Unified Design Concept for Structural Joints in Building Frames Application to Composite Construction

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ABSTRACT

In Eurocode 3 (Eurocode 3 1992) on steel buildings, the design of structural joints is covered by Chapter 6 and, for joints between H or I profiles, by Annex J. During the recent revision of Annex J (Revised Annex J of Eurocode 3 1998), a new comprehensive design approach for the design of joints mainly subjected to bending moments has been developed and the so-called "component method" has been introduced as a basic procedure for the derivation of the rotational stiffness and strength properties of the structural joints, whatever is the joint configuration (single-sided or double-sided beam-to-column joints, beam splices, ...) and the connection type (welded connections, bolted connections with end-plates, flange cleats, ...). More recently, the application of the component method has been extended to base plates configurations (COST C1 a 1999) and composite steel-concrete joints (COST C1 b 1999).

In the present paper, the new design approach suggested by Eurocode 3 is presented and its application to beam-to-column composite joint is briefly addressed.

THE CONCEPT OF JOINT REPRESENTATION

During many years, the research activity in the field of structural joints mainly concentrated on two aspects:

- the evaluation of the mechanical properties of the joints in terms of rotational stiffness, moment resistance and rotation capacity;
- the analysis and design procedures for frames including the actual joint behaviour.

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But progressively it has been understood that there were intermediate steps to consider in order to integrate in a consistent way the actual joint response into the frame analysis; this is known as the *joint representation*.

The joint representation includes four successive steps respectively named:

- ***the joint characterisation***
  i.e. the evaluation through appropriate means of the rotational stiffness, resistance and ductility properties of the joints (full M-φ curves or key values – M is the applied moment and φ is the relative rotation between the connected members);
- ***the joint modelling***
  i.e. the way on how the joint is physically represented in view of the frame analysis;
- ***the joint classification***
  i.e. the tool providing boundary conditions for the use of conventional types of joint modelling (e.g. rigid or pinned);
- ***the joint idealisation***
  i.e. the derivation of a simplified moment-rotation curve so as to fit with specific analysis approaches (e.g. linear idealisation for an elastic analysis).

These four items are discussed in the next pages.

<u>Joint characterisation</u>

The procedure adopted in Revised Annex J for the characterisation of mechanical properties of the structural joints is based on the "component method".

In the characterisation procedures, a joint is generally considered as a whole and is studied accordingly; 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 (single-sided beam-to-column joint with an extended end-plate connection subject to bending), the relevant components are the following :

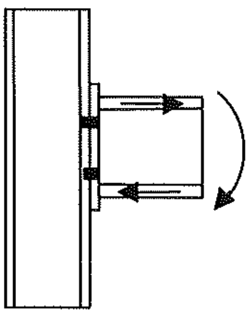


Fig. 1. Steel joint with an end-plate

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

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 of each individual basic component (Jaspart, J.P. 1997); 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) identification of the active components for the studied joint;

b) evaluation of the mechanical characteristics of each individual basic component (specific characteristics - initial stiffness, design strength, ... - or the whole deformability curve);

c) "assembly" of the components in view of the evaluation of the mechanical characteristics of the whole joint (specific characteristics - initial stiffness, design resistance, ... - or the whole deformability M-φ curve).

These three steps are schematically illustrated in Figure 2 in the particular and simple case of a steel beam-to-column joint with a welded connection.

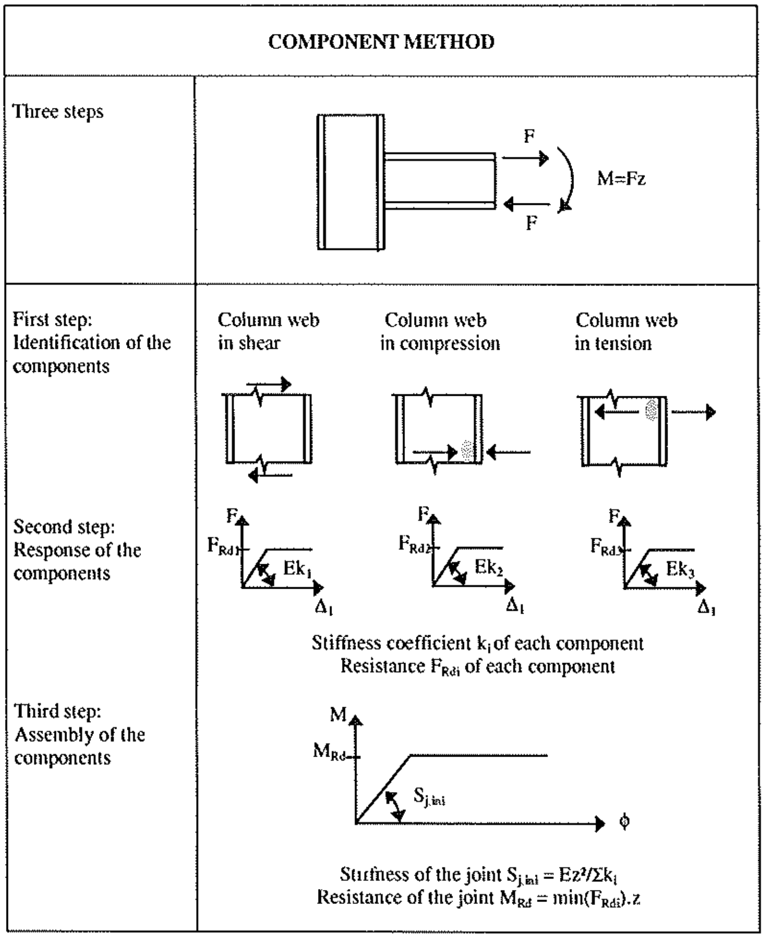


Figure 2. Application of the component method to a welded steel joint (simplified bi-linear component and joint deformability curves)

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 according to the instantaneous stiffness and resistance of each component. Distributions of internal forces may be obtained through different ways as discussed in (Jaspart, J.P. 1997).

The application of the component method requires a sufficient knowledge of the behaviour of the basic components. The components active in the traditional steel joints have been deeply studied and recommendations for their characterisation are given in the Revised Annex J of Eurocode 3. 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 are concerned. Rules for extra components are available in the scientific literature; through their use the characterisation of the following joints may contemplated:

- Weak axis joints where the beam is connected to the web of a H or I column profile (Jaspart, J.P. 1997);
- Joints between I beam profiles and tubular columns (Vandegans, D. 1996);
- Joints subject to bending moment (and shear) and axial compression or tension forces (Jaspart, J.P. 1997);
- Steel joints with beam haunches, end-plate stiffeners or high strength steels (Jaspart, J.P. 1997);
- Joints in pitched-roof portal frames where beams and columns form an angle higher than 90° (Jaspart, J.P. 1997);
- Joints between slender built-up welded profiles (Jaspart, J.P. 1997).

In the ongoing conversion process of Eurocode 3 from a pre-standard to a full European norm, material on column bases (COST C1 a 1999) has also be added. In (COST C1 b 1999) it is shown that the extension of the component method to steel-concrete composite joints may be easily contemplated through the development of detailed rules for specific new components (reinforcement bars in tension, ...).

Preliminary works also indicate that the component method seems also suitable for the characterisation of joints subjected to extreme loading conditions as earthquakes or fire, but also to joints in pre-cast and timber construction. So it may reasonably be thought nowadays that an unified characterisation procedure for all structural joints is now developing and will be the common basis for the future design codes whatever is the material or the combination of materials used. This is likely to lighten the work of the designers, in particular when composite construction is of concern (the composite action between the materials is or not effective according to the erection stages and both the calculation of the steelwork connection and composite connection have to be performed).

Joint modelling

Joint behaviour affects the structural frame response and shall therefore be modelled, just as for beams and columns, for the frame analysis and design. Traditionally, the following types of *joint modelling* are considered :

For rotational stiffness :
- rigid
- pinned

For resistance :
- full-strength
- partial-strength
- pinned

When the joint rotational stiffness is of concern, the wording *rigid* means that no relative rotation occurs between the connected members whatever is the applied moment. The wording *pinned* postulates the existence of a perfect (i.e. frictionless) hinge between the members. In fact these definitions may be relaxed. Indeed rather flexible but not fully pinned joints and rather stiff but not fully rigid joints may be considered respectively as effectively pinned and perfectly rigid. The stiffness boundaries allowing one to classify joints as rigid or pinned are discussed in the next section.

For joint resistance, a *full-strength joint* is stronger than the weaker of the connected members, which is in contrast to a *partial-strength joint.* In the everyday practice, partial-strength joints are used whenever the joints are designed to transfer the internal forces but not to resist the full capacity of the connected members. A *pinned joint* is considered to transfer only a limited moment. Related classification criteria are also introduced in the next section.

Consideration of rotational stiffness and joint resistance properties leads traditionally to three significant joint models: rigid/full-strength, rigid/partial-strength and pinned.

However, as far as the joint rotational stiffness is considered, joints designed for economy may be neither rigid nor pinned but semi-rigid. There are thus new possibilities for joint modelling: semi-rigid/full-strength and semi-rigid/partial-strength.

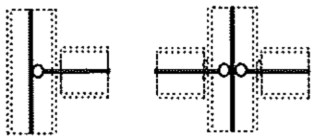
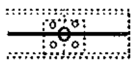
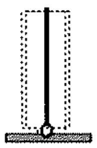
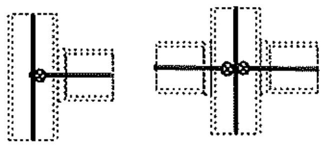
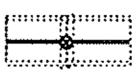
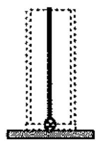
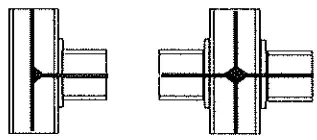
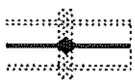
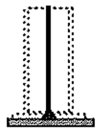
With a view to simplification, Eurocode 3 accounts for these possibilities by introducing three joint models (Table 1) :

- *continuous* : covering the rigid/full-strength case only;
- *semi-continuous* : covering the rigid/partial-strength, semi-rigid/full-strength and semi -rigid / partial-strength cases;
- *simple* : covering the pinned case only.

Table 1. Types of joint modelling

STIFFNESS	RESISTANCE		
	Full-strength	Partial-strength	Pinned
Rigid	Continuous	Semi-continuous	*
Semi-rigid	Semi-continuous	Semi-continuous	*
Pinned	*	*	Simple
* : Without meaning			

Table 2. Simplified modelling of joints for frame analysis

JOINT MODELLING	BEAM-TO-COLUMN JOINTS MAJOR AXIS BENDING	BEAM SPLICES	COLUMN BASES
SIMPLE			
SEMI-CONTINUOUS			
CONTINUOUS			

The interpretation to be given to these wordings depends on the type of frame analysis to be performed. In the case of an elastic global frame analysis, only the stiffness properties of the joint are relevant for the joint modelling. In the case of a rigid-plastic analysis, the main joint feature is the resistance. In all the other cases, both the stiffness and resistance properties govern the manner in which the joints should be modelled.

The usual physical representation of the joints for frame analysis is illustrated in Table 2 (use of rotational springs for semi-continuous construction).

<u>Joint classification</u>

- ***Stiffness Classification***

The stiffness classification into rigid, semi-rigid and pinned joints is performed by simply comparing the design joint stiffness to two stiffness boundaries (Figure 3). For sake of simplicity, the stiffness boundaries are derived so as to allow a direct comparison with the *initial design* joint stiffness, whatever the type of joint idealisation that is used afterwards in the analysis. The value of the stiffness boundaries vary according to the "braced" or "unbraced" character of the structural system.

- ***Strength Classification***

The strength classification simply consists of comparing the joint *design* moment resistance to "full-strength" and "pinned" boundaries (Figure 4).

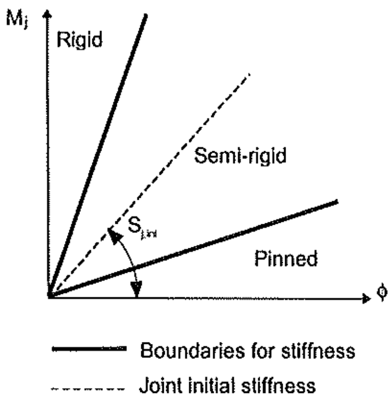


Figure 3. Stiffness classification boundaries

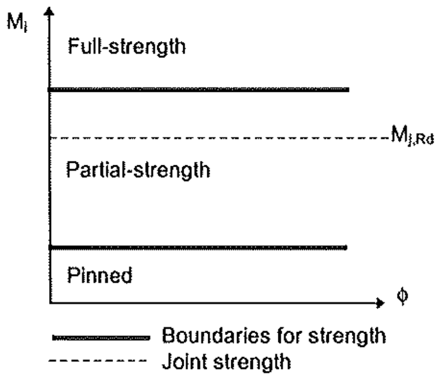


Figure 4. Strength classification boundaries

- ***Ductility Classes***

Experience and proper detailing result in so-called *pinned* joints which exhibit a sufficient rotation capacity to sustain the rotations imposed on them. For moment resisting joints the concept of ductility classes is introduced to deal with the question of rotation capacity.

Rather few studies have been devoted to the evaluation of the rotation capacity of joints. This is clearly illustrated in Eurocode 3 Revised Annex J where only a quite limited amount of information is given. Criteria should therefore be established to distinguish between "ductile", "semi-ductile" and "brittle" joints. Ductile joints are suitable for plastic frame analysis while brittle ones do not allow any redistribution of internal forces. The use of semi-ductile joints in a plastically designed frame can only result from a preliminary comparison between the available and required rotation capacities.

Joint idealisation

The non-linear behaviour of the isolated flexural spring (see Table 2) which characterises the actual joint response for frame analysis does not lend itself towards everyday design practice. However the moment-rotation characteristic curve may be idealised without significant loss of accuracy. One of the most simple possible idealisations is the elastic-perfectly plastic relationship (Figure 5.a). This modelling has the advantage of being quite similar to that used for the modelling of member cross-sections subject to bending (Figure 5.b).

The moment $M_{j,Rd}$ that corresponds to the yield plateau is termed the *design moment resistance* in Eurocode 3. It may be considered as the *pseudo-plastic moment resistance* of the joint. Strain-hardening effects and possible membrane effects are henceforth neglected, which explains the difference in Figure 5.a between the actual M-ϕ characteristic and the *yield plateau* of the idealisation.

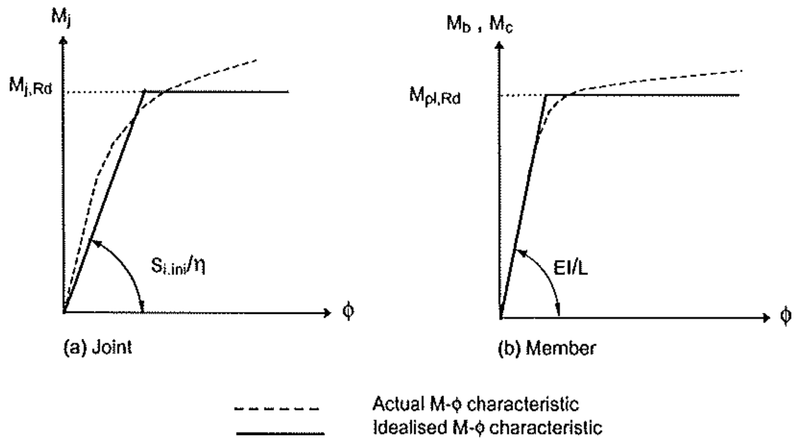


Figure 5. Bi-linearisation of moment-rotation curves

The value of the joint constant stiffness $S_{j.ini}/\eta$ is discussed in (Jaspart, J.P. 1997) and practical values are given in Eurocode 3 Revised Annex J for steel joints and in the latest draft of Eurocode 4 for composite ones (see also ECCS Technical Committee 11 1999). This coefficient results from the high non-linearity of the joint M-φ curves in comparison to those of the members.

APPLICATION OF THE COMPONENT METHOD TO COMPOSITE JOINTS

By referring to the component method, a composite joint is seen as a steel joint with a steelwork connection to which some new "composite" components have been added (Figure 6):

- longitudinal reinforcement in tension (under hogging moments);
- slab (or part of it) in compression (under sagging moments);
- possible slip at the interface between the steel beam and the reinforced slab;
- slab in compression against the column (in case of unbalanced loading).

Therefore the component method applies similarly than explained before as soon as design rules for the prediction of the stiffness and resistance properties of the new components are now. In (COST C1 b 1999), such rules are presented and their good agreement with experimental test

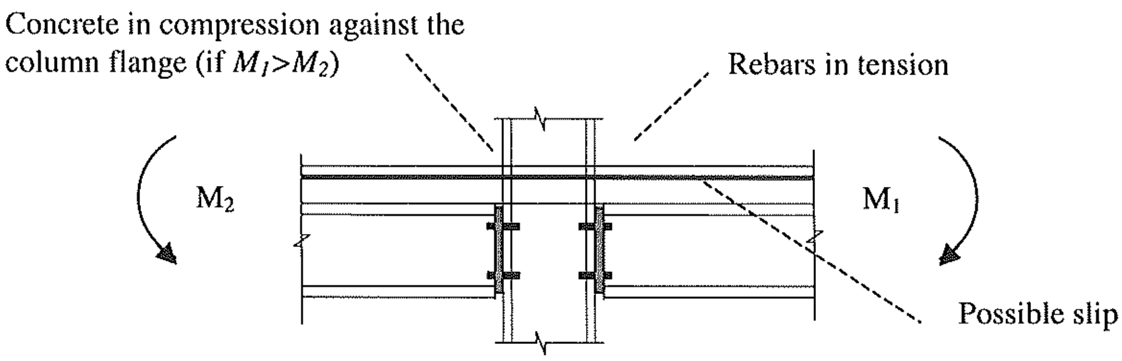


Figure 6. New "composite" components in a composite joint ($M_1 > M_2$)

results on components is shown. Background explanations on these rules are also provided. In this publication, information is finally given on how much the stiffness and the resistance properties of column webs in compression or in shear are improved in cases where partially encased columns are used.

All these rules have now been implemented in the latest draft of Eurocode 4 and simple design tools for practical applications have been made available in (ECCS Technical Committee 11 1999) for composite beam-to-column joint configurations with contact plates, header plates or flush end-plates.

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