DESIGN OF JOINTS IN INDUSTRIAL PORTAL FRAMES MADE OF SLENDER BUILT-UP MEMBERS

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1. ABSTRACT

Annex J of Eurocode 3, Part 1-1 [1], gives rules for the design of beam-to-column joints in steel structures. This annex has been recently revised [2] in order to incorporate recent knowledges acquired in the last years throughout Europe. Notably, the so-called « component method » , briefly described in Section 2, has been adopted.

However, the revised Annex J still has limitations, the main one being the restriction to joints subjected mainly to bending and belonging to rectangular frames made of H or I profiles.

In the present paper, recent developments aimed at investigating the behaviour of joints in pitched roof lightweight portal frames and extending the scope of the revised Annex J to such joint configurations are presented. This work, which has resulted in the preparation of a design software, is the fruit of a close collaboration between a fabricator, COMMERCIAL INTERTECH, ASTRON Building Systems (Luxembourg), and the University of Liège, MSM Department (Belgium).

2. PRINCIPLES OF THE COMPONENT METHOD

The component method may be presented as an application of the well-known finite element method for the calculation of structural joints.

The originality of the component method is to consider any joint as a set of "individual basic components". In the particular case of Figure 1, the relevant components are the following :

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

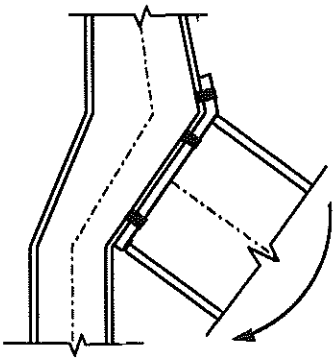


Figure 1 Joint in bending with an extended end-plate

Each of these basic components possesses its own strength and stiffness in tension, compression or shear.

The application of the component method requires the following steps :

a) listing of the active components for the studied joint;
b) evaluation of the stiffness and/or strength properties of each individual basic component;
c) "assembly" of the components in view of the evaluation of the stiffness and/or strength characteristics of the whole joint.

A sufficient knowledge of the behaviour of the basic components is of first importance. The revised Annex J of Eurocode 3 [2] provides information on twelve common components. The combination of these components allows to cover a wide range of joint configurations, what should largely be sufficient to satisfy the needs of practitioners as far as beam-to-column joints and beam splices in bending between H- or I-shaped profiles in rectangular frames are concerned.

It should be noted that 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 experimentations in laboratory, numerical simulations by means of finite element programs or analytical models based on theory. The latter may be developed with different levels of sophistication according to the persons to whom they are devoted :

- Complex expressions covering the influence of all the parameters which affect significantly the component behaviour (strain hardening, bolt head and nut dimensions, bolt prestressing, ...) from the beginning of the loading to the collapse.
- Rules as those introduced in Annex J of Eurocode 3 which are more simple and are therefore more suitable for hand calculations.
- Simplified approaches as now available in [3] and [4] where the procedures for stiffness and strength evaluation are reduced to the essentials and allow a quick and nevertheless accurate prediction of the main joint properties.

Similar levels of sophistication also exist for what regards the joint assembly. This one 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 according to their instantaneous stiffness and resistance.

As said before, the parallelism with the finite element method is obvious. To "component" and "joint" may be substituted the words "finite element" and "structure".

3. PRESENT LIMITATIONS OF THE REVISED ANNEX J OF EUROCODE 3

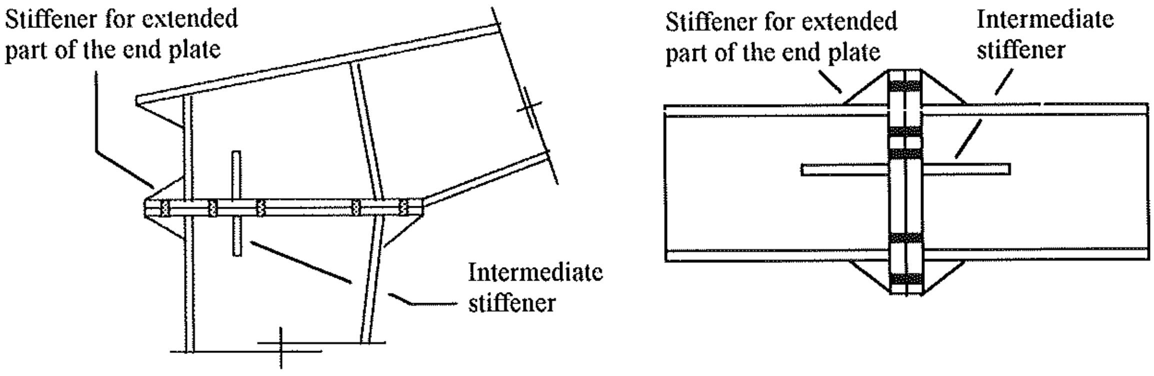
Some fields of application are not yet covered by the codes. Amongst them:

- Joints subjected to bending moment (and shear) and axial compression or tension forces have been less studied and, in particular, the way to distribute the internal forces for stiffness and strength calculations (the stiffness and strength component properties remain unchanged whatever is the type of loading).
- In some cases, the connected elements form an angle higher than 90°. This requires specific amendments to be made to the existing characterization procedures.

- When built-up sections are used, thinner plates than in hot-rolled sections are often selected, what increases the risk of local plate buckling. A quite critical example is that of the unstiffened panel, mainly loaded in shear, in the knee joints of portal frames.
- In built-up construction, beam sections are most of the time momosymmetrical, end plates are extended at both ends, and specific stiffening systems are applied (intermediate stiffeners and stiffeners of the extended parts of the endplates in Figure 2).

The joints shown in Figure 2 belong to pitched roof industrial portal frames; they exhibit most of these particular features.

In the next pages, all these various aspects are discussed and the way they have been modelled is briefly described.



a - Knee joint

b - Beam splice

Figure 2 Joints in pitched roof portal frames

4. DEVELOPMENT STRATEGY

Three main research approaches may be contemplated in the development of appropriate design tools for joints: the experimental one, the numerical one and the theoretical one. To derive the rules included in Eurocode Annex J, the three ones have been successfully applied:

- Hundreds of experimental tests on joints or on components have been performed these last years. Standardized data sheets for test data recording have been prepared at the european level and a database program called SERICON [8] and including the available information on joints has been developed.
- FEM techniques represent a powerful tool for the study of joint as far as their use is particularly well mastered. They allow to obtain information - distribution of stresses in the connection elements, spread of plasticity, contact forces, ... - which can usually not be well measured in laboratory. The validity and the accuracy of the numerical simulations are checked by means of comparisons with experimental results on joints or components. As soon as this is done, the numerical approach may then be used for parametric studies, so replacing expensive experimental programmes.
- In parrallel, prediction models based on theory and on the experience gained from tests and numerical simulations have been developed so as to allow an analytical evaluation of the main joint properties. Sophisticated research-oriented models have first been proposed and their validity has been demonstrated through comparisons with experimental and numerical available data. After simplifications, rules have then been derived for inclusion in Eurocode

3 Annex J and practical tools for designers have finally been extracted. These are described in [3] and [4].

In the present study, a quite similar approach is followed by the authors on the basis of the available experimental and numerical results [7]. Additional numerical simulations are now in progress and complementary test results on ASTRON joints are planned in a near future.

5. OVERVIEW OF NEW DEVELOPMENTS

5.1. Column web panel in shear

Recommendations for the calculation of column web panels in shear are included in the revised Annex J of Eurocode 3. For what regards the shear design resistance, the evaluation formula writes :

$$V_{n,Rd} = \frac{0,9 A_{vc} f_{ywc}}{\sqrt{3}\gamma_{M0}} \tag{1}$$

where : A_{vc} is the shear area of the column cross-section;
f_{ywc} is the yield stress of the column web.

It is however restricted to non-slender panels, i.e. for which:

$$\frac{d_c}{t_{wc}} \leq 69\varepsilon \tag{2}$$

where : $\varepsilon = \sqrt{235/f_{ywc}}$ (f_{ywc} expressed in Mpa)
d_c is the clear depth of the column web

In the case of transversally stiffened panels, an additional shear resistance is provided by the frame constituted by the column flanges and the transverse web stiffeners.

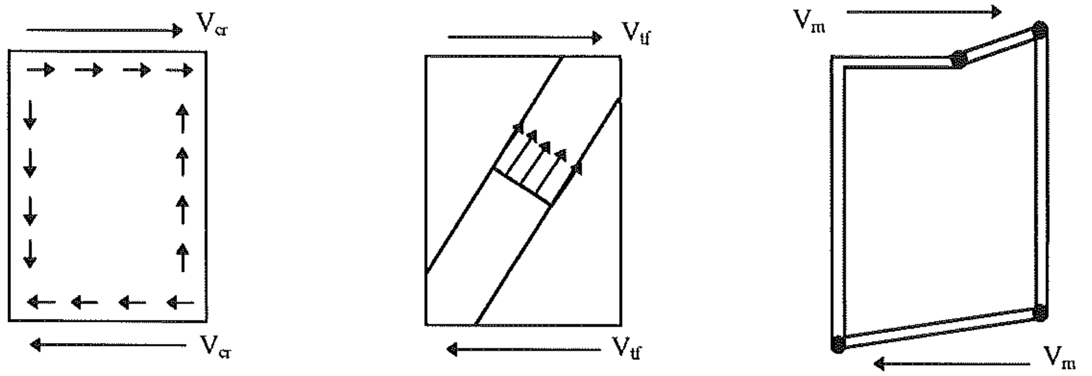
For slender panels ($d_c/t_{wc} > 69\varepsilon$), buckling phenomena occur before the shear plastic resistance given by Formulae (1) is reached. A classical idealization of the panel response at ultimate state consists in isolating three contributions to the resistance and summing them up as follows (see Figure 3):

$$V_{n,Ru} = V_{cr} + V_{tf} + V_m \tag{3}$$

where : V_{cr} is the critical shear resistance of the panel;
V_{tf} is the shear resistance associated to the diagonal tension field which results from the non-iniform distribution of shear stresses in the panel consecutive to its critical shear buckling;
V_m is the shear resistance of the frame constituted by the surrounding plates.

This idealization has been first applied to beam in bending and shear - the well-known Cardiff model - before being applied years later to column web panels in shear by Pasternak [6] who proposed evaluation formulae for each of the three contributions to the ultimate shear resistance. For design purposes, it could probably be considered that only the two first contributions have to be taken into consideration. From comparisons with experimental test results [7], the reasonable accuracy of the model may be shown. No indication is however given by Pasternak on how to derive the shear stiffness of the panel in the elastic range nor in the non-elastic one.

In [7], the available models and test results are discussed and proposals for improvement of the Pasternak prediction model are suggested.



(b) Critical contribution (c) Tension field contribution (d) Yield mechanism contribution

Figure 3 Contribution to the shear resistance of slender column web panels

5.2. Stiffening systems

Stiffening and strengthening of the extended part of an end-plate in bending

The stiffening and the strengthening of the extended part of an end-plate may be achieved by welding a triangular stiffener as indicated in Figure 2.

The stiffness and the strength of the extended part may be evaluated through the concept of T-stub introduced in Eurocode 3 revised Annex J for plates subjected to transverse bolt forces. The use of the formulae proposed in Eurocode 3 however requires the evaluation of appropriate effective lengths for the equivalent T-stub which has to be substituted to the actual stiffened extended part of the end plate in bending. These have been derived and the interested reader will find the related information in [5].

Intermediate stiffeners

Such so-called intermediate stiffeners are welded there where additional stiffness or resistance is required at the level of a specific bolt-row, as shown in Figure 2.

The concept of the T-stub idealization may again be referred to in this particular situation and this again requires the definition of appropriate effective lengths for the column flange or the end-plate in bending at the level of the bolt-row being considered.
Eurocode 3 Annex J provides the designer with adequate rules for effective lengths as long as two successive stiffeners are separated by two bolt-rows at least. When it is not the case, as in Figure 2, the effective length to apply has been derived. Its expression, given in [5], appears simply as an extension of the cases covered by Annex J.

5.3. Sloped rafters

To cover cases, as in pitched-roof industrial portal frames, where the structural elements are not perpendicularly connected (Figure 4), slight modifications have to be made to the

Eurocode 3 rules for joint characterization. In fact, the three main following aspects have to be considered :

- the external loading on the joint;
- the distribution of internal forces in the joint;
- the properties of the constitutive components.

They are successively addressed here below.

Loading

Because of the inclination of the rafter in Figure 4, the internal forces $M_{r,Sd}$, $V_{r,Sd}$ and $N_{r,Sd}$ acting at the rafter extremity and obtained through a frame analysis have to be transformed into a bending moment M_{Sd}, a shear force V_{Sd} and an axial force N_{Sd} acting on the connection cross-section.

These forces are derived as follows :

$$M_{Sd} = M_{r,Sd} \tag{4.a}$$

$$V_{Sd} = V_{r,Sd} \cos a + N_{r,Sd} \sin a \tag{4.b}$$

$$N_{Sd} = N_{r,Sd} \cos a - V_{r,Sd} \sin a \tag{4.c}$$

M_{Sd}, N_{Sd} and V_{Sd} are expressed at the level of the rafter neutral axis.

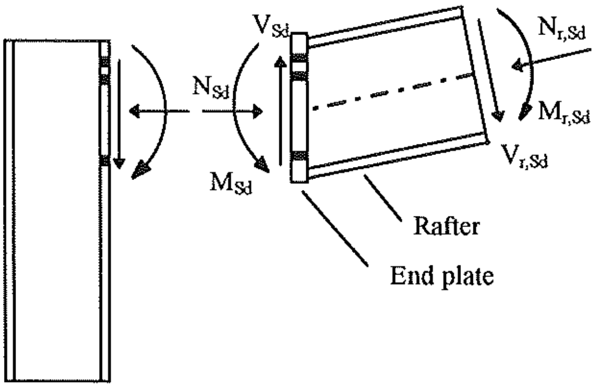


Figure 4 External forces acting on the connection

Distribution of internal forces

The distribution of the external forces M_{Sd}, N_{Sd} and V_{Sd} into internal forces within the joint components relates to what is defined in Section 2 as the step number three « joint assembly » of the component method. It is not affected by the non-perpendicularity between the connected members.

Component properties

It may be shown that:

- some components are affected by the rafter inclination;
- some components are not affected at all;
- some components can no more be used as soon as the rafters are inclined.

In Table 1, the components available in Eurocode 3 Annex J are classified according to these three categories and it is seen that the influence of the rafter inclination is restricted to five com-ponents. In [5], the way to amend the related formulae for stiffness and resistance prediction is expressed.

N°	Components	Affected	Not affected	No more available
1	Column web panel in shear		×	
2	Column web in compression	×		
3	Beam flange and web in compression	×		
4	Column flange in bending	×*		
5	Column web in tension	×*		
6	End-plate in bending	×		
7	Beam web in tension		×	
8	Flange cleat in bending			×
9	Bolts in tension		×	
10	Bolts in shear		×	
11	Bolts in bearing			×
12	Plate in tension or compression			×

* For welded connections only

Table 1 Influence of rafter inclination on the component properties

5.4. Combination of applied axial forces and bending moments

Several joints are subjected to axial compressive or tensile forces in addition to in-plane bending moments and shear forces. These forces affect the joint response in terms of stiffness, resistance and rotation capacity. They can therefore not be disregarded.

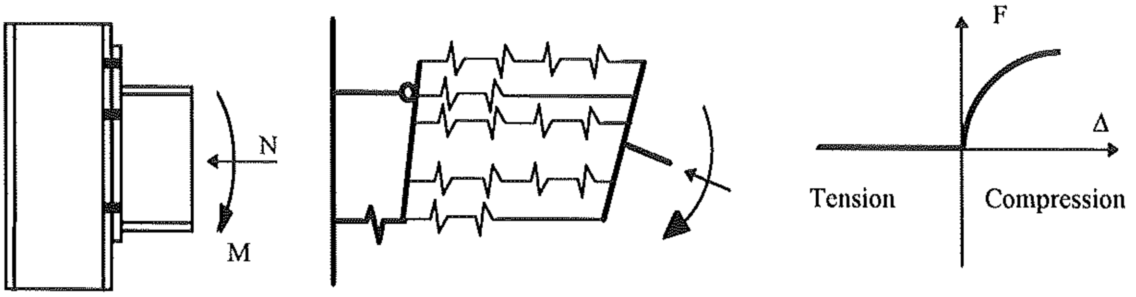
In revised Annex J of Eurocode 3, this reality has been recognized and a range of validity has been defined where it is assumed that the axial forces are not influencing significantly the joint response and where it is therefore accepted to evaluate the joint properties under bending moments and shear forces only. The related criterion writes :

$$\left|\frac{N_{Sd}}{N_{c,Rd}}\right| \leq 0,1 \qquad (5)$$

where : N_{Sd} is the axial force in the beam;
$N_{c,Rd}$ is the design resistance of the connected member in compression.

For joints which would not fulfil this "10 % rule", Eurocode 3 gives no recommendations. In fact, the designer may still refer to the component method to evaluate the joint properties - the individual response of the basic components being not dependent on the external loading of the joint,- but he has to determine by himself the procedure to assemble the components. As a matter of fact, few research works have been devoted to this topic - these are summarized in [5] - and none of them may be considered as fully satisfactory. Therefore a software approach has been worked out, in which the component method is referred to and all the aspects of stiffness, resistance and deformation capacity are taken into consideration. The software is based on a so-called mechanical model in which [5] (see Figure 5) :

- each component is simulated by an extensional spring (Figure5.b);
- the non-linear behaviour law of each component is that predicted by Eurocode 3 revised Annex J or by additional rules presented in Sections 5.1 to 5.3 of the present paper;
- the four basic requirements that any distribution of internal forces should fulfil are satisfied, i.e: (i) equilibrium between internal and external forces, (ii) compatibility of the internal displacements, (iii) limitation of the internal forces to their design values and (iv) limitation of the deformation of the components to their maximum value.



(a) Joint detailing

lechanical model

(c) Behaviour law for components (here,column web in compression)

Figure 5 Mechanical model

The deformability curve characterizing the response of the whole system is built progressively by applying successive increments of loads to the mechanical model and evaluating then the resulting deformation of the system and its constitutive components. As the components exhibit a non-linear behaviour, the solution may only be found through an iterative procedure. At each iteration, the tangential stiffness of each component is evaluated so as to reflect the actual contribution of the latter to the stiffness of the whole system .

In a second step, this sophisticated tool, aimed at reflecting as closely as possible the actual response of the joint throughout its whole loading, can then be used in the frame of parametrical studies to better understand how the joints behave, and constitute a sort of reference when validating, at the end, simplified hand calculation procedures based on the knowledge acquired in the previous research steps.

Such applications of the model to actual joint configurations and parametrical studies have been performed, in [5] and [9], which show the ability of the software to characterize the response of the specific joints here envisaged. It is however too early to publish extensive results of the work. This could be done in a near future.

6. REFERENCES

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