Design of beam-to-column steel-concrete composite joints: From Eurocodes and beyond

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ABSTRACT: The design of beam-to-column structural joints and, in particular, of steel-concrete composite joints is covered in the Eurocodes through the application of the well-known component method which is nowadays recognized as one of the most appropriate analytical method for the characterization of joints. However, even if the concept behind the component method allows the covering of a wide range of joint configurations and of loading situations, the detailed application rules as presently provided in the Eurocodes allow to only cover specific loading situations. It is particularly the case for composite joints for which their characterization is only possible for hogging moments. In the present paper, it is proposed to provide a global overview of recent researches which aimed at overcoming this limitation and at proposing new application rules for new loading conditions met in actual design projects.

1 INTRODUCTION

Nowadays, the component method is recognized as a reference analytical approach able to predict accurately the main mechanical characteristics of structural joints. In particular, this method is behind the design recommendations reported in the Eurocodes and, in particular, in Eurocode 3, Part 1-8 (EN 1993-1-8 2010) dedicated to steel joints and in Eurocode 4, Part 1-1 (EN 1994-1-1 2004) which provides additional rules to allow the characterization of steel-concrete composite joints.

The application of the component method requires three main steps (J.-P. Jaspart and Weynand 2016):

1. the identification of the joint components activated under the considered loading condition;
2. the characterization of the so-identified individual basic components in terms of stiffness and/or resistance and;
3. the assembly of all the individual basic components to determine the stiffness and/or the resistance of the whole joint.

The component method can be seen as an application of the finite element approach at a macro scale in which the activated basic components are represented by springs as illustrated in

Figure 1 and through which the mechanical properties of the whole joint are obtained by applying the principles of the static and cinematic theorems.

As mentioned above, the application of the component method requires rules for the characterization of the basic components; the ones covered in Eurocode 3, Part 1-8 and in Eurocode 4, Part 1-1 are listed in Table 1. In addition, Eurocode 4, Part 1-1 also provides rules for components for which their mechanical properties are affected by the possible presence of concrete, i.e. the column web panel in shear and the column web in compression.

Figure 1. Example of a spring model for a composite flush end-plate connection subjected to hogging moments (Anderson 1999).

Table 1. Joint components covered by Eurocode 3, Part 1-8 (components 1 to 12) and Eurocode 4, Part 1-1 (components 13 and 14).

N°	Joint components	N°	Joint components
1	Column web panel in shear	8	Flange cleat in bending
2	Column web in compression	9	Bolts in tension
3	Beam flange and web in compression	10	Bolts in shear
4	Column flange in bending	11	Bolts in bearing
5	Column web in tension	12	Plate in tension or compression
6	End-plate in bending	13	Longitudinal steel rebars in tension
7	Beam web in tension	14	Steel contact plate in compression

With the so-available joint components, it is possible to characterize a wide range of structural joint configurations and to predict their main mechanical properties, i.e. their stiffness, their resistance in bending and their resistance in shear. Also, the Eurocodes allows estimating their ability to exhibit a sufficient ductility for the realization of a plastic analysis (with plastic hinges forming at the level of the joints) even if an explicit computation of the joint ductility or rotation capacity is not possible.

But, looking closer to the rules provided in the Eurocodes regarding composite joints, it can be observed that rules are only provided to predict the resistance of composite joints under shear forces and hogging moments.

However, the design of composite structures considering actions such as earthquake, fire... or the request for robustness in case of exceptional event requires to be able to characterize composite joints under other loading conditions, i.e. under sagging bending, under cyclic loading, under combined moment and axial force (M-N), under elevated temperature or under dynamic loading.

Within the present paper, it is proposed to give a global overview of some recent researches conducted in the field of composite joints; in particular, it will be demonstrated how the component method can be easily adapted to cover new loading conditions.

Section 2 first addresses the behavior of composite joints under sagging moment. Then, Section 3 deals with the behavior of composite joints under M-N and Section 4 with the behavior of composite joints at elevated temperature. Section 6 presents recent investigations on the behavior of joints subjected to dynamic loading and finally, Section 7 reports on a method allowing predicting the ductility of joints and, in particular, of composite joints.

2 COMPOSITE JOINTS UNDER SAGGING MOMENT

Under usual loading conditions, composite beam-to-column joints are mainly subjected to shear forces and hogging moments. However, for some specific loading conditions such as moment resisting frames subjected to significant horizontal forces (for instance associated to

an earthquake) or composite frames subjected to a column loss scenario, sagging moments may occur at the level of the joints.

Looking to the global concept behind the component method as presented in the previous section, the latter is applicable whatever are the loading conditions if the designer is able (i) to characterize the activated basic components and (ii) to proceed with the assembly of the basic components. For composite joints under sagging moment, the assembly procedure as proposed in the Eurocodes can be extended in a straightforward way to cover this specific loading condition. But the characterization of composite joints under sagging moments requires the characterization of a new component which is not reported in Table 1 and so not yet covered in the Eurocodes: the concrete slab in compression. Indeed, when a sagging moment is applied at the level of a composite joint, the bottom part of the connection is subjected to tension while the upper part which is mainly composed of the slab connected to the beam is subjected to compression (Figure 2).

In the last decades, the behavior of composite joints under sagging moments have been studied through different researches ((Liew, Teo, and Shanmugam 2004; Ferrario 2004; J.-F. Demonceau 2008; J.-F. Demonceau et al. 2008; Braconi, Elamary, and Salvatore 2010; Piluso, Rizzano, and Tolone 2012) amongst other). In particular, in (J.-F. Demonceau 2008), it is proposed to characterize the “concrete slab in compression” through the definition of an equivalent cross-section with an effective width as proposed in (Ferrario 2004) and with a height defined as proposed in (Liew, Teo, and Shanmugam 2004):

- The effective width is taken as equal to $b_{eff,conn} = b_c + 0.7h_c \leq b_{eff}$ where b_c is the width of the column profile flange, h_c the height of the column profile cross section and b_{eff} , the effective width of the concrete/composite slab to be considered for the beam in the vicinity of the joint; b_c represents the contribution of the concrete in contact with the column flange while $0.7h_c$ is the contribution of the developed concrete rods in the “strut-and-tie” behavior (Figure 3);
- The height of the equivalent cross-section is computed expressing the equilibrium between the compression developing in the concrete slab and the components activated in tension assuming a rectangular stress distribution in the concrete (equal to $f_{cd} = 0.85 f_{ck}/\gamma_c$ in a design as recommended in Eurocode 4, Part 1-1 – see Figure 2):

$$z = \frac{\sum_i F_{Rd,i}}{b_{eff,conn} \cdot (0.85 f_{ck} / \gamma_c)} \leq h_{concrete}$$

where $h_{concrete}$ is the total height of the concrete slab (in case of a composite slab, $h_{concrete}$ is equal to the concrete above the ribs), f_{ck} is the characteristic strength of the concrete, γ_c is the safety coefficient for the concrete material and $F_{Rd,i}$ is the tensile resistance of bolt row i .

The resistance of the “concrete slab in compression” can be obtained using the following formula, assuming that the latter is located at mid-height of the contributing part of the slab (z):

Figure 2. Composite joint subjected to sagging moment (J.-P. Jaspart and Weynand 2016).

Figure 3. Development of a strut-and-tie behavior in the vicinity of the joint – Definition of an equivalent effective width (J.-F. Démonceau et al. 2008).

$$F_{Rd,CSC} = b_{eff,comm} \cdot z \cdot f_{cd}$$

In (J.-F. Démonceau et al. 2008), a proposal for the characterization of this component in terms of stiffness is also made and is founded on an approach which is proposed in (Weynand 1999) for the characterization of a concrete block against a rigid plate, configuration which can be met in column bases:

$$k_{csc} = \frac{E_{cm} \cdot \sqrt{b_{eff,comm} \cdot z}}{1,275 \cdot E_a}$$

where E_{cm} is the secant Young modulus for the concrete, E_a , the elastic Young modulus for the steel and k_{csc} , the stiffness of the component “concrete slab in compression” to be used in the component method.

The so-proposed model for the characterization of the new component “concrete slab in compression” has been validated in (J.-F. Démonceau 2008) through comparisons to experimental tests results performed in the framework of RFCS European projects (Bitar et al. 2006; Bursi et al. 2008). Such an example of validation is presented in Figure 4 where the prediction obtained through the proposed analytical model is compared to experimental tests performed in Trento (Bursi et al. 2008) on single sided composite joints in isolation. It can be observed on this figure that two experimental curves are reported; the two reported tests differ from the configuration of the slab: TEST 2 joint is made of a composite slab while TEST 3 joint is made of a concrete slab. From the comparison, it can be seen that a very good agreement is reached between the analytically predicted curve and the experimental ones, at least

Figure 4. Composite joint under sagging moment – comparison of the analytical prediction to experimental results (J. Démonceau and Ciutina 2019).

up to point A, i.e. up to the plastic resistance of the studied joint which corresponds to the targeted value with the component method as presently proposed in the Eurocodes. How to obtain analytically the rest of the curve, i.e. the part of the curve after point A, will be discussed in Section 6. This demonstrate how the component method can be easily adapted to new loading conditions.

3 COMPOSITE JOINTS UNDER M-N INTERACTION

When a structure is subjected to a column loss scenario, the joints which are initially subjected to shear forces and bending moments are progressively subjected to axial forces while the membrane forces are developing in the structure (J.-F. Demonceau and Jaspart 2010). In particular, if partial strength joints are met at the extremities of the beams, this transition from a pure bending mode to a bending plus axial force mode takes place when the joints are already yielded in bending; accordingly, this transition can only occur if a sufficient ductility is available at the level of the yielded joints. The mastering of this process requires to be able to accurately predict the response of joints under M-N interaction.

If reference is made to the Eurocodes, the characterization of joints under M-N is covered through a simplified approach proposed in Eurocode 3, Part 1-8, for steel joints. In this approach, it is assumed that the influence of M-N interaction can be disregarded as long as the axial force N_{Ed} applied to the joint is smaller than 5% of the axial design plastic resistance of the connected beam cross-section $N_{pl,Rd}$. Above this limitation, a linear interaction between M and N is assumed. The so-defined criterion is illustrated in Figure 5.

However, it has been demonstrated in (Cerfontaine 2003) that this criterion does not allow to accurately predict the actual resistant curve of steel joints under M-N and can even provide an unsafe prediction of the joint resistance. Also, this procedure is proposed for steel joints but nothing is proposed for composite ones; this mainly comes from the “5 %” criterion for which no scientific background is provided and which is quite questionable.

For all these reasons, the behavior of joint under M-N has been the topic of different researches in the past decades ((Simões Da Silva and Girão Coelho 2001; Kuhlmann et al. 2008; Rodrigues et al. 2010; Gao et al. 2019) amongst other).

In particular, a new analytical model has been recently developed at the University of Liège and is presented in (Jean-François Demonceau, Cerfontaine, and Jaspart 2019). The proposed model is in full agreement with the component method philosophy (and so with the Eurocode philosophy) and is funded on a new assembly approach to account for the combined

Figure 5. M-N resistant interaction curve proposed in Eurocode 3, Part 1-8 (Jean-François Demonceau, Cerfontaine, and Jaspart 2019).

application of axial forces and moments on the joints. The applicability of the proposed model to steel and steel-concrete composite joints has been checked comparing the analytical predictions obtained with the model to experimental test results.

The validation of the model through comparisons to experimental test results obtained at the University of Stuttgart in the framework of a RFCS project (Kuhlmann et al. 2008) is illustrated in

Figure 6. The five reported tests relate to a single joint configuration but have been realized so as to cover the “M-N” interaction domain, including sagging and hogging moments, but also axial tension forces.

On Figure 6, two analytically predicted curves are given:

- one named “plastic resistance curve” obtained using the actual elastic strengths of the materials and;
- one named “ultimate resistance curve” computed using the actual ultimate strengths of the materials.

Through this comparison, it can be seen that the analytical curves are in very good agreement with the experimental ones. Indeed, it appears that the experimental curves are between the plastic analytical resistance curves and the ultimate analytical resistance curves; this corresponds to the loading sequence followed during the tests.

On Figure 6, the curves which would have been obtained using the Eurocode 3 criterion reported in Figure 5 are also provided. It can be observed that the latter does not allow to accurately predict the experimental results; this confirms the inadequacy of the criterion presently proposed in the Eurocodes.

Figure 6. Comparison between the predicted analytical curves and the experimental ones (J. F. Demonceau, Cerfontaine, and Jaspert 2019).

4 COMPOSITE JOINTS AT ELEVATED TEMPERATURES

In case of fire, joints can also be subjected to M-N interactions:

- bending and compression due to the dilatation of the members at the beginning of the fire and;
- bending and tension due to the development of membrane forces at the end of the fire when significant deformations and displacements are appearing.

But, in addition to these combined loadings, the joints are also subjected to elevated temperatures which affect their properties.

The characterization of composite joints under M-N and at elevated temperature has been investigated in the framework of a European RFCS project called ROBUSTFIRE (J. Demonceau et al. 2012) dedicated to the investigation of the response of car parks subjected to a localized fire leading to a column loss. In particular, experimental tests on joints subjected to M-N combinations and to elevated temperatures were conducted at the University of Coimbra. With the so-obtained test results, it was then possible to validate the adaptation of the model mentioned in the previous section to accurately predict the response of joints at elevated temperature (Haremza et al. 2016). This adaptation requires to predict first the temperatures of the different activated components and then to account for the effects of these temperatures on the component properties.

An example of comparisons between the analytical prediction and experimental results obtained for a composite joint subjected to a temperature of 700°C is provided in Figure 7. The accuracy of the proposed model prediction can be observed.

5 BEHAVIOUR OF COMPOSITE JOINTS UNDER CYCLIC LOADING

According to Eurocode 8, Part 1 (EN 1998-1 2004), the seismic design of composite structures is based on the concept of dissipative structures, in which specific zones of the structures are identified and designed to develop plastic deformations in order to dissipate the seismic energy. In moment resisting frames, the beam extremities are generally used as dissipative zones, and the beam-to-column joints are designed in order to resist to the internal forces associated to the development of plastic hinges at the beam extremities. However, such an approach may lead to quite expensive joint solutions, mainly due to the fact that the possible overstrength and strain hardening effects developing in the dissipative zones have to be taken

Figure 7. Double-sided composite joint at 700°C - Analytical prediction vs. experimental results (Haremza et al. 2016).

into account when designing the non-dissipative zones. EN 1998-1 allows the use of partial-strength joints as dissipative zones but, in this case, the ductility and the dissipation capacity of the joints should be demonstrated by means of experimental tests, which is not realistic for practical projects.

Through different recent researches, the ability of composite joints in dissipating the seismic energy through an appropriate level of ductility has been investigated, mainly through experimental investigations ((Braconi, Elamary, and Salvatore 2010; Ciutina, Aribert, and Lachal 2004; Lee and Lu 1989; Dubina, Ciutina, and Stratan 2002; Ferrario 2004) amongst other). Through these investigations, it has been demonstrated that it is possible to reach the level of rotation capacity under cyclic loading as required in Eurocode 8, Part 1, to dissipate sufficient energy at the joint level, i.e. 35mRad for high seismic zone. This requires to ensure the activation of ductile joint components at yielding such as the end-plate in bending or the column flange in bending but also the rebars in tension using Class C rebars.

For steel joints, a step further has already been achieved through the outcome of the EQUALJOINTS RFCS project which aimed at prequalifying steel joints for seismic actions (Landolfo et al. 2018a, 2018b). Through this project, different beam-to-column steel joint configurations have been prequalified and sophisticated and simplified design procedures have been provided and will be proposed for codification in the European standards. Such a procedure could also be contemplated for the prequalification of composite joints in the future.

6 BEHAVIOUR OF COMPOSITE JOINTS UNDER DYNAMIC LOADING

The design for robustness of a structure may also include the consideration of dynamic actions such as impact or explosion. These dynamic actions can induce dynamic effects within the structure and, in particular, at the level of the joints. The behavior of joints under impact has been the topic of recent researches ((Barata et al. 2016; D’Antimo et al. 2018; Santos et al. 2020; Ribeiro et al. 2015; Keller 2019; Jean-François Demonceau et al. 2017) amongst other). In particular, the dynamic response of composite joints subjected to dynamically applied combined axial forces and bending moments was experimentally investigated in (Keller 2019).

Through these researches, it has been demonstrated that significant strain rate effects can develop at the level of some joint components and can significantly influence the joint properties in terms of resistance and ductility. In particular, the resistance exhibited by the joint appears to be improved under dynamic loading when compared to its static response while the ductility appears to be more limited.

The component method could be adapted to predict the joint properties under dynamic loading if the strain rates is appropriately accounted for as demonstrated in (Santos et al. 2020). But the main encountered difficulty is the prediction of the strain rates developing in the different basic components, strain rates which is different for each of them. The prediction of the strain rates can be performed through the development of sophisticated FEM models as illustrated, for instance, in (Santos et al. 2020; D’Antimo 2020) but the use of such tools is of course not appropriate for the daily practice of design engineers. So, there is still a need for developing simplified approaches allowing predicting with a sufficient accuracy the strain rates developing within a joint subjected to a dynamic loading. This is a topic of investigation which is still ongoing in different institutions.

7 DUCTILITY OF COMPOSITE JOINTS

For steel and composite joints, very few information is provided in the Eurocodes which would enable the designer to check whether enough plastic rotational capacity is locally available. However, the estimation of this property is crucial when partial strength joints are used, in particular when it is intended to activate the yielding of the joints to allow plastic redistributions within the structure or to dissipate energy in case of seismic actions.

In (J. P. Jaspart, Corman, and Demonceau 2019), a procedure to estimate the rotation capacity of joints is presented using the component method approach. The application of this procedure requires, first, the estimation of the ultimate resistance of the joint M_{Ru} and, second, the estimation of the post-yielding stiffness $S_{j,st}$. With these two properties, it is possible to predict the post-yielding behaviour of the joint and so to predict the rotation capacity defined here as the rotation corresponding to the ultimate resistance M_{Ru} . The application of this procedure is illustrated in Figure 4 to predict the part of the analytical curve after point A. In this figure, it can be observed that a good prediction of the ultimate resistance and of the post-yielding stiffness of the joint is obtained for TEST 3 while it is not the case for TEST 2. The difference observed for TEST 2 is due to a premature failure of the component “concrete slab in compression” due to a lack of ductility occurring for a joint rotation of 29mRad. This highlights the fact that the application of the proposed procedure required the mastering of the ductility of the basic component which is not yet the case for the newly identified “concrete slab in compression” component.

An alternative to the accurate prediction of the rotation capacity is the proposal of design criteria to ensure a sufficient joint ductility for specific requirements. As previously mentioned, it is the strategy which is adopted in the Eurocodes which are proposing such criteria to allow for plastic analyses with plastic hinges forming at the level of partial strength joints. Such criteria have also been derived in (Rölle and Kuhlmann 2014) to ensure a sufficient ductility at the level of partial strength joint in case of column loss scenario. However, such criteria are not yet available to cover the different joint configurations and loading conditions that a designer could meet in practice.

The ductility of joints and, in particular, of composite joints is still a topic of investigations and studies are still progressing with the objective (i) to provide a good prediction of the ductility of at a local level, i.e. at the level of the component and (ii) to provide an appropriate assembly procedure to predict the global joint ductility and that for different loading conditions (quasi-static, cyclic, dynamic. ...).

8 CONCLUSIONS

Even if the scope of the present draft of the Eurocodes and, in particular, of Eurocode 4, Part 1-1, is limited to beam-to-column composite joints subjected to hogging moments, it has been demonstrated through the global overview proposed in this paper that recent research outcomes allow to go far beyond this limitation and to cover a lot of other loading conditions that the practitioners have to account for in their design approach, considering the request in terms of seismic performance, of fire design or of design for robustness. This offers very interesting perspectives for possible improvement and development of the future draft of the Eurocodes!

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