

PLASTIC CAPACITY OF END-PLATE AND FLANGE CLEATED CONNECTIONS-PREDICTION AND DESIGN RULES

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Abstract

A refined evaluation of the plastic capacity of the tensile zone in end-plate and flange cleated connections is presented. Compared to experimental results, it provides a better accuracy than existing methods.

1. INTRODUCTION

Beam-to-column joint using end-plate or cleated connections with no stiffening of the column web is very economical. Generally, such a joint has a semi-rigid behaviour and is partially resistant. The prediction of its non-linear response, in terms of beam end moment M_b - relative rotation ϕ , is especially of concern. Amongst the parameters governing the idealized $M_b - \phi$ response of the connection properly, the plastic capacity M_y plays a paramount role ; its determination is the subject of present paper. The space allocated to the paper prevents from developing in detail the theoretical aspects, for which the reader is begged to refer to (Jaspart, 1991). Only the basic ideas are presented and discussed herewith, as well as comparisons between theoretical predictions and experimental data.

A knowledge of the Annex J of EC3 (Eurocode 3, 1990) and its background would be very helpful to fully understand what follows.

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2. PLASTIC CAPACITY OF AN EXTENDED END-PLATE CONNECTION

2.1. General

The theoretical plastic capacity $M_{v, th}$ of a connection should basically be defined as the maximum bending moment developed by a connection made with a material which exhibits an elastic-perfectly plastic stress-strain diagram ; thus strain-hardening would be fully disregarded. To identify such a capacity on an experimentally recorded $M_b - \phi$ curve is neither obvious nor easy because of unavoidable strain-hardening effects. How to define the experimental plastic capacity is discussed elsewhere (Jaspart, 1991) ; within present paper, it is given as shown in figure 1.

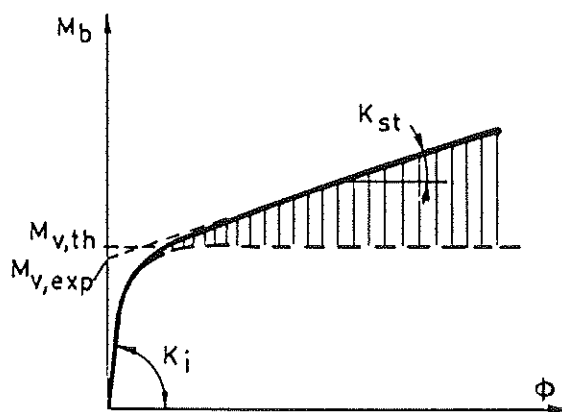


Figure 1

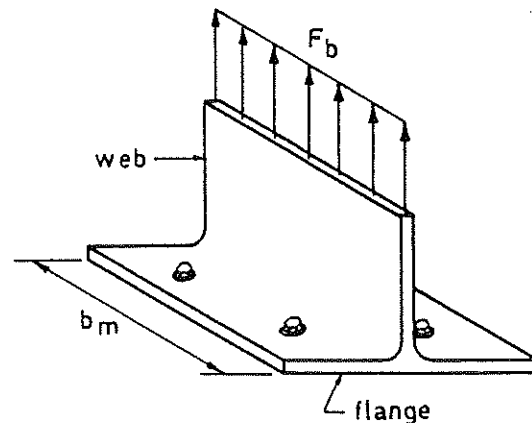


Figure 2

Usually, the bending moment at the beam end is substituted by a pair of statically equivalent tensile and compressive forces F_b in the connection. Thus the strength of a connection corresponds to the onset of a limiting design resistant force $F_{b,Rd}$ in the flanges. The resistance of a connection can be exhausted when any of all the possible local collapse modes takes place, either in the tensile or compression zone. Because it is deeply desired that the connection be prevented from a brittle mode of collapse, fracture of the fillet welds can never be governing. In addition, the resistance of the column web to load introduction, either in tension or in compression, is a specific problem which is solved elsewhere (Jaspart, 1991). Consequently, it remains to look at the resistance of an end-plate connection in the tensile zone which may be associated to the collapse either : i) of the bolts, or ii) of the end-plate, or iii) of

the column flange. The two last collapse modes involve plate components subject to transverse loads : both can similarly be analysed suitably based on some idealization of the connection part. Several attempts have been made in this respect ; they are relative to one of the two general approaches termed respectively "plate model" and "T-stub model" ; both allow for predicting the aforementioned limiting force $F_{b,Rd}$ when either the column flange, or the end-plate is of concern.

Model	Column flange	End-plate	Both
Plate	Packer-Morris Zoetemeijer	Wittaker-Walpole Zanon Surtees-Mann Zoetemeijer	Zoetemeijer EC3 Packer-Morris
T-stub	Zoetemeijer EC3	Zoetemeijer Packer-Morris Kato-McGuire Agerskov EC3	

Table 1

Experimental results have been compared with the theoretical values computed according to the methods listed in Table 1 (see § 2.3). It has been found that EC3 method, based on the T-stub model, is quite valuable. The T-stub idealization consists in reducing the tensile part of the connection to T-stub sections of appropriate equivalent length b_m , connected by their flange onto a presumably infinitely rigid foundation (presumably by 4 bolts) and subject to a uniformly distributed force acting in the web plane (fig. 2).

Though based on rather simple expressions, EC 3 method is widely applicable. It is barely - but then very slightly - unconservative. Its accuracy, which can vary largely and look like too conservative, is dependent on the collapse mode of the T-stub. The latter can be due to (fig.3) :

- a) bolt fracture with no prying forces, as a result of a very large stiffness of the T-stub flange, or
- b) onset of a yield lines mechanism in the T-stub before the strength of the bolts be exhausted, or
- c) mixed collapse involving yield lines at the toe of the fillets in the T-stub and exhaustion of the bolt strength.

The accuracy is found especially satisfactory when the plastic capacity is governed by collapse mode (a) or (c) ; EC3 is found much too safe when a plastic mechanism forms in the T-stub. Similar conclusions can be drawn from the tests on flush end-plate connections (Moore, 1988).

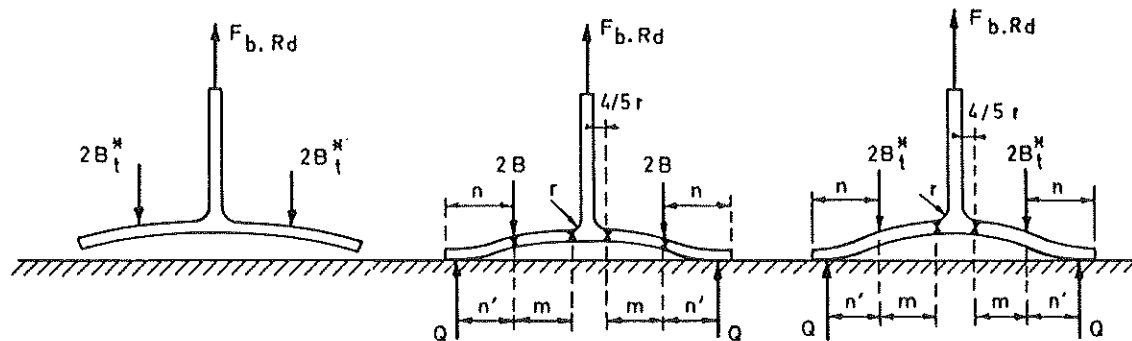


Figure 3

2.2. Amendments to the T-stub model of EC3.

The question raises whether refinements could be brought to the T-stub model of EC3 with the result that the amended model would provide a higher resistance for above collapse mode (b) without altering significantly the accuracy regarding both collapse modes (a) and (c).

An attempt in this respect has been made recently by the junior author (Jaspart, 1991). In all the existing methods, it shall be noticed that the forces in the bolts are always idealized as point loads. Thus, it is never explicitly accounted for the actual sizes of bolts and washers, on the one hand, and on the degree of bolt preloading, on the other hand. Care taken of the both aspects should influence first, the location of some of the yield lines forming the plastic mechanism, and second, the contribution of the external loads to the virtual work relative to this mechanism.

In the T-stub model, the plastic mechanism is composed of parallel straight yield lines which develop in the flange of the T section. Two of them are always located at the toe of the fillets. The two others are located in the vicinity of the bolt rows. Either they coincide with the axes of the bolt rows (Zoetemeijer, 1974; Eurocode 3, 1990) ; that means the bolt size is fully disregarded and the load is applied on the axis of the bolts (fig. 4.a). On the contrary, bolts and washers are assumed so stiff that the yield lines are forced to develop at the inner extremity of the bolt/washer diameter (Kishi et al, 1987), where the bolt load is also assumed to be applied (fig. 4.c). None of these models is in very fair agreement with experimental observations. Indeed the lines of maximum curvature are actually not straight but slightly curled and their pattern in the close vicinity of the bolts is found to depend on the stiffness of bolts and on the degree of bolt preloading (fig. 4.b). For practice purposes, one cannot imagine to account for such a complex actual pattern. It must be noticed that, for well proportioned connections, the yield lines are not far from complying with Zoetemeijer's assumption ; it is therefore justified to refer to the latter for what regards the location of the yield lines.

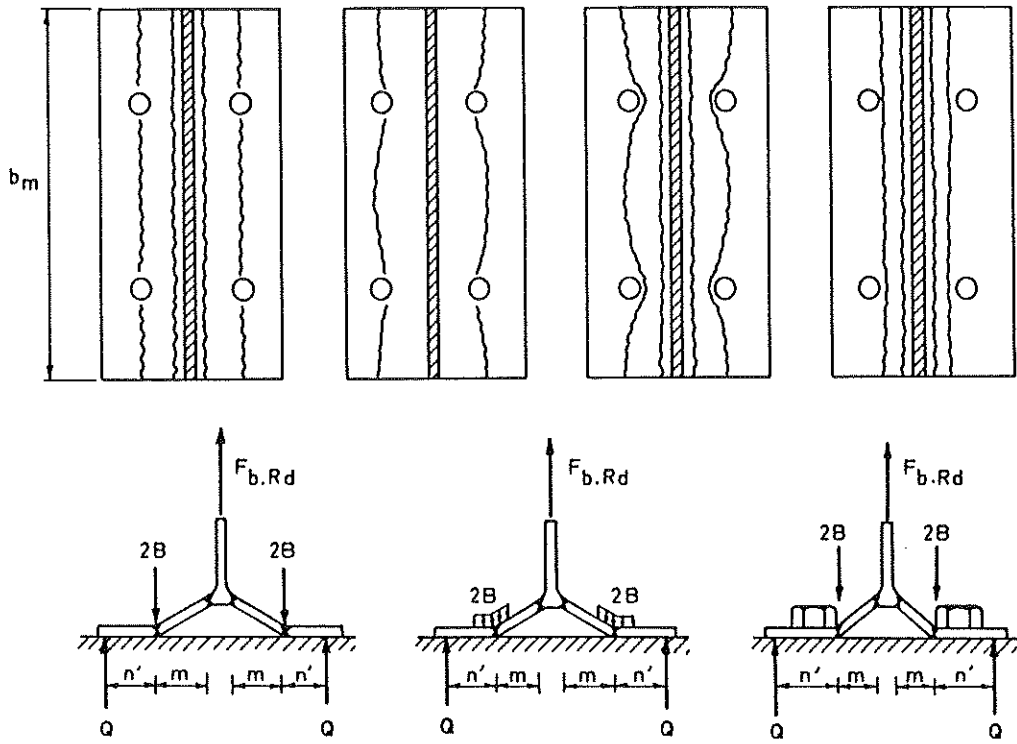


Figure 4

However account will be taken of the bolt size ; it will be assumed that the bolt load exerted onto the T-stub flange is uniformly distributed over a certain length D located symmetrically with respect to the bolt axis (fig. 4.b) ; D means the diameter of the bolt head/screw or washer. (Of course, the location of the yield lines does no more coincide necessarily with the section of maximum bending moment and results in a non-compliance with the fundamental theorems of plastic design ; the authors are of the opinion that the error remains sufficiently small to be acceptable). Accordingly half of the force in the bolts develops a negative external work when the plastic mechanism forms with the result of an expected higher connection capacity compared to EC3 model. For sake of simplicity, the resultant bolt loads $2B$ is substituted by two equal statically equivalent load components B acting at a distance $\pm e = 0.25 D$ from the bolt axis (fig. 5).

Applying the principle of virtual work to above plastic mechanism, on the one hand, and the equations of equilibrium, on the other hand, provides the limiting force $F_{b.Rd}$ associated to collapse by onset of a plastic mechanism :

$$F_{b.Rd} = (8n' - 2e) b_m m_p / [2mn' - e(m + n')] \quad (1)$$

$$\text{with : } n' = \text{Min} [n ; 1,25 m] \quad (2)$$

$$m_p = 0.25 f_y t^2 \quad (3)$$

b_m in accordance with EC3

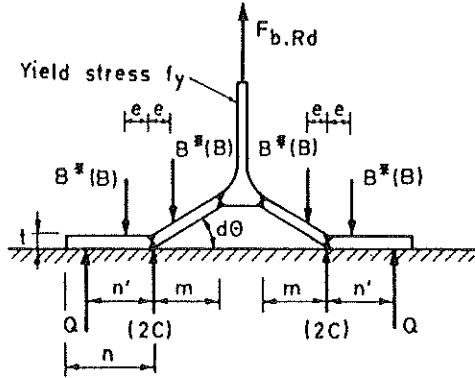


Figure 5

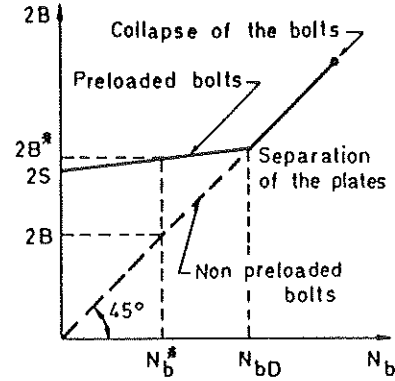


Figure 6

Of course, equ. (1) confines itself to Zoetemeijer's and EC3 formulae when distance e is vanishing.

What is said above is not explicitly influenced by the degree of bolt preloading. Actually the force in preloaded bolts of an elementary assemblage subject to an increasing external load N_b (parallel to the bolt axis) evolves according to figure 6. First, the bolt tension increase is a reduced proportion of the external load because of the compensating effect of the reduction in plate compression $2C$. When the latter becomes equal and opposite to the initial contraction of the plate ($N_b = N_{bD}$), the plates start to separate and the system becomes statically determinate. At any higher load, the bolts experience the whole load N_b . Separation occurs at :

$$N_{bD} = 2S/K^* \quad (4)$$

where S is the preloading force per bolt and $K^* = 1/(1 + 1/\xi)$. The factor $\xi = A_t/A_b$ is the ratio between the axial stiffness of the effective plate compression area A_t and the resisting bolt cross-sectional area A_b ; it is taken as 5 as an average value (Agerskov, 1976). Proceeding as before with attention duly paid to the effect of bolt preloading, yields the amended expression of the limiting force $F_{b,Rd}^*$ (Jaspart, 1991) :

$$F_{b,Rd}^* = \{[8n'-2(1-K^*)e]b_m m_p + 4n'eS\}/[2mn' - e(1-K^*)(m+n')] \quad (5)$$

under the reservation that :

$$2B \equiv (F_{b,Rd}^* n' + 2 b_m m_p) / (2n' - e) \leq N_{bD} \quad (6)$$

because equ. (5) is valid in the range prior to plate separation. Should

condition (6) not be fulfilled, then reference is made to (5) where $K^* = 0$, what results in $F_{b,Rd}^* = F_{b,Rd}$ with $F_{b,Rd}$ given by equ. (1).

The limiting force according to (5), subordinated to the additional check (6), constitutes a refinement of the relevant EC3 design rule. The capacity associated to the plastic mechanism can be assessed with a better accuracy than before (see § 2.3.). It would be easy to demonstrate (Jaspart, 1991) that above bolt effects do not at all alter the capacities associated respectively to the two other collapse modes of the T-stub.

The capacity of the T-stub is given as the lowest of the capacities relative to the three possible collapse modes.

Of course, the T-stub model is used several times when designing and extended end-plate connection : i) in the extended portion of the end-plate, ii) in the portion of the end-plate adjacent to the tensile flange of the beam, and iii) in the flange of the column. Above formulae must be written in an appropriate manner for each of these situations (Jaspart, 1991).

2.3. Comparison of the refined model test results.

Only few test specimens have been sufficiently instrumented to allow for a valuable comparison. It is referred to results obtained on isolated end-plates in Milano (Zanon and Zandonini, 1987) and on full connections in Liège (Jaspart, 1991) and Delft (Zoetemeijer, 1974).

Predictions according to the authors' proposal are superimposed in figure 7.a and b to a diagram established elsewhere (Damiani, 1986) for isolated end-plates ; those relative to full connections are listed in table 2.

It may be concluded to a very significative improvement of the present EC3 design rules and to a better accuracy. The refined model is still somewhat too conservative in a range where the bolts are not well proportioned to the stiffness of the plates (see especially the Italian tests with a end-plate thickness of 12 and 15 mm) ; then the conditions become close to Kishi's assumption with the result of an increase in the corresponding capacity. Such a range of not well proportioned connections will probably be met only exceptionnally because not economical at first sight ; anyway the approach provides conservative results in such cases.

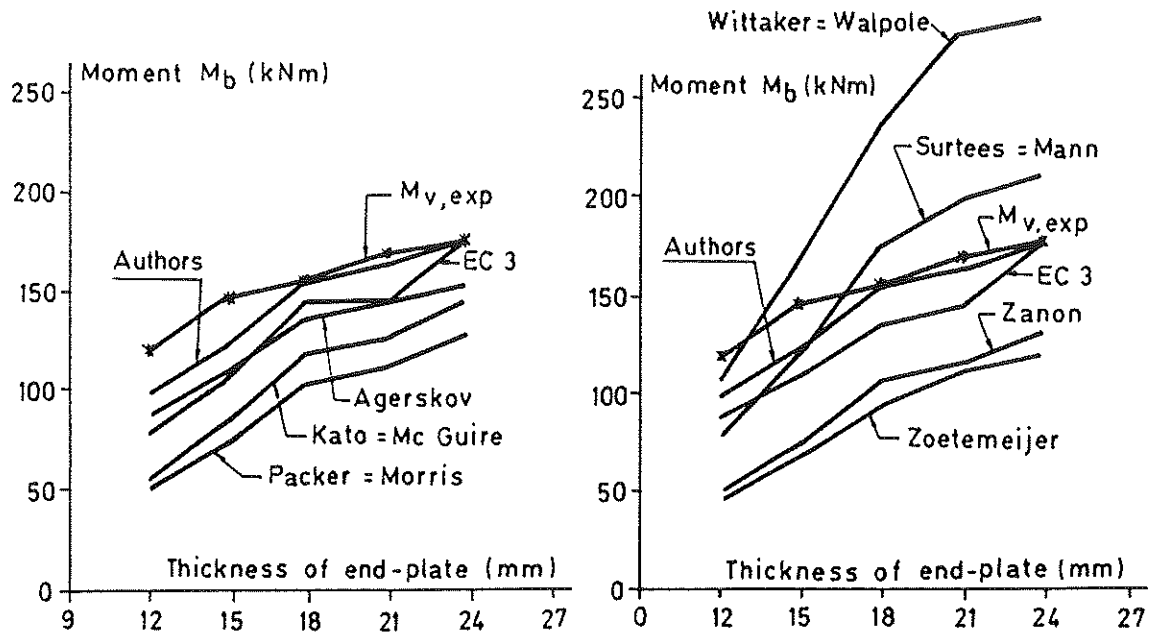


Figure 7

Test	Laboratory	$M_{v, theor} / M_{v, exp}$		
		Authors	EC3	Packer-Morris
01	Liège	0.98	0.98	1.10
04	Liège	1.04	1.04	1.15
07	Liège	0.98	0.98	1.08
014	Liège	1.01	1.00	0.91
T9	Delft	1.02	0.80	0.77
T20	Delft	1.08	0.91	0.90

Table 2

3. PLASTIC CAPACITY OF A FLANGE CLEATED CONNECTION

The critical part of a flange cleated connection is usually the tensile cleat and the adjacent zone (bolts in tension and column flange). Mainly two methods for assessing the pseudo-plastic capacity of the tensile zone are available (Hotz, 1983 ; Kishi et al, 1987). Both have been used for a comparison with fully instrumented test results performed in Trento (Bursi, 1990) on isolated cleats and in Liège (Jaspart, 1991), Sheffield (Davison et al, 1987) and Hamburg (Hotz, 1983) on cleated connections. It results that Kishi's method is largely unconservative and Hotz's one much too conservative. The large discrepancy is, to the authors' opinion, due to specific problems - linked to the cleated connection - which are not properly accounted for by both methods. It follows from experimental observations that :

- The collapse of a cleated connection by formation of a plastic mechanism involves a three-yield lines mechanism (two in the tensile cleat, one in the compression cleat) ;
- The initial clearance between the beam end and the column flange is likely to change the location of one yield line in the tensile cleat; the latter always develops at the toe the cleat fillet, at one time in the vertical leg, at one time in the horizontal leg.

In addition, the sole way to define the experimental plastic capacity of a cleated connection is not likely to correspond to the lowest strength of the connection components (Jaspart, 1991). Let us just mention that the degree of bolt preloading and the onset of an appreciable membrane action are the main reasons.

A fully original approach has been developed - on a basis similar to that used for end-plate connections - which accounts for the more accurate location of the yield lines, the sizes of the bolts/or washers, the bolt preloading and the plastic mechanism of the connection in its whole. As a result, a set of design formulae have been suggested, which are relative to all the possible collapse modes : bolts fracture, mixed plastic mechanism in the whole connection, and yield lines mechanism either in the cleats and in the column flange (Jaspart, 1991).

Test	Laboratory	M / M		
		v. theor	v. exp	
		Authors	Kishi-Chen	Hotz
03	Liège	1,01	(-)	0,52
06	Liège	1,01	(-)	0,55
012	Liège	1,02	(-)	0,78
JT08	Sheffield	1,05	(-)	0,75
TT1(*)	Trento	0,86	1,40	0,42
TT2(*)	Trento	0,89	1,46	0,44
A	Hamburg	0,89/1,04	1,28/1,64	0,51/0,65
B	"	0,83/0,97	1,16/1,51	0,47/0,60
E	"	0,89/1,04	1,21/1,57	0,49/0,63
F	"	1,01/1,15	(-)	0,47/0,60
G	"	0,80/0,94	1,15/1,47	0,45/0,58
H	"	0,92/1,06	1,25/1,62	0,51/0,65
I	"	1,00/1,12	(-)	0,48/0,61

Table 3

- (*) not well proportioned connection (-) method not applicable
 ../. extreme values because yield stress not measured

The theoretical results computed in accordance with this new approach have been compared with test data (table 3). It may be concluded that the method, that is founded on sufficiently simple formulae to allow for the daily practice, has

a wide range of application and a very good accuracy. It could constitute an improvement to EC3, the Annex J of which is restricted to end-plate connections only.

4. CONCLUSIONS

Present paper is devoted to one aspect only of the design of beam-to-column joints : the plastic capacity of the tensile zone of the connection. It is shown that some amendments to EC 3 design rules for end-plate connections could be brought - without increasing the complexity of the design expressions - with a view to get a better and more homogeneous accuracy of the predictions. There is thus matter for thought when the Annex J of EC 3 will be reviewed by the relevant CEN Technical Committee. In addition, a set of design formulae for flange cleated connections, detailed elsewhere by the junior author, are found likely to be used as the background for a possible future additional Annex devoted to this type of connections. Further computations have shown (Jaspart, 1991) the non-significative influence of M-N-V interaction in the yield lines on the connection plastic capacity.

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