

Full paper

Experimental and numerical investigations on the T-stub component made of S690 & S960 steel grades

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**Abstract**

In the framework of a RFCS European project entitled Connect4C aiming at developing demountable and adaptable joint solutions to enhance the reuse of steel structural members, several experimental campaigns assessing the behaviour of joint components made of High-Strength Steel were conducted. In particular, within this project, T-stub components made of S690 and S960 steel grades have been analytically, numerically and experimentally studied with the objectives of (i) investigating the accuracy of the existing design rules as proposed in EN1993-1-8 and, if required, (ii) to adapt to latter to allow for the characterisation of T-stubs made of such high strength steel grades.

The paper presents the so-conducted investigations. After a review of the current design codes and latest research models predicting the resistance of T-stub components, a detailed description of the performed experimental tests and of the associated results is proposed. Then, the laboratory tests are reproduced in Abaqus and validated against the experiment evidence. Afterwards, an extensive parametrical study is conducted to investigate the influence of key parameters on the T-stub behaviour. Finally, the so-obtained results are compared to analytical predictions obtained using the EN1993-1-8 recommendations.

Keywords

Laboratory tests, T-stub, High-Strength Steel, Joint, Component, Eurocode, reusability

1 Introduction

Recently, climate changes raised concerns about carbon emissions and more specifically on how reducing them. In particular, legislations were adopted in the construction sector as a major emitter. Consequently, as part of the Green Deal [1], new construction should reach carbon neutrality by 2050. To help the industry in this green turnover, RFCS funded projects such as Reduce [2] and Connect4C [3]-[4] addressed this issue by enhancing the reusability of structural elements through concepts of innovative dismountable adaptive joints [5]-[6] which may act as fuse elements in case of overloading.

However, maintaining mechanical efficiency whilst designing joints to prevent apparition of plasticity in some key components might be challenging. Henceforth, in the framework of Connect4C, the use of High-Strength Steel (HSS) up to S690 and S960 locally in the connection is contemplated for sake of local strengthening. However, EN1993-1-8:2024 [7] do not cover such steel grades and limited related knowledge is available in the literature.

Thus, several experimental campaigns testing components made of S690 and S960 have been conducted in the framework of Connect4C. Whilst all components are covered in [8], this paper focuses more specifically on the equivalent T-stub component modelling the tension zone of connections as shown in Figure 1. In particular, T-stubs with 2 and 4 bolts per row will be considered.

Within the present paper, the results of the 18 performed tests as well as the first conducted numerical investigation are summarised. More information can be found in [8].

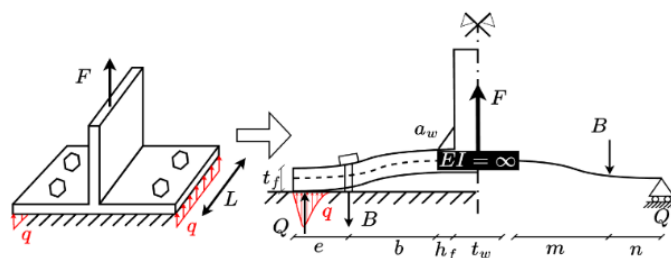


Figure 1 Equivalent T-stub model

2 Review of existing analytical models for T-stub with 2 bolts per row

Since the main objective of this study is to assess the validity of current design rules as proposed in EN1993-1-8:2024 [7], models presented hereafter focus on the predicting of both the plastic resistance and the initial stiffness for the tested bolting configurations with two and four bolts.

2.1 Plastic resistance

Initially, T-stubs were modelled by McGuire [9] as a simply supported beam of total length $2(m+n)$, loaded punctually by the bolts at bolt lines and at mid-span by its web as illustrated in Figure 1. From this model, still included in EN1993-1-8:2024 [7], three failure modes were identified and characterized. The first one, called Mode 3, is achieved when the axial bearing capacity of the bolts is exceeded (cf Figure 2c). This brittle failure can be expressed as:

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

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

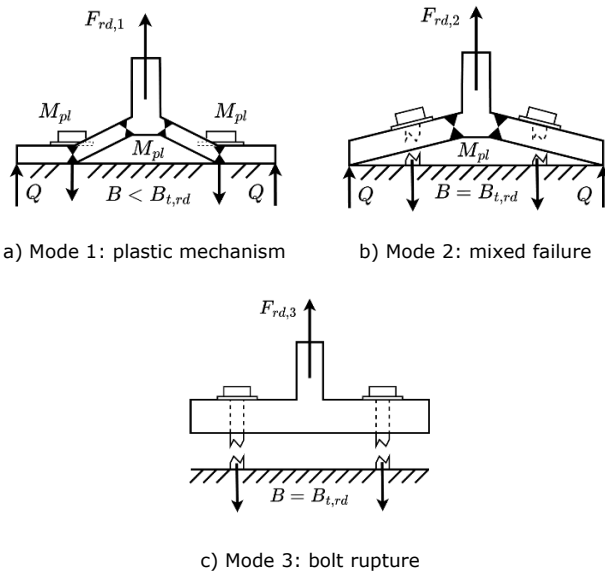


Figure 2 T-stub failure modes

Alternatively, once a pair of plastic hinges is formed in the vicinity of the web root radius, another bolt failure may be caused by the lever arm created with the prying forces Q . This failure of intermediate ductility depicted in Figure 2b is stated as Mode 2 and can be computed as:

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

with n and m , geometrical properties shown in Figure 1; L_{eff} , the effective length as defined by EN1993-1-8:2024 [7]; and

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

where t_f is the thickness of the T-stub flange; f_y is the yield strength of the T-stub flange; and γ_{M0} is a partial factor.

Lastly, a full plastic mechanism within the T-stub flange may develop prior to the failure of the bolts. This ductile failure mode is illustrated in Figure 2a, is identified as Mode 1 and can be computed as:

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

This equation called "Method 1" has been derived from the static scheme shown in Figure 1 modelling the bolts as punctual loads. As this proposition was proved to be too conservative [10]-[12], a refined model assuming a uniformly distributed load below the bolt head or washer was proposed in [13] and is yet included in EN1993-1-8:2024 as "Method 2" [7], [14]. The associated resistance can be assessed as follows:

$$F_{rd,1, method 2} = (8n - 2e_w)m_{pl}L_{eff} / (2mn - e_w(m + n)) \quad (5)$$

where e_w is taken as equal to a quarter of the washer or bolt head diameter.

Nevertheless, despite its improved accuracy, this second Method has also been proved to be conservative [10], [11]. Accordingly, another modelling of the load distribution below the bolt head or washer paired with an improved m assessment to better account for the yielding line localisations was proposed by Neuteler in [10]. This model is not presented herein for sake of concision but is nonetheless considered in following sections. Besides, independently of the formula used to compute Mode 1, the T-stub resistance is assumed to be equal to the minimum of the resistance of the three possible failure mode:

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

2.2 Initial stiffness

As a starting point to predict the stiffness, several authors [15]-[17] used the classical beam theory to predict the deflection considering the static scheme proposed by McGuire (cf. Figure 1). Despite their accuracy, these models were deemed too complex for everyday use. Therefore, a simplified model uncoupling the bolt deformation from the plate one was proposed by Jaspart [13] for inclusion in EN1993-1-8:2024 [7]. Expressions assessing both plate ($K_{p,init,Jaspart}$) and bolt ($K_{b,init}$) stiffness are:

$$K_{p,init,Jaspart} = \frac{0.85L_{eff}t_f^3}{m^3} E \quad (7)$$

$$K_{b,init} = \frac{1.6A_s E}{L_b} \quad (8)$$

where E is the steel Young's modulus taken as equal to 210 GPa.

Aforementioned expressions can then be assembled following the same philosophy as the component Method [14]. For a configuration where two T-stubs are connected, the T-stub initial stiffness $K_{j,init}$ can be written as:

$$K_{j,init} = \frac{1}{K_{p,init}^{-1} + K_{b,init}^{-1} + K_{p,init}^{-1}} \quad (9)$$

2.3 Analytical model for T-stubs with 4 bolts per row

Despite commonly used in several countries, T-stub configuration with four bolts per row are not yet included in EN1993-1-8:2024 [7]. Some models are however available in literature. In particular, Demonceau proposed characterization models in [18], validated in [19]. The increased number of bolts does not modify completely the system behaviour. Hence, both Mode 3 and Mode 1 related to the failure of the bolts and the development of a plastic mechanism respectively can still be computed using Eqs.(1) and (5). It should nonetheless be noted that appropriate effective length defined in [18] should be used in these models. Regarding Mode 2, two cases can be identified depending on the position of the prying forces. If the latter are located between the inner bolts (i.e. the bolts close to the web) and the outer bolts (i.e. the bolts far from the web), then Eq.(2) can be used with appropriate prying force positions (see [18]). Otherwise, the outer bolts line is activated and contributes to the plastic resistance as outlined in the following expression:

$$F_{rd,2,p} = \frac{2m_{pl}L_{eff} + \frac{\sum B_{trd}}{2} \left(\frac{n_1^2 + 2n_1n_2 + 2n_2^2}{n_1 + n_2} \right)}{m + n_1 + n_2} \quad (10)$$

with n_1 and n_2 prying lever arms as defined in [18].

Lastly, the initial stiffness can be predicted using Eq.(9) but accounting twice the bolts contribution.

3 Experimental campaign

3.1 Specimens and setup

In the framework of Connect4C, 18 tests have been performed, investigating different plates thicknesses (10 & 15mm), steel grades (S690 & S960) and bolting configurations: 1R2C, T-stubs with one row of two bolts; 2R2C, T-stubs with two rows of two bolts; and 1R4C, T-stubs with one row of four bolts. Henceforth, specimens are named as "Configuration - t_f - Steel grade (- BIS)" where the BIS denomination stands for S690 specimens which have been produced twice. Remaining geometrical properties (see Figure 3) are summarized in Table 1, while the actual material properties are reported in Table 2.

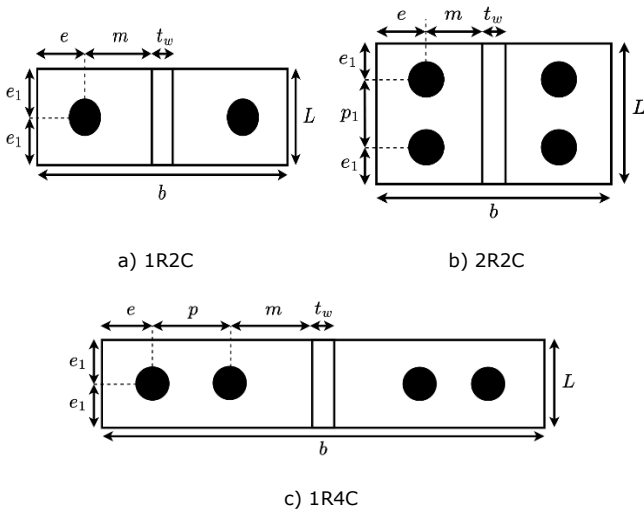


Figure 3 Configurations geometrical properties

Table 1 Specimens geometrical properties

	1R2C	2R2C	1R4C
b [mm]	70	50	60
e [mm]	60	40	60
L [mm]	80	120	80
t_w [mm]	15	15	15
p [mm]	/	/	60
e_1 [mm]	40	40	40
p_1 [mm]	/	40	/

Due to its high variability, weld throats are not reported herein for sake of concision but is nonetheless reported in [8]. Besides, for each specimen, EN14339 M16 10.9 HR bolts **Erreur ! Source du renvoi introuvable.** were used.

Table 2 Material properties

	t_f [mm]	f_y [MPa]	f_u [MPa]	ε_u [%]
S690	10	784.67	842.48	6.12
S690	15	762.07	814.33	7.07
S690-BIS	10	795.62	843.18	6.34
S690-BIS	15	804.11	842.75	5.73
S960	10	1047.89	1079.42	4.59
S960	15	1044.12	1081.16	4.14
M16 HR	/	1017	1113	0.07

As shown in Figure 4 hereafter, flange opening has been monitored during the tests by a pair of LVDT transducers. In addition, another LVDT transducer has been installed on the hydraulic jack to measure accurately the imposed displacement and overall system deformation, including the webs elongation.

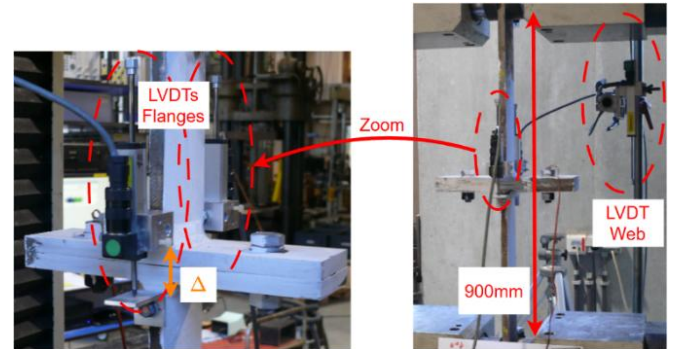


Figure 4 Test setup

3.2 Test results

As an outcome of the tests, most relevant properties, i.e. the initial stiffness $K_{j,init}$, the plastic resistance F_{pl} (as defined by EN1993-1-8:2024 [7]), the resistance at failure F_u and the maximum displacement Δ_u were characterised and reported in Table 3. The plastic resistance F_{pl} was associated with failure mode 1 or failure mode 2, as expected through the specimen design. The failure mode observed at F_u were associated to a failure of a bolt, except for some S960 specimens for which cracks developed in the weld toe, exclusively in S960 specimens. Furthermore, sufficient plastic deformation appeared in all specimens allowing plastic redistribution within joint whilst some specimens showed high reserve of ductility up to a maximum of 51.7mm flange opening (cf Figure 5).



Figure 5 1R2C-10-690-BIS specimen at failure

Table 3 Test results

Specimen	$K_{j,init}$ [kN/mm]	F_{pl} [kN]	F_u [kN]	Δ_u [mm]
1R2C-10-690	25.94	113.22	141.14	39.8
1R2C-10-690-BIS	22.62	110.29	128.6	51.7
1R2C-15-690	56.31	199.15	230	10.2
1R2C-15-690-BIS	57.52	193.67	214.65	10.2
1R2C-10-960	24.37	131.97	150.61	15.1
1R2C-15-960	60.89	215.96	243.5	7.5
2R2C-10-690	84.04	230.15	302.09	24.7
2R2C-10-690-BIS	72.21	219.86	261.51	15.7
2R2C-15-690	168.41	397.19	457.26	7.6
2R2C-15-690-BIS	163.69	385.97	440.12	7
2R2C-10-960	79.05	259.6	309.6	9.3
2R2C-15-960	172.19	425.81	480.07	6.6
1R4C-10-690	36.9	139.78	165.14	30.3
1R4C-10-690-BIS	31.72	132.1	156.01	35.4
1R4C-15-690	76.49	223.96	266.62	10.2
1R4C-15-690-BIS	74.77	237.27	266.68	10.2
1R4C-10-960	33.58	153.74	171.43	19.1
1R4C-15-960	78.88	240.24	287.23	8.4

with F_{pl} the intersection of the elastic and the hardening responses [7].

Nevertheless, despite achieving the expected designed failure modes, failure mode 1 analytical resistance predicted according to EN1993-1-8:2024 [7] has been proved to be conservative when compared to experimental results, as already observed for mild steel [10], [11]. In particular, Method 1, i.e. Eq (4), is the most conservative, with an underestimation of around 30%, while this value drops to 20% for Method 2 (Eq.(5)). Moreover, a more advanced model as presented by Neutellers in [10] leads to more accurate predictions as depicted in Figure 6. However, the latter model is identified as unsafe for some specimens; according to the experimental observations, for these specimens, significant M-N interactions developed within the bolts while this interaction is not yet accounted for in the different analytical models. This constitutes a perspective of improvement of the proposed advanced model.

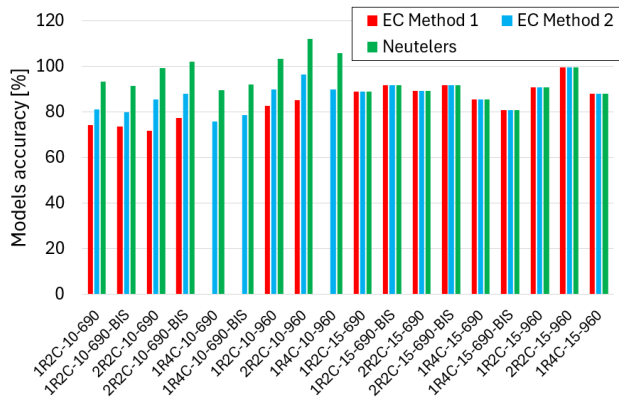


Figure 6 Analytical predictions VS experimental results

4 Numerical simulations

Whilst results presented in the previous Section seem promising for extending the current EN1993-1-8:2024 [7] T-stub design rules to HSS, more study cases are required to assess the reliability of such conclusions. Henceforth, current database has been extended numerically using Abaqus as described hereafter.

4.1 Modelling procedure

The followed modelling procedure to reproduce the experiments through Abaqus software has been developed in [10] and validated against different campaigns [21]-**Erreur ! Source du renvoi introuvable.** emphasizing its reliability. Thus, geometrical properties of Table 1 have been reproduced in Abaqus and the actual material mechanical properties (Table 2) obtained from coupon tests [8] with damage have been implemented as detailed in [23]. Also, normal contacts are modelled with a "hard contact" condition preventing element interpenetration while tangential contact behaviour is modelled considering a 0.3 friction coefficient. The setup boundary conditions were reproduced by restraining all the degrees of freedom of the lower T-stub web edge. Similar conditions have been applied to the other T-stub web extremity except along the web axis perpendicular to the flange as a displacement is imposed in this direction. The simulation is conducted with a dynamic implicit procedure accounting for geometrical and material non-linearities. Besides, a minimum of four C3D8R cubic elements with reduced integration were used over plates thickness to ensure proper convergence. As illustrated on Figure 7, satisfying results were obtained, except at failure. Indeed, it appears that the implemented initiation damage criterion [23] is inadequate to reproduce the bolt rupture and a more complex one should be used [24]. However, as the objective within the present study is to investigate the behaviour of T-stubs in terms of stiffness and plastic resistance, properties which are appropriately reproduced numerically, no further investigation on this aspect has been conducted at this stage.

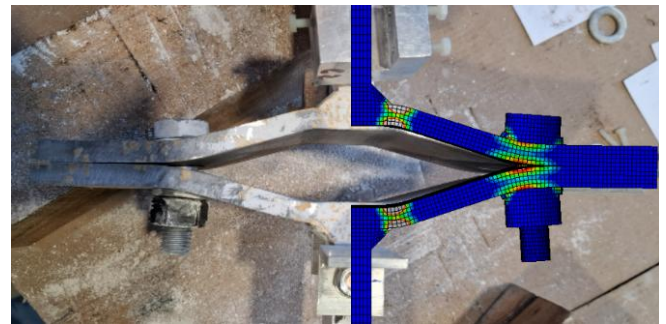


Figure 7 1R2C-10-690 validation

4.2 Parametrical study

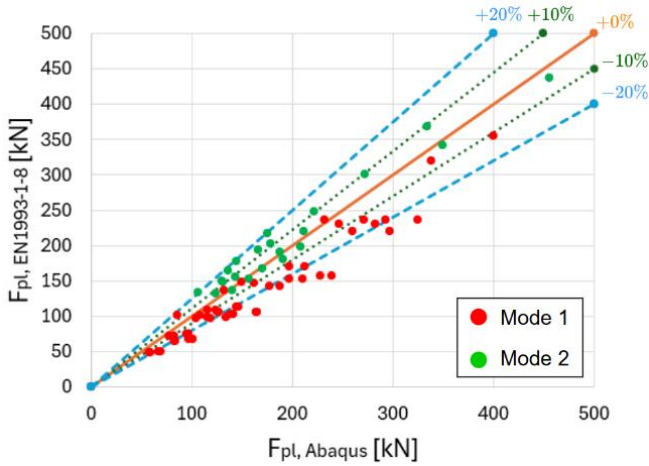
Based on the so-validated numerical modelling procedure, an extended set of 216 specimens has been produced. The latter is composed of 72 specimens with two bolts (1R2C) and 144 configurations with four bolts (1R4C). These simulations cover each combination of the following parameters detailed in Table 4 and are named according to the following nomenclature: "Configuration - t_f - m - (p) - d_b - f_{ub} ".

Table 4 Parametrical set

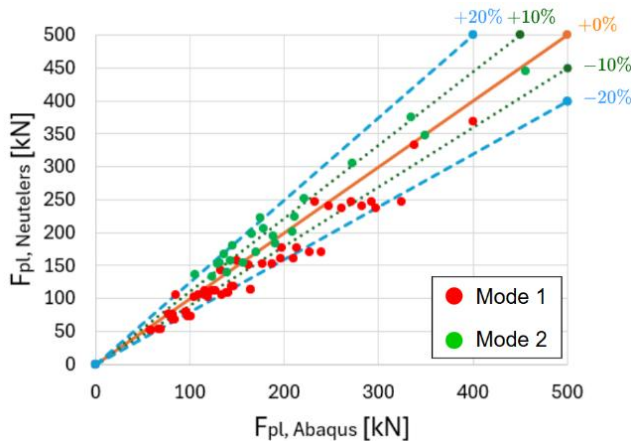
t_f [mm]	10; 15	m [mm]	50; 75; 100
p [mm]	50; 75; 100	d_b [mm]	16; 24
f_{ub}	8.8; 10.9		

NB: other parameters are unchanged and kept constant.

In Figure 8, comparisons between the plastic resistances obtained numerically (as defined by the norm [7]) and analytical predictions of existing models are proposed. Preliminary conclusions drawn in Section 3.2 are confirmed for Mode 1. Hence, EN1993-1-8:2024 Method 2 predictions are in average 9.6% conservative. Discomposing this value as a function of the failure mode leads to a mean underestimation of 17.7% for Mode 1 whilst Mode 2 are surprisingly overestimated by 8.3%. Besides, the standard deviations are 10.9% and 10.2% respectively for Modes 1 and 2. Henceforth, despite its conservatism, the model for mode 1 is likely to be considered as reliable according to EN 1990: 2023 [26] while mode 2 requires more investigations. Further simulations are nonetheless required to confirm this outcome. On the other hand, Neutellers model [10] shows a better accuracy of -6.2% in average. Dissociating Mode 1 from Mode 2 gives accuracies of -13.5% and +10.16% respectively. Whilst standard deviations keep the same order of magnitude (10.9% and 10.5% for Mode 1 and 2), some predictions fall unconservative. Thus, the model should be refined by further improving the prediction of the bolt resistance as previously addressed.



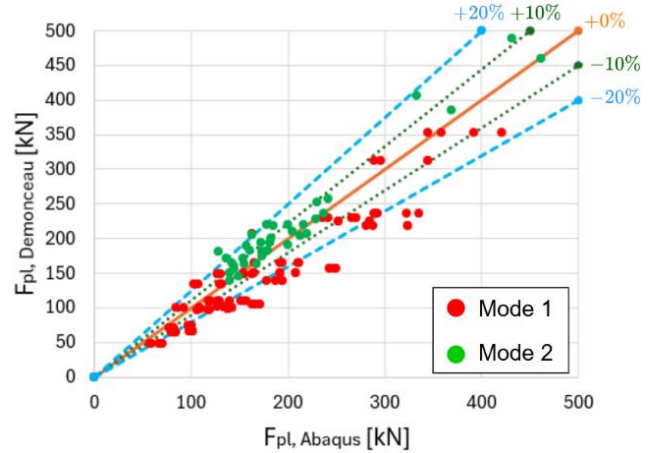
a) EN1993-1-8:2024 Method 2 model



b) Neutellers model

Figure 8 Accuracy of existing model predicting F_{pl}

Lastly, conclusions drawn for configuration with four bolts are identical to configuration with two bolts as illustrated in Figure 9. This can be explained by the fact that the outer bolt row is never activated. This is straightforward in case of Mode 1 whilst, for Mode 2, it means that the prying forces are always located between the outer and inner bolts, making the presence of the two additional bolts useless in terms of tensile resistance. Additional studies are required to better identify when the outer bolts are activated or not.

**Figure 9** Demonceau model accuracy predicting plastic resistance of T-stub with 4 bolts per row

5 Conclusions and perspectives

In this paper, results of 18 experimental tests conducted on T-stubs made of S690 and S960 were presented. Comparing the analytical predictions obtained using the EN1993-1-8:2024 model [7] to the experiment results highlighted the conservativeness of current models, as already observed for mild steel. These observations are corroborated by the conducted numerical parametrical study. So, an extension of EN1993-1-8:2024 [7] from mild steel to HSS can be contemplated, but further improvements could be considered, in particular for the prediction of failure Mode 1 resistance to increase its accuracy. As shown in both Sections 3.2 and 4.2, model presented in [10] exhibits a better accuracy due to its improved modelling of the load distribution below the bolt head or washer and a better prediction of the plastic hinge locations, i.e. m parameter. However, the latter model may predict unsafe results when significant M-N interactions develop within the bolts. Accordingly, the model should be further improved to account of the effect of this M-N interaction on the T-stub behaviour.

Finally, results obtained for T-stub configuration with four bolts per row show that the outer bolts are in practise rarely activated, at least for the considered T-stub geometries. Further simulations are required to confirm this observation.

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