Effect of bolt preloading on joint behaviour

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ABSTRACT: In Eurocode 3 Part 1-1 as well as in most of the existing models for prediction of the stiffness and strength properties of structural bolted joints, the effect of bolt preloading is disregarded. In the present paper, the influence of this factor on the characteristic joint deformability curves is pointed out and related formulae for stiffness and strength prediction are proposed.

1. INTRODUCTION

Structural unstiffened bolted joints - beam-to-column joints, beam-to-beam joints, beam splices,... - are very economical for fabrication and erection. Generally, such joints have a semi-rigid behaviour and are partially resistant. The prediction of their rotational response, in terms of moment M - relative rotation ϕ, is therefore of particular importance in view of the study of their influence on the global structural response of the building frames.

In the most recent analytical procedures for the prediction of the joint response (Jaspart 1991; Revised EC3 Annex J 1994), the so-called component method (Jaspart et al 1994) is used. The originality of this method is to consider any joint not as a whole but as a set of «individual basic components». In the particular case of an unstiffened beam-to-column joint with extended end plate connection subjected to bending, the relevant components are the following:

- compression zone :
  - column web in compression ;
  - beam flange in compression ;
- tension zone :
  - column web in tension ;
  - column flange in bending ;
  - bolts in tension ;
  - end plate in bending ;
  - beam web in tension ;
- in shear zone :
  - column web panel in shear.

Each of these basic components possesses its own level of strength and stiffness in tension, compression or shear and may therefore be characterized by a F-Δ curve where F is the applied force and Δ the related deformability. The coexistence of several components within the same joint element - for instance, the column web which is simultaneously subjected to compression (or tension) and shear - can obviously lead to stress interactions that are likely to decrease both strength and stiffness of each individual basic component; this interaction affects the shape of the deformability curve of the related components but does not call the principles of the component method in question again.

The application of the component method requires the following steps :

a) listing of the components that are "activated" in the joint ;
b) evaluation of the stiffness and/or strength characteristics of each individual basic component (specific characteristics - initial stiffness, design strength,... - or whole deformability curve) ;
c) «assembly» of the components in view of the evaluation of the stiffness and/or strength characteristics of the whole joint (specific characteristics - initial stiffness, design resistance,... - or whole deformability curve).

The «assembly» is based on a distribution of the internal forces within the joint. As a matter of fact, the external loads applied to the joint distribute, at each loading step, between the individual components;they do that in accordance with the instantaneous stiffness of each component. The application of the component method requires obviously a sufficient knowledge of the behaviour of the basic components.

The framework of the component method is sufficiently general to allow the use of various techniques of component characterization and joint «assembly».

In particular, the stiffness and strength characteristics of the components may result from experiments in laboratory, numerical simulations by means of finite element programs or analytical models based on theory. In Liège, experimentations and numerical simulations have been performed and used as references when developing and validating analytical models (Jaspart 1991).

The analytical models may be developed with different levels of sophistication according to the persons to whom they are devoted:

- the expressions presented in (Jaspart 1991) are able to cover the influence of all the parameters which affect significantly the component behaviour (strain hardening, bolt head and nut dimensions, bolt prestressing,...) since the beginning of the loading up to collapse and fit therefore well with a scientific publication ;
- the rules which have been introduced, for instance, in Annex J of Eurocode 3 (1993) - annex devoted to joint design - and in its revised version (1994) to which the University of Liège has largely contributed with the University of Aachen (D) and TNO Delft (NL) are far more simple and are therefore more suitable for practical use.

Similar levels of sophistication exist also for what regards the joint «assembly».

In the present paper, attention is paid to the tension zone of the bolted joints and more especially to the plate components subjected to transverse forces such end plates or column flanges, including bolts in tension.

Two general approaches termed respectively «plate model» and «T-stub model» have been proposed to analyse these components. In the «plate model», the components are considered as plates in bending and studied accordingly while the T-stub idealization consists in reducing the components to T-stub sections of appropriate length b_m that are connected by their flange onto a presumably infinitely rigid foundation and are subjected to a uniformly distributed force acting in the web plane (figure 1).

The T-stub idealization allows to derive relatively simple prédiction rules for stiffness and strength which can similarly be applied to end plates, column flanges or cleats; for all these reasons, it has been adopted by different authors and is also referred to in EC3 Annex J (1993; 1994).

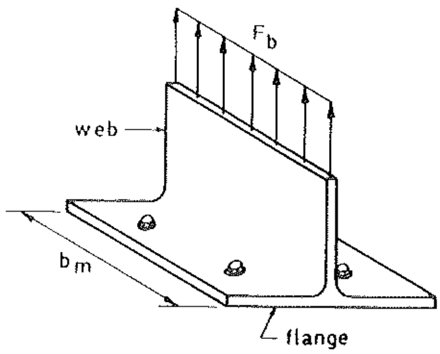

Figure 1 - T-stub

In the present paper, the effect of the bolt prestressing on the tensile response of the T-stub is contemplated. It influences the stiffness and strength properties of the T-stubs but is still disregarded in the revised EC3 Annex J (1994). Indeed same design rules are given for joints with preloaded and non-preloaded bolts.

2. EXPERIMENTAL AND DESIGN T-STUB DEFORMABILITY CURVES

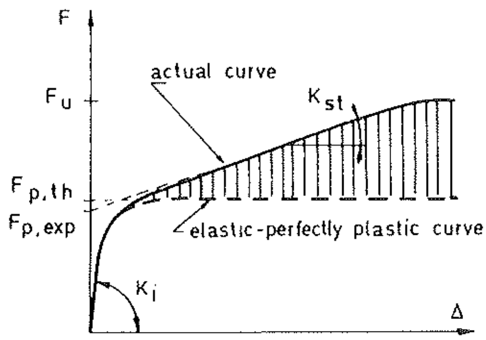

Figure 2 - Characteristics of a F-Δ curve

A T-stub tested in laboratory exhibits a non linear behaviour, as shown in figure 2. The corresponding F-Δ curve may be characterized by 4 main parameters: the initial stiffness K_i, the "plastic" resistance F_p, the strain-hardening stiffness K_{st} and the ultimate resistance F_u. The plastic capacity F_p is theoretically defined as the maximum tension force developed by a T-stub made of a material which exhibits an elastic-perfectly plastic stress-strain

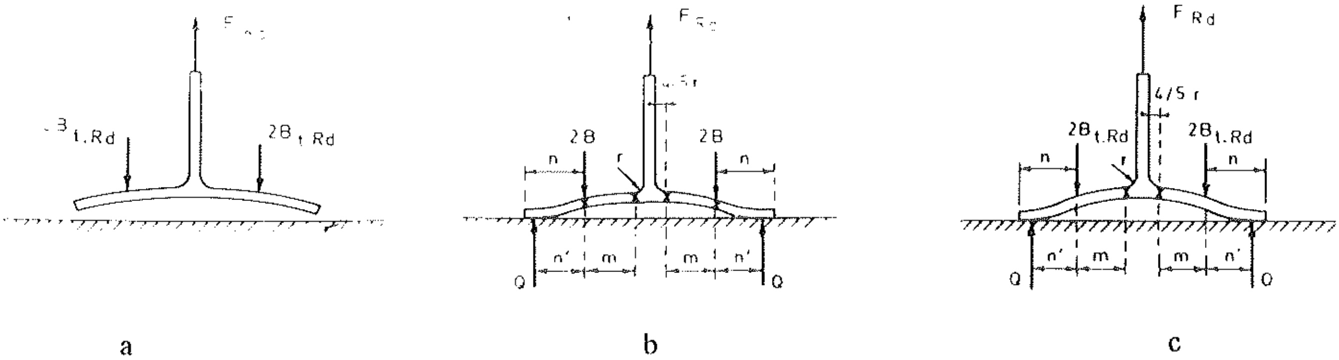

Figure 3 - Collapse modes in a T-stub.

diagram; thus strain-hardening would be fully disregarded. To identify such a capacity on an experimentally recorded F-Δ 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 2.

In EC3 Annex J, design rules are provided to derive a so-called *design* F-Δ curve. When applied to an actual T-stub tested in laboratory, i.e. on the basis of:

- the measured geometrical properties,
- the measured mechanical properties of steel,
- partial safety factors equal to 1,0,

the EC3 design curve should identify itself to the "elastic-perfectly plastic" curve defined in figure 2; indeed strain-hardening is disregarded.

The EC3 design curve is fully derived from the sole knowledge of two main characteristics: the initial stiffness K_i and the design resistance F_{Rd}. F_{Rd}, which is supposed to be equal to the "plastic" F_p when aforementioned conditions apply, is dependent on the collapse mode of the T-stub. The latter can be due to (figure 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 related F_{Rd} values are expressed as follows (4 bolts in tension):

Mode a: bolt fracture (figure 3a)

$$F_{Rd,a} = 4\ B_{t.Rd} \qquad (1)$$

Mode b: plastic mechanism (figure 3b)

$$F_{Rd,b} = \frac{4\ b_m\ m_p}{m} \qquad (2)$$

Mode c: mixed collapse (figure 3c)

$$F_{Rd,c} = \frac{2\ b_m\ m_p + 4\ B_{t.Rd}\ n'}{m + n'} \qquad (3)$$

where $m_p = \frac{1}{4}\ t^2\ \frac{f_y}{\gamma_m}$ (t = flange thickness; f_y = steel yield stress; γ_m = partial safety factor) and n' = n ≤ 1,25 m. $B_{t.Rd}$ is the design resistance of the bolts and b_m - see figure 1 - is defined in accordance withe EC3. The design strength F_{Rd} of the T-stub is derived as the smallest value got from expressions (1) to (3).

3. EFFECT OF BOLT PRELOADING ON T-STUB RESPONSE

The effect of bolt preloading on the F-Δ response of a T-stub is pointed out in figure 4 which relates to tests recently performed in Liège on quite similar T-stubs connected respectively by means of preloaded and non-preloaded bolts. Tests show that:

- the bolt preloading has a significative influence on the initial stiffness and on the "plastic" resistance of the connection and ;
- a non significative influence on the ultimate state due to the complete loss of preloading between the connected flanges at that load level.

The effect of bolt preloading is disregarded in EC3; the use of EC3 design rules for joints with non preloaded bolts can therefore lead to underestimations of the initial stiffness and of the design strength.

In (Jaspart 1991; Jaspart et al 1991), numerous comparisons between experimental results on extended end plate connections and theoretical F_{Rd} values computed according to the 1993 draft of EC3 Annex J allow to conclude that a good agreement is found only when the tension capacity of the T-stub is governed by collapse mode a or c (figure 3). When a plastic mechanism forms in the T-stub (collapse mode b), EC3 is found much too safe. Similar conclusions can be drawn from the tests on flush end plate connections (Moore 1988) as well as from the tests of figure 4 where mode b is relevant.

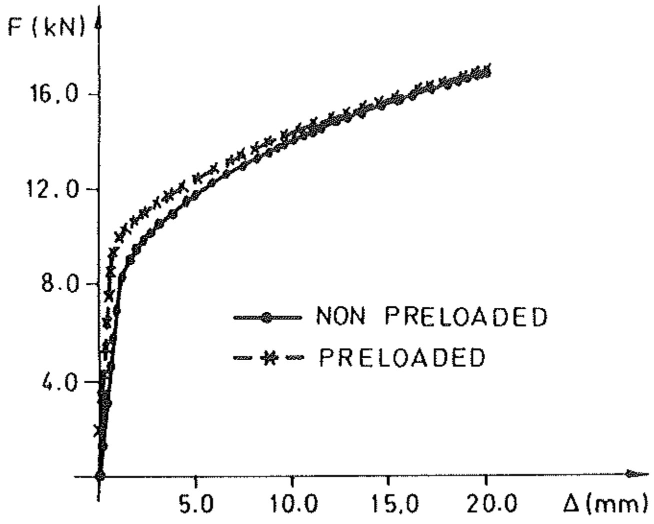

Figure 4 - Effect of bolt preloading on the T-stub response

In the two following sections, the necessary modifications to bring to the existing prediction design rules for the initial stiffness K_i and the design resistance F_{Rd} are presented.

4. EFFECT OF BOLT PRELOADING ON THE DESIGN RESISTANCE

Refinements can be brought to the T-stub model of EC3 with the result that the amended model provides a higher resistance for collapse mode b without affecting significantly the accuracy regarding both collapse modes a and c.

An attempt in this respect has been made by the junior author (Jaspart 1991). In most of the existing models, the forces in the bolts are always idealized as point loads. Thus, it is never explicitely 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 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) - what is done in EC3 -; that means the bolt size is fully disregarded and the load is applied in the axis of the bolts (fig. 5.a). Or 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 1988), where the bolt load is also assumed to be applied (fig. 5.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. 5.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 (1974); it is therefore justified to refer to the latter for what regards the location of the yield lines. 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. 5.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. 6).

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:

$$F_{Rd} = (8n' - 2e)\, b_m\, m_p/[2\, mn' - e(m + n')] \quad (4)$$

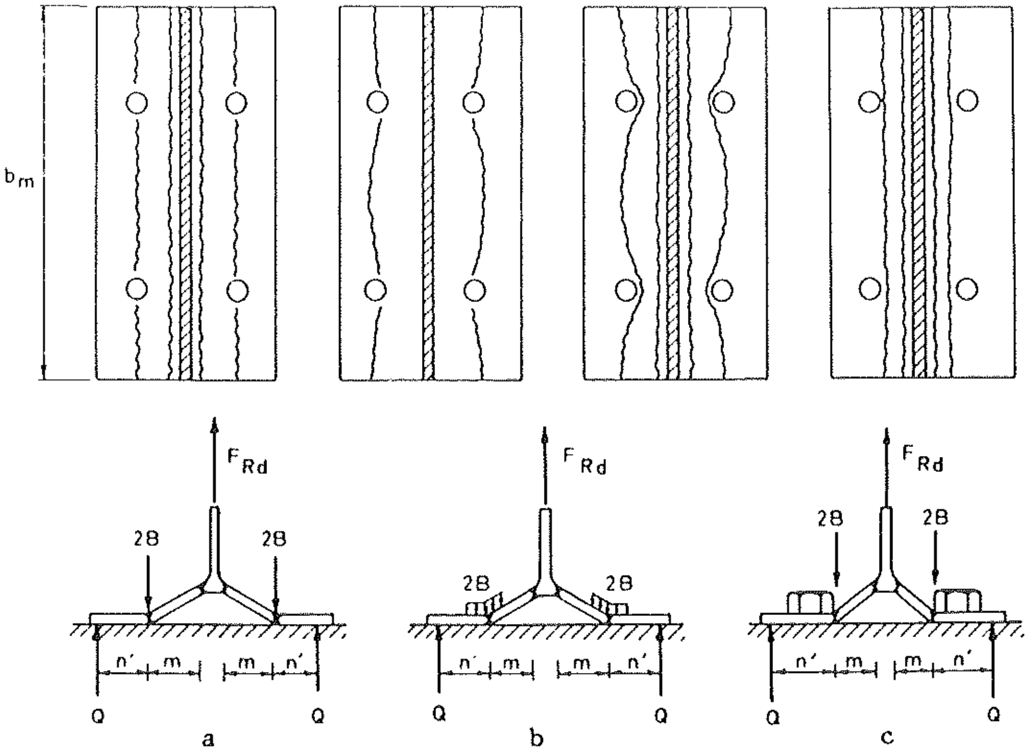

Figure 5 - Yield mechanisms

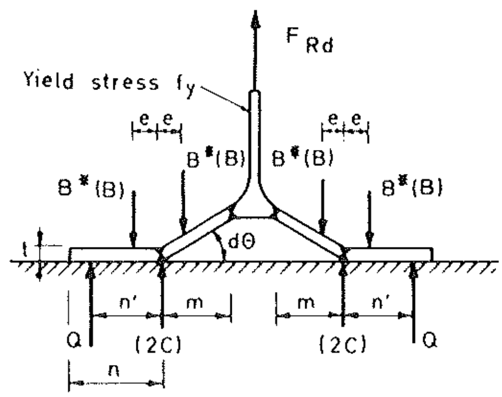

Figure 6 - Forces acting on the T-stub

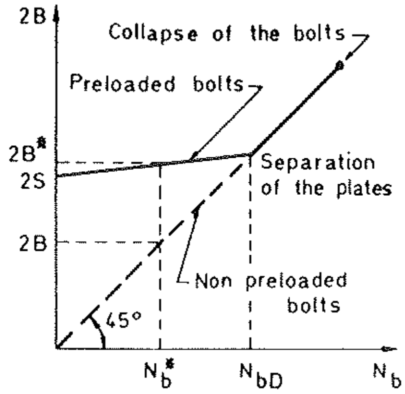

Figure 7 - Bolt force evolution

with : $n' = \min [n; 1{,}25m]$ (5)

$m_p = 0.25\ f_y\ t^2$ (6)

b_m in accordance with EC3.

Of course, equ.(4) confines itself to Zoetemeijer's (1974) and EC3 (1993) formulae when distance e is vanishing. Formula (4) has been included in the revised Annex J of EC3 (1994) as a less conservative alternative to formula (3).

What is said above is not explicitely 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 7. 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 preloading force 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:

$$N_{bD} = 2S/K^* \qquad (7)$$

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^*_{Rd} :

$$F^*_{Rd} = ([8n' - 2(1 - K^*)e]\ b_m\ m_p + 4n'eS)/[2mn' - e(1 - K^*)(m + n')] \qquad (8)$$

under the reservation that :

$$2B \equiv (F^*_{Rd}\ n' + 2\ b_m\ m_p)/(2n' - e) \not> N_{bD} \qquad (9)$$

because equ.(8) is valid in the range prior to plate separation. Should condition (9) not be fulfilled, then reference is made to (8) where $K^* = 0$, what results in $F^*_{b.Rd} = F_{b.Rd}$ with $F_{b.Rd}$ given by equ.(4).

The limiting force according to (8), subordinated to the additional check (9), constitutes a refinement of the relevant EC3 design rule. It is easy to demonstrate (Jaspart 1991) that above bolt effects do r at all alter the strength capacities associated respectively to the two other collapse modes of the T-stub.

5. EFFECT OF BOLT PRESTRESSING ON THE INITIAL STIFFNESS

The initial stiffness is related to the elastic deformation of the T-stub flange in bending and the bolts in tension. When two T-stubs are connected together - as, for instance, the column flange and endplate idealized T-stubs in an endplate beam-to-column connection - the initial stiffness of each T-stub can not be evaluated independently. As a matter of fact, the bolts in tension belong to the two T -tubs and, through their deformability, the compatibility of the respective deformabilities of the T-stub flanges is ensured. In (Jaspart 1991), expressions providing the elastic initial stiffness of each T-stub have been proposed; they allow the coupling effect between the T-stubs to be taken into consideration. When non preloaded bolts are used, the elongation Δ_b (figure 8) of the bolts simply results from the elongation of the bolt shank subjected to tension. On the contrary, when bolts are preloaded, tension forces result more in a decrease of the compression forces between the connected plates than in an increase of the bolt tension force, as stated in section 4. The "decompression" stiffness of the plates is much higher than that of the bolts in tension. The relative stiffness between the plates and the bolts has been expressed in section 4 in the format of a ξ factor. Preloading therefore results in a higher global stiffness of the T-stub. Formulae for the B - Δ_b deformability at the bolt level have been proposed by Agerskov (1976):

- for non preloaded bolts

$$\Delta_b = \frac{B}{EA_b}(k_1 + 2k_4) \qquad (10)$$

- for preloaded bolts

$$\Delta_b = \frac{B\ (t_{e1} + t_{e2})}{10EA_s}\ \frac{1}{1 + \frac{k_3}{k_2}} \qquad (11)$$

where (figure 9):

$$k_1 = l_s + 1{,}43l_t + 0{,}71l_n$$

$$k_2 = l_s + 1{,}43l_t + 0{,}91l_n + 0{,}4l_w$$

$$k^*_3 = \frac{t_{e1} + t_{e2}}{5}$$

$$k_4 = 0{,}1l_n + 0{,}2l_w$$

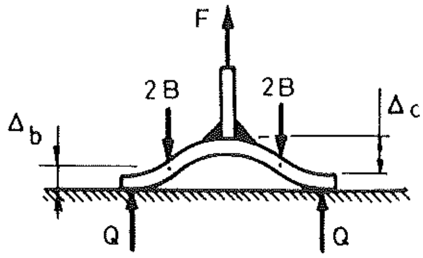

Figure 8 - T-stub deformability

In the revised EC3 Annex J (1994), the elastic stiffnesses of the relevant T-stubs and bolts are expressed in order to avoid complexity due to coupling effects. Expression (10) has been approximated by the following:

$$\Delta_b = \frac{L_b\ B}{EA_b} \qquad (12)$$

with $L_b = t_{e1} + t_{e2} + l_w + \frac{l_n}{2} + \frac{l_n}{2}$

According to EC3, this expressionhas also to be used for joints with preloaded bolts, even if it only

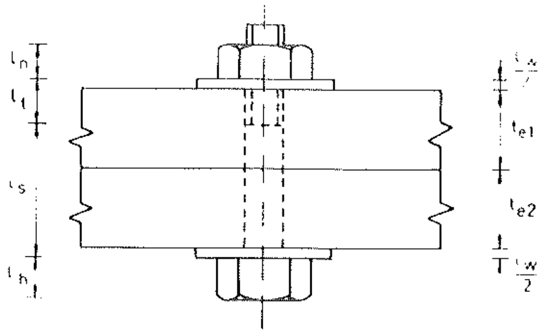

Figure 9 - Bolt geometrical properties

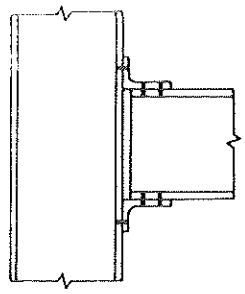
Figure 10 - Joint with flange cleats

characterizes the deformabilityof the bolt shank in tension. Based on the Agerskov's proposal (1976) to approximate the value of the plate-to-bolt stiffness ratio ξ to 5, it may be demonstrated that the following simple expression may be substituted to (11):

$$\Delta_b = \frac{L_b\, B}{6EA_s} \qquad (13)$$

Through this expression, the influence of the bolt preloading on the T-stub initial stiffness could be simply taken in consideration in the revised EC3 Annex J (1994).

6. NUMERICAL APPLICATION

In figure 11, the revised EC3 Annex J (1994) has been used in combination with above formulae (8), (9) and (13) to derive the deformability moment-rotation curve of a beam-to-column joint with flange cleats (figure 10) and preloaded bolts. This joint has ' n tested some years ago at Sheffield University (Davison et al 1987). Besides the experimental curve, three analytical curves are reported in figure 11. They correspond respectively to:

- the revised EC3 Annex J (1994) where the forces in the bolts are idealized as point loads - formulae (1),(2) and (3) for strength evaluation -;
- the revised EC3 Annex J (1994) where the forces in the bolts are assumed to be uniformly distributed under the bolt head/nut/washer - formula (1),(3) and (4) for strength evaluation -;
- a case similar to the previous one but with bolt preloading taken into consideration through formulae (8) for strength and (13) for stiffness.

The effect of the bolt preloading on the joint strength is found to be quite significant in such a case where the cleat in tension is the weaker part of the joint and fails through Mode 1. The increase of the initial stiffness is less marked. This is clearly justified by the relatively small contribution of the bolt deformation (or plate "decompression") to the total deformability of the joint; the latter results mainly from the cleat and column flange deformation.

The good agreement between the experimental curve and the analytical one taking the bolt preloading into consideration has to be highlighted. Many other comparisons with results of experimental tests performed in various european research centres are reported in (Jaspart 1991).

7. EFFECT OF THE BOLT PRELOADING ON THE SHAPE OF THE ANALYTICAL JOINT DEFORMABILITY CURVES

In the revised annex J (1994), the secant stiffness of a joint moment-rotation curve corresponding to the design moment resistance M_{Rd} is defined as $S_{j.ini}/\eta$ where $S_{j.ini}$ is the joint initial stiffness and η = 3 (for welded joints and joints with endplates) or 3,5 (for joints with flange cleats). The value η = 3,5 in EC3 is valid for flange cleated joints where bolts are non preloaded or where bolts are preloaded in such a way that no slip occurs between the cleats and the beam flanges before M_{Rd} is reached. In the first case, the stiffness calculation includes the bearing deformability of the cleats and the beam flanges as well as the shear deformability of the related bolts. These deformability sources are disregarded in the second case. In the particular case of figure 11, the bolts are preloaded but the slip resistance of the joint is lower than M_{Rd}. When slip occurs, the bearing deformability of the plates and the shear deformability of the bolts have to be added to the other joint deformability sources; then the secant joint stiffness corresponding to M_{Rd} is found significantly lower than $S_{j.ini}/3,5$. In (Jaspart 1991), more refined values of η have been proposed to

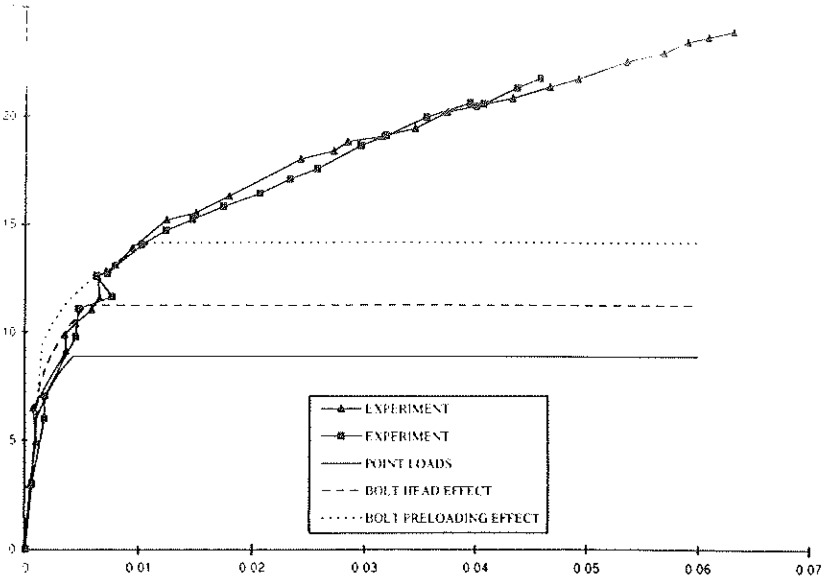

Figure 11 - Comparison with an experimental test

cover such cases:

$$\eta = 3 \qquad si\ \alpha_g \geq 1$$
$$= -11\alpha_g + 14 \qquad si\ 0{,}2 \leq \alpha_g < 1 \qquad (14)$$

In (14), α_g is the ratio between the slip moment resistance of the joint and M_{Rd}. For cases where $\alpha_g \geq 1$, EC3 suggests a value of $\eta = 3{,}5$ while a value of $\eta = 3$ is obtained through formula (14). This is justified in (Jaspart 1991) based on comparisons with numerous test results. For α_g values lower than 0,2, the bolts may be considered as non preloaded.

Formula (14) has been used to derive the analytical curves of figure 11.

8 CONCLUSIONS

In this paper, the effect of bolt preloading on the stiffness and strength properties of structural joints is pointed out. Simple formulae are suggested which could be used to implement the possibilities offered by the revised Annex J of Eurocode 3 which disregards the influence of the bolt prestressing. An application of EC3 in combination with the herein proposed formulae is performed in order to highlight the possible benefit to be drawn from the consideration of bolt preloading. Lastly it is referred to another document where the new proposed formulae have been validated through comparisons with numerous test results.

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