request from some engineers to incorporate "non-interaction" ranges, as it is currently the case with the criteria defined in the European standards. It is therefore proposed to incorporate these "non-interaction" ranges into the eight-point criterion by simply extending a vertical line from the pure bending resistances of the joint, until it intersects the criterion curve again. As a result, they will no longer appear on both sides of the horizontal axis, but only on the sides corresponding to the maximum bending resistances of the joint (hogging & sagging). Their size is also no longer constant, as it strongly depends on the shape of the eight-point criterion, as visible on Figure 6.

The coordinates of the intersection points, whose N-values may serve as new thresholds, can be directly determined from the coordinates of the other characteristic points, by simply applying the Thales theorem. Nevertheless, note that if the points of maximum bending resistance were positioned on the horizontal axis of the graph, it would then be impossible to create a "non-interaction" range without compromising the safety of the design.

Although these "non-interaction" ranges exclude the use of the curve's horizontal extremities, this does not appear to be an issue, as these regions in the M-N interaction criteria and the ductile resistance interaction curve are always difficult to exploit. It is indeed primordial to ensure that, in these regions, both the axial force (N_{Ed}) and the bending moment (M_{Ed}) applied to the joint are generated by the same load. Otherwise, if N_{Ed} changes rapidly while M_{Ed} remains constant, the resulting point may fall outside the interaction criterion or the ductile resistance interaction curve, which would indicate joint failure.

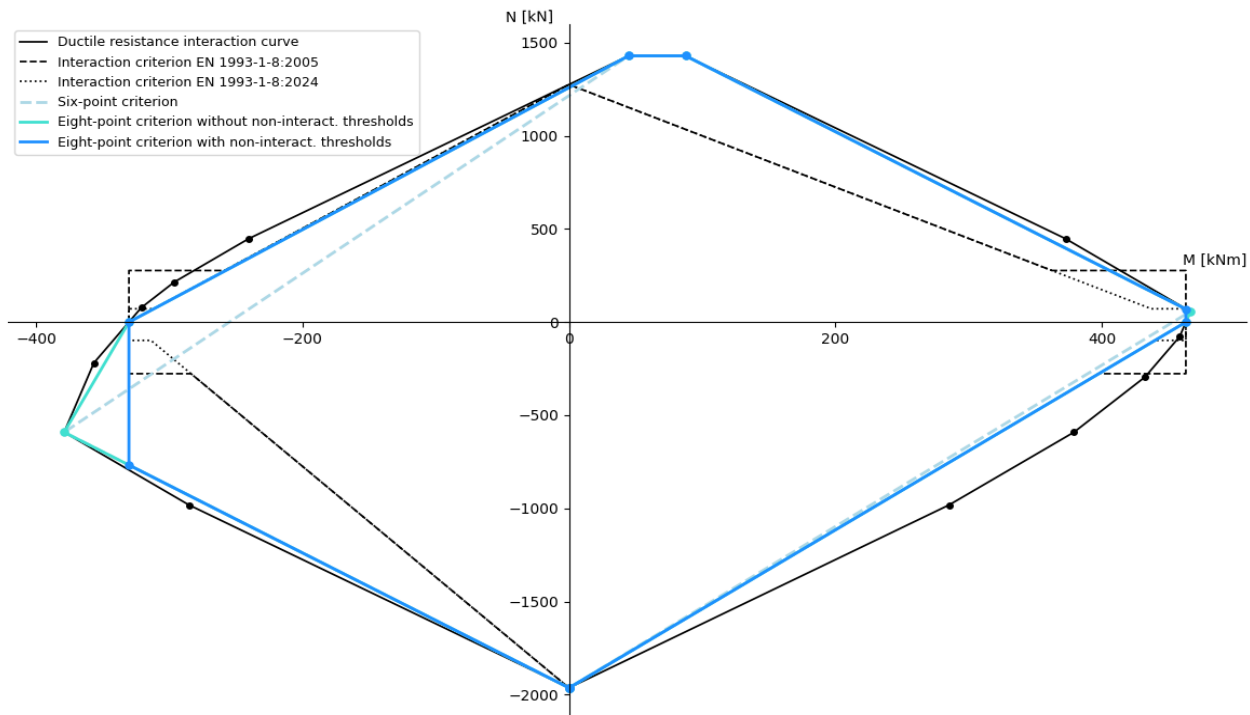


Figure 6 Application of the three new M-N interaction criteria to the joint configuration C2 [9]

5 Conclusions and perspectives

This research work led to three key findings: (i) the lack of guidance in the standard for practical implementation of the proposed M-N interaction criterion, (ii) the complete absence of scientific justification for their use, and last but not least, (iii) the systematic apparition of insecure regions when they are overlaid with the ductile resistance interaction curves derived analytically.

To address the identified issues, three distinct M-N interaction criteria have been developed, with a view to a potential inclusion in a future revision of the European standard. For each of these design recommendations, a comprehensive derivation procedure has been provided, along with several illustrative application examples.

However, their use remains subject to the validation of the two ductility criteria outlined in Section 2. Nevertheless, given the deserved evolution of the robustness requirements that structures must meet, it is highly likely that ductile joints will become the standard, thereby making these recommendations always applicable.

References

- [1] Jaspart, J.-P. (1991) *Étude de la semi-rigidité des nœuds poutre-colonne et son influence sur la résistance et la stabilité des ossatures en acier* [PhD Thesis]. University of Liège.
- [2] Cerfontaine, F. (2003) *Étude de l'interaction entre moment de flexion et effort normal dans les assemblages boulonnés* [PhD Thesis]. University of Liège.
- [3] Demonceau, J.-F. (2008) *Steel and composite building frames: sway response under conventional loading and development of membrane effects in beams further to an exceptional action* [PhD Thesis]. University of Liège.
- [4] Golea, T. (2020) *Behaviour of steel joints under dynamic actions* [Master Thesis]. University of Liège.
- [5] Mathieu, J. (2020) *Développement d'un modèle novateur de caractérisation du comportement précis d'assemblages de construction métallique et mixte acier-béton* [Master Thesis]. University of Liège.
- [6] Corman, A. (2022) *Characterization of the full non-linear behaviour up to failure of the sheared panel zone under monotonic loading conditions* [PhD Thesis]. University of Liège.
- [7] Jaspart, J.-P.; Corman, A.; Demonceau, J.-F. (2022) *Characterization of unstiffened column webs in transverse compression in steel beam-to-column joints*. Thin-Walled Structures, Vol. 180, 109848. <https://doi.org/10.1016/j.tws.2022.109848>
- [8] Neutelers, A. (2023) *Improvement of the mechanical model for mode 1 t-stub plastic strength* [Master Thesis]. University of Liège.
- [9] Archambeau, L. (2025) *Structural steel joints under M-N – from advanced modelling to design recommendations* [Master Thesis]. University of Liège.
- [10] Jaspart, J.-P.; Weynand, K. (2016) *Design of joints in steel and composite structures*. ECCS – European Convention for Constructional Steelwork.
- [11] EN 1993-1-8. (2005) *Eurocode 3: Design of steel structures – Part 1-8: Design of joints*. European committee for standardization. May 2005.
- [12] EN 1993-1-8. (2024) *Eurocode 3 – Design of steel structures – Part 1-8: Joints*. European committee for standardization. March 2024.
- [13] Demonceau, J.-F. et al. (2021) *D3-1: Design recommendations against progressive collapse in steel and steel-concrete buildings – FAILNOMORE*. ECCS – European Convention for Constructional Steelwork.
- [14] De Lima, L.R.O (2003) *Comportamento de Ligações com Placa de Extremidade em Estruturas de Aço Submetidas a Momento Fletor e Força Axial* [PhD Thesis]. Pontifical Catholic University of Rio de Janeiro.
- [15] Simões da Silva, L.; de Lima, L.R.O.; da S. Velasco, P.C.G.; de Andrade, S.A.L. (2004) *Behaviour of flush end-plate beam-to-column joints under bending and axial force*. Steel and Composite Structures, Vol. 4, No. 2, p. 77-94.
- [16] De Lima, L.R.O.; Simões da Silva, L.; da S. Velasco, P.C.G.; de Andrade, S.A.L. (2004) *Experimental evaluation of extended endplate beam-to-column joints subjected to bending and axial force*. Engineering Structures, Vol. 26, p. 1333-1347. <https://doi.org/10.1016/j.engstruct.2004.04.003>
- [17] Feldmann + Weynand GmbH (2022) COP – The connection program [software]. <https://cop.fwi-ing.de/#>
- [18] 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, p. 320-331. <https://doi.org/10.1016/j.jcsr.2019.05.030>
- [19] Haremza, C.; Santiago, A.; Demonceau, J.-F.; Jaspart, J.-P.; Simões da Silva, L. (2016) *Composite joints under M-N at elevated temperatures*. Journal of Constructional Steel Research, Vol. 124, p. 173-186. <https://doi.org/10.1016/j.jcsr.2016.05.012>
- [20] Cruz, I.A.S (2025) *Análise Numérica da Interação Esforço Axial-Momento Fletor num Sistema de Ligações* [Master Thesis]. University of Coimbra.