

Full paper

Steel joint ductility: coupling effect in adjacent T-stubs

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Abstract

The reusability of structural elements is considered as one of the most promising strategies to reach the carbon neutrality of the civil engineering sector in 2050, as recommended in the Paris agreement. And the structural joints are identified as key elements to promote the demountability and reusability of structures. In addition, the joint components could be designed to act as ductile fuse elements in case of overloading, to protect the structural elements to be reused. But to achieve this objective, it requires to master the full behaviour law of the fuse components both in the elastic and plastic fields. The latter concern is particularly of importance in the tension zone of joints where ductile components in bending such as the end-plates or angles, usually modelled as equivalent T-stubs, could be activated.

The present paper highlights a newly identified coupling effect between adjacent T-stubs, inducing a premature yielding of the stronger connected T-stub and so possibly compromising the fuse role of the weakest one. In addition, this coupling effect also leads to a reduction of the resistance of the overall system. A review of the literature is first proposed before presenting physically the above-mentioned coupling phenomenon. Afterwards, numerical simulations are conducted to identify the parameters governing and influencing the new identified failure mode. Lastly, real case examples including the coupling effect are covered to highlight the major outcomes and practical design applications.

Keywords

T-stub, Resistance, coupling effect, Joint, Component, Eurocode

1 Introduction

Due to the recent climate change, normative actions were taken worldwide to limit the carbon emissions. Among these, the European Green Deal [1] will impose the carbon neutrality for each new construction by 2050. To reach this objective, reusing the structural elements is one of the most promising solutions. Moreover, recent RFCS projects, Reduce [2] & Connect4C [3] determined that designing joints with a fuse concentrating all damage outside the structural elements significantly enhance the reusability. Nevertheless, this approach requires to fully master the behaviour of joint components and the apparition of plasticity. Among the classical components, the equivalent T-stub, modelling the tension zone of connections, is often designed to be the failure mode due to its high capacity of deformation. Therefore, this paper focuses on this component and its modelling assumptions. In the following sec-

tions, it is shown how a small discrepancy between idealized T-stubs and real configurations trigger an interaction between two connected T-stubs impairing the reusability of both elements. This interaction phenomenon is latter referred to as “coupling effect”.

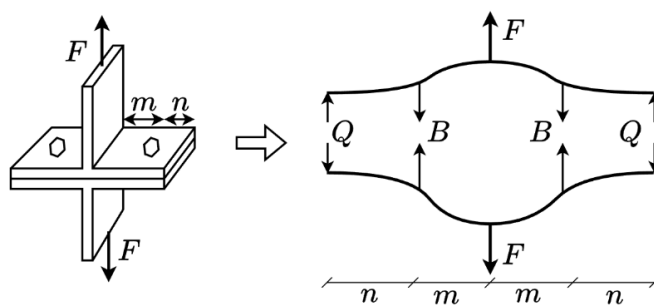


Figure 1 Equivalent T-stub beam model

2 Concept of equivalent T-stub

2.1 Idealized configurations

First, T-stubs were studied in isolation by McGuire [4]. The latter proposed to model this configuration by a simply supported beam loaded punctually at the bolt lines and at mid-span through its web as illustrated in Figure 1. This model was considered for the derivation of the design recommendations implemented in EN1993-1-8:2024 [5], resulting in the consideration of three possible failure modes as a function of the element's geometries and material properties. Failure Mode 3 is related to the bolt failure in tension (see Figure 2d) and its resistance can be expressed as:

$$F_{rd,3} = \sum 0.9 A_s f_{ub} / \gamma_{M2} = \sum B_{t,rd} \quad (1)$$

where A_s is the effective tensile area of the bolts; f_{ub} is the ultimate strength of the bolts; and γ_{M2} is a partial safety factor.

Another failure implying a rupture of the bolts is failure Mode 2 illustrated in Figure 2c. In the latter, whilst the bolts also attain their tensile bearing capacity, a pair of plastic hinges form prior to the bolt failure in the vicinity of the web. Consequently, the resistance associated to this failure mode can be written as:

$$F_{rd,2} = (2m_{pl}L_{eff} + n \sum B_{t,rd}) / (m + n) \quad (2)$$

where m and n are geometrical parameters illustrated in Figure 1; L_{eff} is the effective length as defined in the norm [5]; and

$$m_{pl} = f_y t_f^2 / 4 \gamma_{M0} \quad (3)$$

with f_y , the yield strength of the plate; t_f , the thickness of the flange; and γ_{M0} , a partial safety factor.

In absence of bolt failure, a second pair of plastic hinges forms near the bolt lines as shown in Figure 2b. Hence, the number of plastic hinges is sufficient to form a plastic mechanism within the T-stub flange which resistance can be evaluated as:

$$F_{rd,1, method 1} = 4m_{pl}L_{eff} / m \quad (4)$$

Lastly, it should be mentioned that EN1993-1-8:2024 [5] considered an additional failure mode. The latter occur when the bolt elongation is sufficient to cancel the contact between the T-stub and its support and so to prevent the developed of prying forces Q , see Figure 2a. Consequently, the static scheme becomes a cantilever beam which only requires two plastic hinges to form a plastic mechanism:

$$F_{rd,0} = 2m_{pl}L_{eff} / m \quad (5)$$

A formula is proposed in [5] to determine if contact is cancelled or not at yielding.

Finally, the expected failure mode to occur is the one of least resistance and should be computed as follows in absence of contact loss:

$$F_{rd} = \min (F_{rd,1}, F_{rd,2}, F_{rd,3}) \quad (6)$$

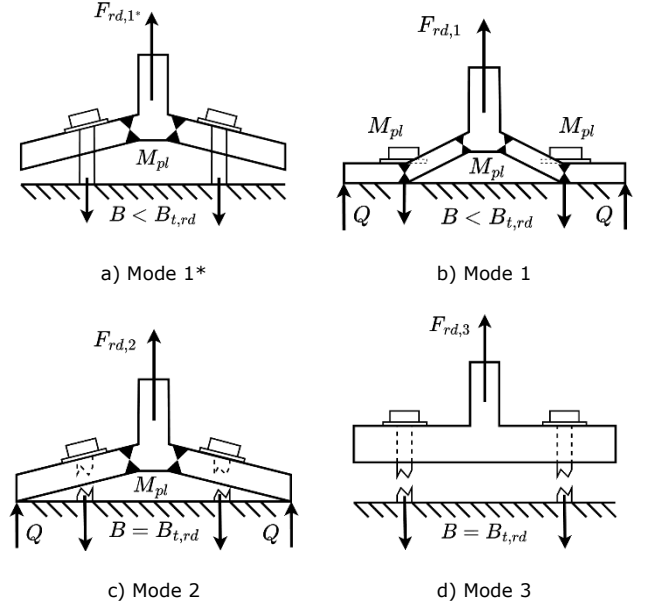


Figure 2 T-stub plastic failure modes

Whilst McGuire model is convenient for its simplicity, Mode 1 was proven to be conservative [6], [7]. Hence, by further refining the loads developing below the bolt head or washer when any, Jaspart [8] proposed an improved version of Eq (4) which can be expressed as follows. This model is also included in the norm as "method 2" [5], [9].

$$F_{rd,1, method 2} = (8n - 2e_w)m_{pl}L_{eff} / 2mn - e_w(m + n) \quad (7)$$

with $e_w = d_w/4$, the equivalent bolt load position.

Despite its improved accuracy, Eq.(7) is still conservative [6], [7]. Henceforth, a new model has been developed in [7] accounting for variable positions of the plastic hinges in the T-stub flange and a new bolt load distribution below the bolt head or washer. The new formulas are not provided here for concision's sake.

2.2 Actual configurations

Whilst Eq.(1) to (7) were developed for idealized T-stubs configurations, meaning that the plastic hinges consists of two straight lines, actual plastic patterns might differ. To cover these situations, Zoetemeijer [10] defined the concept of effective length expressing the plastic resistance equivalency between the actual yielding pattern and the idealized one. Additional patterns have later been characterized in [11] and [12].

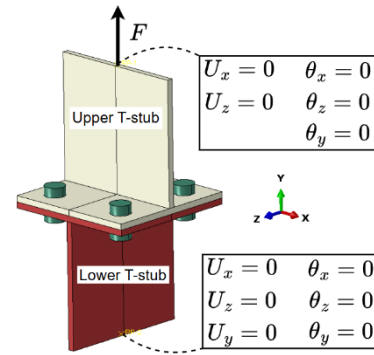
Nevertheless, concerns have been raised in [10] regarding the prying forces compatibility between two non-aligned T-stubs, see Figure 3. Since prying forces are usually assumed to be located at the tip of the flange as shown in Figure 1 and T-stubs computed independently from each other, models become statically incompatible. For such configuration, T-stub flange corners were identified as contact zone and, therefore, as the prying force's location. Besides, this example highlights the influence of the support on the prying force position. Nevertheless, even if this aspect was already raised in the past, this issued has never been addressed. Indeed, most recent and advanced

a) Compatible scheme

b) Incompatible scheme

To fill the so-identified gap of knowledge, parametric numerical studies have been conducted. The first one focuses on “classical” (see Figure 3a) parallel configuration so the influence of the T-stub flange thickness ratio $t_{f,up}/t_{f,lo}$ can be studied. Henceforth, perpendicular configurations representative of extended endplate and cleated connections (see Figure 3b) are investigated. Numerical modelling procedure summarised in Section 3 is used as a basis for the parametrical studies.

Due to the lack of experimental evidence, prospective numerical investigations are conducted on Abaqus. The procedure used to model both bolts and T-stubs has already been successfully validated several times against experiments [7], [16]-[18]. This procedure consists of implementing nominal elastic-perfectly plastic material laws for both S355 plates and 10.9HR bolts geometries detailed in Tables 1 & 2. It should be noted that the Young modulus is taken as 210 GPa. Besides, tangent contact is modelled with a 0.3 friction coefficient whilst a non-interpenetration is used in the normal direction. Loading is applied to the system by an imposed displacement at the tip of the web of the upper T-stub. Remaining degrees of freedom are blocked for this web whilst lower T-stub web is clamped as shown in Figure 4. Relative displacements between the T-stubs are measured from web toe to web toe. Simulations are conducted with a dynamic implicit scheme accounting for material and geometrical non-linearities. Lastly, C3D8R cubic elements are used for meshing. A minimum of 4 elements is used over the thickness of the plates to ensure that bending behaviour is correctly modelled [7], [18].



4.1 Parallel configurations

Table 1 Constant geometrical properties of the parallel configurations

t_w	15mm	e_i	45mm
h_f	12.5mm	f_y	355MPa
$n=e$	50mm	f_{ub}	1000MPa
L	90mm	Bolt M16 10.9 HR EN14339 [19]	

As an outcome, it was first observed that the plastic resistance of the T-stub is not impacted by a modification of the $t_{f,up}/t_{f,lo}$ ratio. This confirms the scope of application of EN1993-1-8:2024 [5] disregarding possible coupling effect between two adjacent T-stubs for the prediction of the T-stub plastic resistance. However, the $t_{f,up}/t_{f,lo}$ ratio has a notable impact on the post-yielding behaviour. In case of $t_{f,up}/t_{f,lo}$ ratio close or equal to 1, both T-stubs fail simultaneously by forming two pairs of plastic hinges for the considered T-stub configurations, inducing significant post-yielding deformations in both T-stubs for a limited increase of the applied load.

However, small $t_{f,up}/t_{f,lo}$ ratios corresponding to thick lower T-stub flange compared to the upper one prevent the apparition of yielding in the lower T-stub flange while the upper one exhibits a failure Mode 1. In the post-yielding phase, the lower T-stub remaining in the elastic range limits the deflection of the upper one, resulting in the development of membrane effect in the upper T-stub. This leads to a significant increase of the applied load to reach failure.

Lastly, in case of intermediate flange thickness ratios, two different responses can be observed. If a pair of plastic hinges has already formed in the lower T-stub in the vicinity of the web when a failure Mode 1 develops in the upper T-stub, a sufficient number of hinges is present in the system to reach a global plastic mechanism involving both T-stub (see Figure 6). Consequently, large deformation can be achieved without increasing significantly the applied load. However, this capacity of deformation implies large plastic rotation in both T-stub, which might be undesired in reusability context. This behaviour is particularly problematic as the lower T-stub fails for an applied load much lower than its plastic resistance predicted using the EN1993-1-8:2024 recommendations. In this situation, it can be observed that the lower T-stub exhibits a failure Mode 1* (Figure 2) even if the criterion imposing to consider this specific failure mode as proposed in the norm is not respected. Therefore, it can be concluded that T-stubs response cannot be predicted individually since it exists a coupling effect affecting each other.

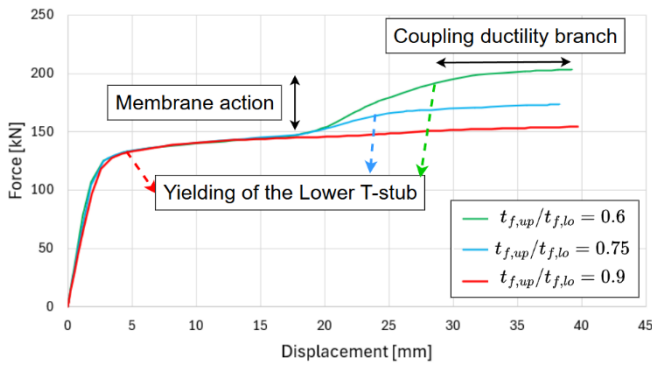


Figure 5 Influence of the base thickness on the coupling effect series T-16-0.2-1-XX [18]

Moreover, due to the mechanism shape, bolts mostly undergo rigid body motion (translation and rotation) when the global plastic mechanism is developed. Thus, for a limited increase of the bolt stress fields, large displacement can be attained. This system response is illustrated in Figure 5 and has been corroborated by experimental evidence in [20]. In the field of robustness, such response implying both membrane actions and large displacements is highly sought and can be a positive contribution to the global behaviour of structures in which joints exhibit such global failure mode.

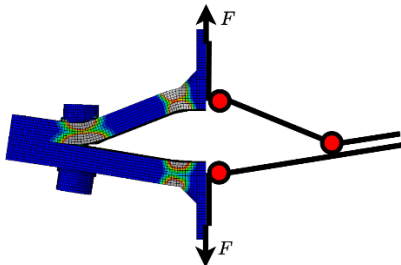


Figure 6 Parallel coupling effect: system plastic mechanism [18]

Consequently, if it is intended to meet both reusability and robustness objectives with such design configuration, the following design approach, in line with the proposal made in [20], could be contemplated:

1. For sake of reusability and robustness, design the upper T-stub, considered as fuse element as follows:

$$F_{rd,up} < F_{rd,lo,M. 1*} (eq. (7)) < F_{rd,lo,M. 3} (eq. (1)) \quad (8)$$

2. Adjust the resistance of the $F_{rd,lo,Mode 1*}$ in order to activate the global plastic mechanism at the good locations and moments in the framework of the design for robustness.

4.2 Perpendicular configurations

As a second step, configurations with T-stubs perpendicular to each other (see Figure 3b) have been studied. Similarly to the study reflected in the previous section, the numerical procedure detailed in Section 3 is used in pair with the properties listed in Table 2 hereafter.

Table 2 Geometrical properties of the perpendicular configurations

t_w	10mm	e_l	50mm
h_f	0mm	p	120mm
$n=e$	50mm	f_y	355MPa
m	55mm	f_{ub}	1000MPa
L	220mm	Bolt M24 10.9 HR EN14339 [19]	

where p is the bolt pitch.

While coupling effect is strictly limited to the post-yielding response for parallel configurations, this conclusion does not apply for perpendicular configurations. In Figure 7, it can be observed that modifying the T-stubs' relative direction causes a plastic resistance drop of 60kN for this specific case; it represents around 25% of difference between both plastic resistances. Moreover, such deviation is unaccounted by EN1993-1-8:2024 [5] which considered the behaviour of two adjacent T-stubs as uncoupled.

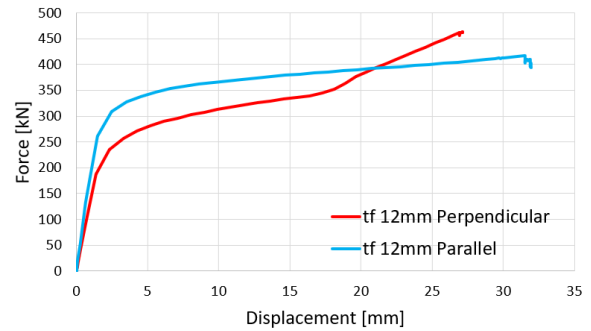


Figure 7 Perpendicular VS parallel configuration

For the conducted parametric study, the magnitude of the deviation is similar to the conservativeness achieved by current normative design rules [6] and [7], meaning that EN1993-1-8:2024 resistance predictions do not fall in the unsafe side. Nevertheless, normative codes should not rely on error compensation and deep understanding of the real connection behaviour is required.

First, as suggested by Zoetemeijer [10], prying forces cannot be modelled as line loads along the flange's free edges

due to compatibility of displacement. Contact zones between perpendicular T-stubs are instead concentrated in the corners. Consequently, a new plastic mechanism may occur as shown in Figure 8, depending on the relative stiffness of the two connected T-stubs.

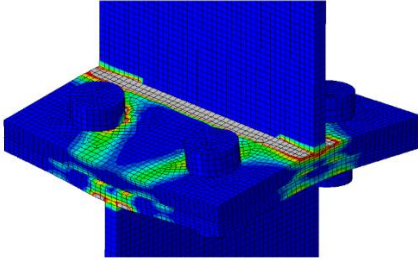


Figure 8 Perpendicular coupling effect: system plastic mechanism

In order to investigate this new mechanism, several simulations modifying the thickness of the lower T-stub flange while keeping the upper one as equal to 12mm were conducted. Results, shown in Figure 9, highlight a correlation between the T-stub thickness ratio and the achieved system plastic resistance. When the $t_{f,up}/t_{f,lo}$ ratio is low, i.e. when $t_{f,lo}$ is thick in comparison to $t_{f,up}$, the prying forces are located as classically assumed, leading to the formation of an idealized beam plastic pattern (see Figure 2b). The plastic resistance is hence unaffected and is equivalent to a parallel configuration. However, increasing the ratio (i.e. reducing $t_{f,lo}$) results in an increase of the lower T-stub flexibility causing the prying forces to be gradually shifted toward the flange corners. This migration of the prying forces is also paired with a modification of the plastic pattern from the aforementioned idealized beam mechanism to the plastic mechanism illustrated in Figure 8. Consequently, a reduction of the plastic resistance is observed even if the properties of the “weaker” upper T-stub are kept constant. As in the previous Section, this observation can be assimilated to a coupling effect.

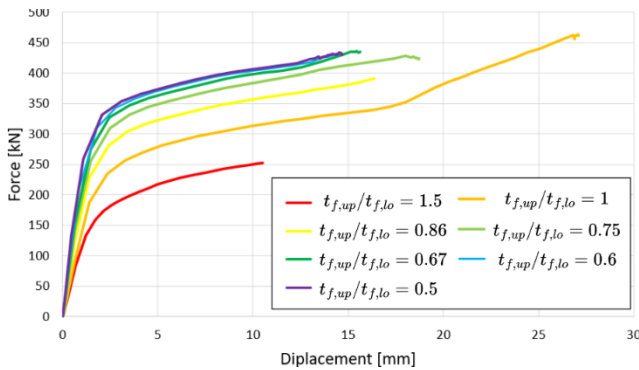


Figure 9 Impact of the base thickness on system response

Unfortunately, such an outcome is critical for reusability since it requires to strengthen the T-stub to be protected (element to be reused) to prevent the development of such coupling and therefore, of remanent plastic deformation in the latter. However, T-stub to be protected are generally associated to the component “column flange in bending” for sake of reusability of the column member. So, increasing the resistance of this local joint component would require to increase the column cross-section or steel grade which is not relevant from an ecological and economical point of view. So, a more efficient solution should nonetheless be proposed to tackle this issue. Since the

coupling effect is induced by an excess of flexibility in regions where prying forces are expected to take place, a rudimentary and yet both economic and efficient solution consists of placing a thick backing plate (BP) between both T-stubs. Thus, due to the high stiffness of the BP, prying forces as assumed by the EN1993-1-8:2024 [5] can develop in the T-stubs (Figure 3b). Figure 10 illustrates the proposed solution efficiency by comparing a parallel configuration to perpendicular ones with and without backing plate (all other parameters remaining constant). Adding the backing plate allows to reach back the plastic resistance of the parallel configuration, meaning that the uncoupling is effective. In this example, T-stubs are 12mm thick while the backing plate is 20mm thick. T-stub displacements are measured web-to-backing plate.

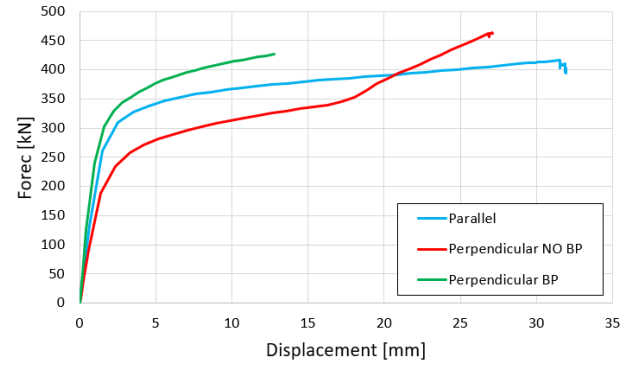


Figure 10 Coupled VS uncoupled system response for short T-stubs

Last but not least, similar simulations were performed with a 600mm long lower T-stub while keeping the upper T-stub length as reflected in Table 2. Results presented in Figure 11 show similar tendencies. Comparing parallel (in blue) and the unprotected perpendicular one (in red), significant loss of resistance can be observed at yielding for both short and long T-stubs. Besides, uncoupled response identical to the parallel one can be obtained by using a backing plate (green curves). Hence, individual resistances as predicted by EN1993-1-8:2024 [5] can be reached for both elements.

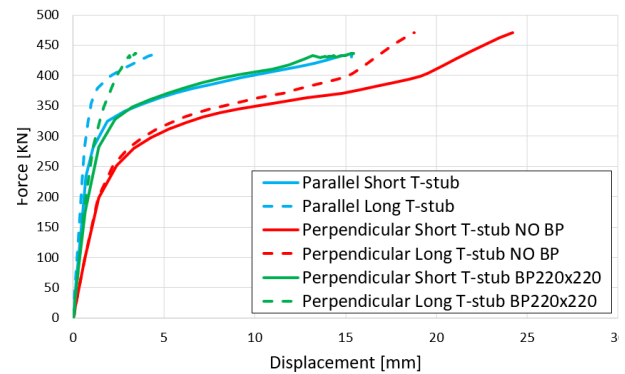


Figure 11 Coupled VS uncoupled system response for short and long T-stubs

5 Insights & perspectives

As shown in Section 4.1, a coupling effect may develop between two T-stubs connected in parallel. Even if this coupling effect does not impact the plastic resistance of the connected T-stubs and, consequently, EN1993-1-8:2024 validity, it may strongly influence the post-yielding

behaviour leading to a premature failure of the stronger connected T-stub. In Section 4.2, a new plastic pattern has been identified in T-stub flanges in perpendicular T-stub configurations, T-stub configuration met for instance in joints with extended end-plates or with cleats. The development of this new pattern is not at all covered by EN1993-1-8:2024, which could lead to an overestimation of the T-stub resistance. Therefore, this effect should be further investigated and codified.

Moreover, in the framework of reusability, coupling effects should be mastered to avoid apparition of premature plasticity and associated remanent deformations in the structural elements to be protected. This can be achieved through the proposal of reliable design procedures or through technical solutions preventing the apparition of these coupling effects as suggested in the present paper.

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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] 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.
- [4] Douty, R. T.; McGuire, W. (1965) *High strength bolted moment connections*. Journal of the Structural Division, Vol. 91, No. 2, pp 101-128.
- [5] EN 1993-1-8 (2024). *Eurocode 3: Design of steel structures – Part 1-8: Design of joints*. Brussels.
- [6] Girao, A. (2004) *Characterisation of the ductility of bolted end plate beam-to-column steel connections* [PhD thesis]. University of Coimbra.
- [7] Neutelers, A. (2023) *Improvement of the mechanical model for mode 1 T-stub plastic strength* [Master thesis]. University of Liege.
- [8] Jaspart, J.-P. (1997) *Recent advances in the field of steel joints – Column bases and further configurations for beam-to-column joints and beam splices* [Aggregation thesis]. University of Liege.
- [9] Jaspart, J.-P.; Weynand, K. (2016) *Design of steel joints and composite structures*. Ernst & Sohn.
- [10] Zoetemeijer, P. (1974) *Design method for the tension side of statically loaded, bolted beam-to-column connections*. Heron, Vol. 94, No. 1.
- [11] Packers, J. A.; Morris, L. J. (1977) *A limit design method for the tension region of bolted beam-column connections*. The Structural Engineering, Vol. 5, No. 10, pp. 446-458.
- [12] Mann, A. P.; Morris, L. J. (1979) *Limit design of extended end-plate connections*. Journal of the Structural Division, Vol. 105, No. 3, pp. 511-526.
- [13] Couchaux, M.; Hjiat, M.; Ryan, I.; et al. (2017) *Effect of contact on the elastic behaviour of tensile bolted connections*. Journal of Constructional Steel Research, Vol. 133, pp. 459-474.
- [14] Couchaux, M.; Hjiat, M.; Ryan, I.; et al. (2017) *Tensile resistance of L-stubs*. Journal of Constructional Steel Research, Vol. 138, pp. 131-149.
- [15] Girao, A.; Bijlaard, F. Sk.; Gresnigt, N.; et al. (2004) *Experimental assessment of the behaviour of bolted T-stub connections made up of welded plates*. Journal of Constructional Steel Research, Vol 60., No. 2, pp. 269-311.
- [16] Neutelers, A.; Corman, A.; Demonceau, J.-F. (2024) *Experimental and numerical investigation of T-stub plastic resistance*. Proceedings of the Nordic Steel 2024.
- [17] Demonceau, J.-F.; Duchêne, L., Neutelers, A., Vermeylen, M.; et al. (2025) *High-Strength Steel connections for circular construction (Connect4C) – Deliverable D4.1*. Project No. 101112300.
- [18] Gillieaux, M. (2025) *Steel joint ductility – Coupling and membrane effects in adjacent T-stubs* [Master thesis]. University of Liege.
- [19] BS EN 14399-10:2009 (2009) *High-strength structural bolting assemblies for preloading Part 10: System HRC – Bolt and nut assemblies with calibrated preload*. London.
- [20] Faralli, A. C., Latour, M.; Tan, P. J.; et al. (2021) *Experimental investigation and modelling of T-stubs undergoing large displacements*. Journal of Constructional Steel Research, Vol. 180, pp. 106580.