Ductility assessment of structural steel and composite joints

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ABSTRACT: Eurocode 3, in its Part 1-8 on the design of structural joints, and Eurocode 4 provide designers with assessment procedures for the initial rotational stiffness and the resistance of steel and composite joints respectively. These design procedures refer to the so-called component approach and have been validated through numerous comparisons with test results and numerical non-linear simulations. For beam and column members, the resistance level considered by the code is the one which could not be exceeded at ULS and it depends on the cross-section class (Class 1 to Class 4). For Class 1 cross-sections, the plastic resistance may be considered and internal rotations may take place and develop in the cross-section in the case ductility criteria are met. If plastic rotation capacity is available, a plastic global analysis of the structure may be contemplated. For connections and joints, a similar concept is to be applied, but unfortunately very few information is provided in the Eurocodes which would enable the designer to check whether enough plastic rotational capacity is locally available. In this paper, a procedure to estimate the rotation capacity of joints is presented. As for the evaluation of the stiffness and resistance properties, it refers to the component method approach. Its validity is demonstrated through comparisons with experimental data.

1 INTRODUCTION TO THE COMPONENT METHOD

1.1 *Principles of the method*

In order to account for the influence of the structural joints on the actual response of building frames, their mechanical properties, in terms of rotational stiffness, resistance and possibly deformation capacity has to be evaluated. To achieve this goal, reference is nowadays widely made (Jaspart and Weynand, 2016) to the so-called "component method" which considers any joint as a set of macroscopic "individual basic components". In the particular case of Figure 1, the relevant components are the following ones:

- 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

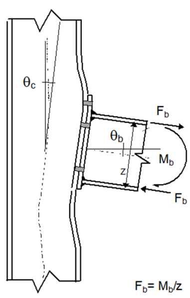


Figure 1. Joint in bending with an extended end-plate connection

Each of these basic components possesses its own level of strength and stiffness in tension compression or shear. 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 the strength and the 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 includes three successive steps:

a) listing of the "activated" or "active" components for the studied joint;
b) evaluation of the stiffness and/or strength properties of each individual basic component (specific properties - 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 properties - initial stiffness, design resistance,… or whole deformability curve).

1.2 *Field of application and levels of refinement*

The combination of all the components for which characterization rules are presently available (CEN, 2004; CEN,2005; Jaspart et al, 2005) allows covering a wide range of joint configurations, what should largely be sufficient to satisfy the needs of practitioners as far as beam-to-column joints, column bases and beam splices are concerned, whatever is the loading situation.

Besides that, the framework of the component method is such that it allows the use of various techniques for the component characterization and the 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. Similar levels of sophistication exist also, as those presented in (Jaspart and Weynand, 2016) for what regards the joint assembly.

In Eurocode 3 Part 1-8 "Design of joints" (CEN, 2005), practical application rules are provided which allow characterizing steel joints under static loading. Complementary rules for steel-concrete composite joints are available in Eurocode 4 (CEN, 2004). And in (Jaspart and Weynand, 2016), extensions of the component method are proposed to accommodate fire or earthquake conditions and to mitigate the risk of progressive collapse.

1.3 *Present limitation to the application of the component method*

Most of research efforts in the last decades have focused on the characterization of the stiffness and resistance properties of the components, while few investigations have been devoted to the prediction of their deformation capacity. This one is however a key parameter to master in different design situations as the three following ones:

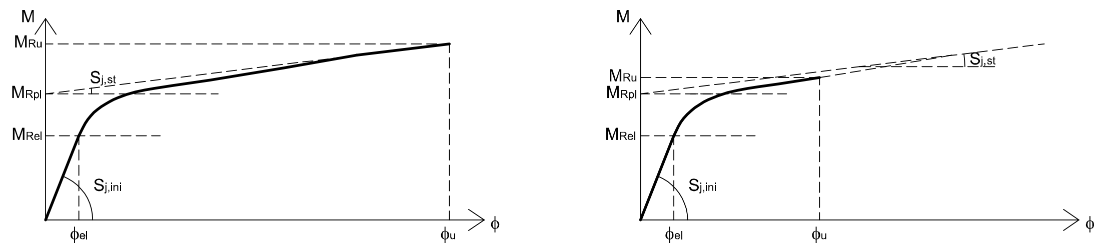
- design of a structure with partial-strength joints based on a plastic global analysis, so requiring from the joints a sufficient plastic rotational capacity;
- design of a structure to mitigate the risk of progressive collapse under exceptional loading through the use of the alternative load-path method;
- design of a structure with rather rigid but partial-strength joints under a severe earthquake, so requiring energy dissipation in the joints.

In the present paper, a general approach for the determination of the rotational capacity of joint is presented and validated through comparisons with results of experimental tests.

2 PREDICTION OF THE JOINT ROTATION CAPACITY

2.1 *General model*

The rotational response of a joint is presented in the form of an M-φ moment-rotation curve where M and φ represent respectively the bending moment to which the joint is subjected and the resultant relative rotation between the connected members. This curve may be drawn as well for joints in bending than for joints subjected to more complex loading, including additional axial forces.



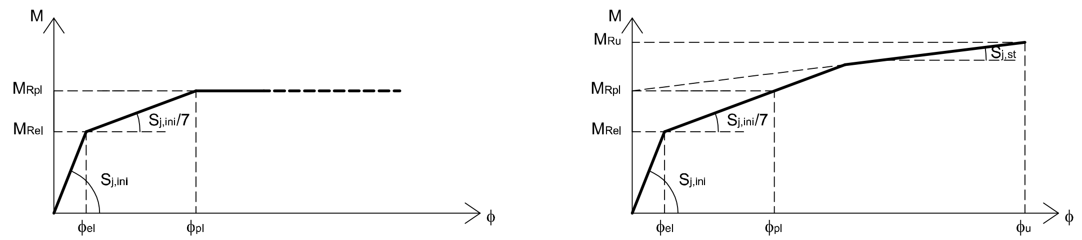
a – Well marked bi-linear response b – Less marked bi-linear response

Figure 2. Main joint properties characterising actual *M-φ* curves

For classical steel or composite joints made of welded and bolted connections, the shape of the *M-φ* curve is approximately bi-linear and may therefore be characterized by four key parameters:

- an initial stiffness $S_{j,ini}$;
- a plastic bending resistance M_{Rpl};
- a strain hardening (more generally post-plastic) stiffness $S_{j,st}$;
- an ultimate bending resistance M_{Ru}.

When no instability or early brittle failure occurs in the joint at ultimate state, M_{Ru} differs significantly from M_{Rpl}, and the bi-linear shape of the *M-φ* curve is well marked (Figure 2.a); when instability or early brittle failure occurs - for instance in the column web in compression or in bolts in tension – M_{Ru} comes closer to M_{Rpl}, what tends to give a more or less round final shape to the *M-φ* curve (Figure 2.b). Whatever the case, the ultimate rotation capacity φ_u may be derived at the intersection of the *M-φ* curve with the M_{Ru} horizontal line.



a – According to Eurocode 3 Part 1-8 b – According to the present paper

Figure 3. Simplified modelling of the joint *M-φ* curves

Several mathematical expressions integrating these four parameters may be used so as to closely approximate the non-linear character of actual *M-φ* curves. In (Jaspart, 1991), reference is made to an exponential expression and its adequacy is shown on the basis of many comparisons with experimental test results in which the four key properties were predicted through rather sophisticated analytical models. In the present paper, the approach is focusing on less complex prediction approaches, as the one proposed in Eurocode Part 1-8 (CEN, 2005).

In this European normative document, expressions are provided for the characterization and the assembly of components, but assembly procedures are only suggested for the evaluation of the initial stiffness $S_{j,ini}$ and the bending resistance M_{Rpl} of the joints. So nothing is said in terms of strain-hardening or post-plastic stiffness $S_{j,st}$ and ultimate bending resistance M_{Ru}. On the basis of the two obtained values, a simplified *M-φ* curve is built as shown in Figure 3.a. In these ones, no limit is provided to the yield plateau.

In the next paragraphs, procedures for the evaluation of the $S_{j,st}$ and M_{Ru} values on the basis of the component approach are proposed, enabling the designer to approximate the actual *M-φ* curve as shown in Figure 3.b and, in line with the objective of the present paper, to derive an estimation of the total joint rotational capacity φ_u and the plastic one (φ_u - φ_{pl}).

2.2 *Derivation of $S_{j,st}$ and M_{Ru}*

2.2.1 *Strain-hardening (post-plastic) stiffness*

In Eurocode 3 Part 1-8, the following expression is proposed for the evaluation of the initial stiffness of a joint in bending:

$$S_{j,ini} = \frac{Ez^2}{\sum_m \Sigma \frac{1}{k_{i,\mathrm{m}}}} \quad (1)$$

where:

- E is the modulus of elasticity of steel
- z is the internal level arm in the joint (see Figure 1)
- k_i is the elastic stiffness coefficient characterising each of the joint components

A similar approach is followed to derive the strain-hardening stiffness $S_{j,st}$.

This requires, in a first step, to evaluate the strain-hardening stiffness coefficient for each basic component. Studies of numerous test results on components (Jaspart, 1991) allow proposing the following expressions:

$$k_{st} = \frac{E_{st}}{E} k_i \quad (2.a)$$

for: column webs in compression/tension and column flanges and end plates in bending;

$$k_{st} = \frac{2(1+\nu)}{3} \frac{E_{st}}{E} k_i \quad (2.b)$$

for: column web panels in shear

where:

k_{st} is the strain-hardening stiffness coefficient;
k_i is the initial stiffness coefficient;
E_{st} is the strain-hardening modulus of elasticity,
ν is the steel Poisson coefficient.

In a second step, the assembly procedure has to be contemplated. This one is highly dependent on the relative importance of the design moment resistance $M_{Rpl,comp\ i}$ of each individual basic component, $M_{Rpl,comp\ i}$ being calculated by considering temporally the component as the only active component in the joint, when compared to joint design moment resistance M_{Rpl}.

For instance, let assume a joint in which one of the components is much weaker than the others. $S_{j,st}$ will result, in such a case, from the combination of the strain-hardening stiffness of the weak component and the initial stiffness of the others; as a matter of fact, the latter remain in the elastic range of behaviour for applied moments higher than M_{Rpl}, while the former is in its strain-hardening range of behaviour.

In more usual joints, the successive apparition of yielding in the different components during the joint loading beyond M_{Rpl} leads to a progressive decrease of the actual strain-hardening stiffness in comparison with the previous case. The complexity of the problem has been overcome in (Jaspart, 1991) as explained here below.

Each component which possesses a high design moment resistance in comparison with M_{Rpl} will contribute in an elastic way to $S_{j,st}$, which, in fact, should probably be better called “post-limit” stiffness. In the contrary, a component, the design resistance of which is closer to M_{Rpl} will experience strain-hardening and will affect more significantly $S_{j,st}$. The simplified evaluation of $S_{j,st}$ consists therefore in the classification of the components according to their design resistance $M_{Rpl,comp\ i}$ in order to distinguish those which will contribute to $S_{j,st}$ by means of their initial elastic stiffness coefficient k_i from those which will contribute by means of the strain-hardening coefficient k_{st}. A deep study of experimental tests on joints with endplates has allowed the determination of a boundary value of the moment capacity:

$$M_{Rpl,\mathrm{limit}} = 1{,}65 M_{Rpl} \quad (3)$$

which allows to classify the components (elastic contribution to $S_{j,st}$ if $M_{Rpl,comp\ i} > M_{Rpl,limit}$; strain-hardening contribution if $M_{Rpl,comp\ i} \leq M_{Rpl,limit}$).

The strain-hardening stiffness of the joint $S_{j,st}$ may therefore be evaluated as follows:

$$S_{j,st} = \frac{Ez^2}{\sum \frac{1}{k^*}} \tag{4}$$

where:

$$\sum \frac{1}{k*} = \sum_m \left(\frac{1}{k_{i,\mathrm{m}}}\right)_{M_{Rpl,\mathrm{comp},j} > M_{Rpl,\mathrm{limit}}} + \sum_k \left(\frac{1}{k_{st,k}}\right)_{M_{Rpl,\mathrm{comp,k}} \leq M_{Rpl,\mathrm{limit}}} \tag{5}$$

k and m are component indices.

2.2.2 *Ultimate moment resistance*

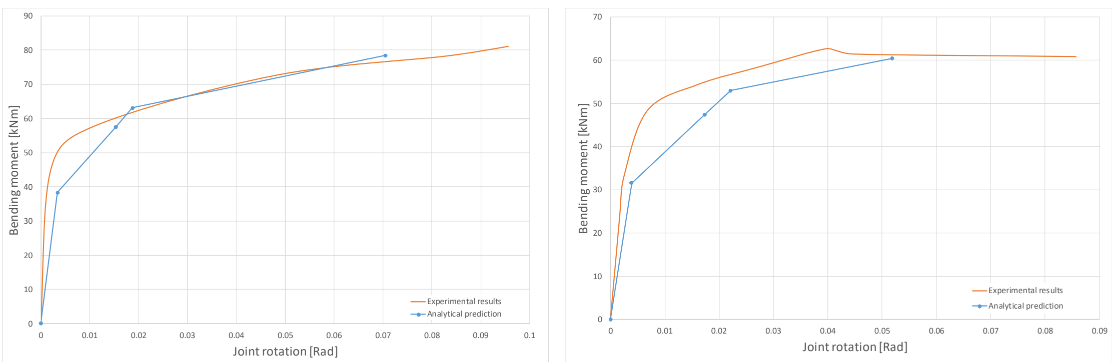
A good estimation of the ultimate moment resistance M_{Ru} of the joint may simply be obtained by substituting:

- the yield stress of the steel material f_y by the ultimate stress f_u;
- the design resistance of the bolt in tension by the ultimate resistance of the bolt in tension (stress area times ultimate yield strength);

in the formulae proposed in (CEN, 2005) for the evaluation of the joint design moment resistance M_{Rpl}. The risks of instability of the column web in compression and of the beam flange in compression have however not to be forgotten. As for M_{Rpl}, the ultimate moment resistance M_{Ru} is associated to the ultimate resistance of the weakest component.

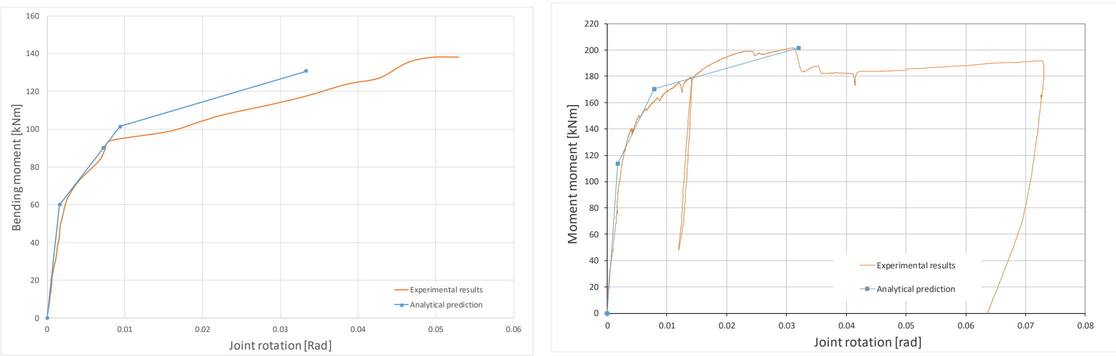
2.3 *Comparisons of full M-φ curves with the simplified proposed model*

Numerous comparisons are presented in (CEN, 2005), for various connection types, and the good agreement between the prediction of the four key values characterizing the joint response, coupled to the use of an exponential *M-φ* joint model, and the test results have allowed to validate the analytical procedure. The fact that series of tests performed by different persons in different laboratories have been considered in this comparative study is likely to increase the confidence in the model. Examples of such comparisons are given in Figure 4, but this time through the use of the simplified *M-φ* joint model presented in Figure 3.b, referring to various failure modes (endplate in bending, column web in compression and concrete reinforcement bars in tension). A quite good agreement is generally obtained, except in cases of thin endplates (or column flanges) in which membrane effects result from the high ultimate component displacements. The predicted rotation capacity is there a bit, but anyway safely, underestimated.



a – Test 07 on a single-sided joint with an extended endplate connection (Jaspart, 1991)

b – Test 013 on a single-sided joint with an extended endplate connection (Jaspart, 1991)



c – Test T9 on a single-sided joint with an extended endplate connection (Zoetemeijer, 1974)

d – Test T1 on a composite joint with an flush endplate steel connection (Demonceau & Jaspart, 2004)

Figure 4. Comparisons between predicted and M-φ curves

2.4 *Evaluation formula for the joint rotational capacity*

As a result, finally, the ultimate rotation capacity of the joints may be evaluated as equal to:

$$\varphi_u = (M_{Ru} - M_{Rpl}) \,/\, S_{j,st} \tag{6}$$

and the plastic rotation capacity (see Figure 3) as:

$$\varphi_u - \varphi_u = (M_{Ru} - M_{Rpl}) \,/\, S_{j,st} - 3M_{Rpl} \,/\, \mathrm{S}_{\mathrm{j,ini}} \tag{7}$$

3 CONCLUSIONS

Present paper proposes an analytical procedure for the evaluation of the ultimate and plastic rotational capacities of joints based on the application of the component approach. It complements provisions provided by the Structural Eurocodes for the design of steel and composite steel-concrete joints. Its application should be of particular interest for the plastic analysis of structures with partial-strength joints, for the design of appropriate joints in structures under seismic actions or even for the justification of the sufficient structural robustness of a building subjected to an extreme exceptional event.

REFERENCES

CEN, 2004. *Eurocode 4: Design of composite steel and concrete structures - Part 1-1: General rules and rules for buildings*, Brussels, European Committee for Normalisation.

CEN, 2005. *Eurocode 3: Design of steel structures - Part 1-8: Design of joints*, Brussels, European Committee for Normalisation.

Demonceau, J.-F. & Jaspart J.-P, 2004. *Experimental and analytical investigations on single-sided composite joint configuration*, 5th International PhD Symp. in Civil Engineering, Balkema, pp. 341-349.

Jaspart, J.P., 1991. *Etude de la semi-rigidité des nœuds poutre-colonne et son influence sur la résistance et la stabilité des ossatures en acier*, PhD Thesis, Liège University.

Jaspart, J.P. & al, 2005. *Development of a full consistent design approach for bolted and welded joints in building frames and trusses between steel members made of hollow and/or open sections*, CIDECT report 5BP, Comité International pour l'Etude et de Développement de la Construction Tubulaire.

Jaspart, J.P. & Weynand, K., 2016. *Design of joints in steel and composite structures*, ECCS Eurocode Design Manual, Wiley, Ernst & Sohn.

Zoetemeijer, P., 1974. *A design method for the tension side of statically loaded, bolted beam-to-column connections*. Heron, Netherlands, Vol. 20, N°1.