# RECENT DEVELOPMENTS ON COMPOSITE CONNECTIONS

## Behaviour of joints subjected to sagging bending moments and presentation of a free design dedicated software

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## INTRODUCTION

In Eurocode 4, design rules are suggested for the evaluation of the mechanical properties of structural steel-concrete composite joints (rotational stiffness, resistance and ductility). These rules cover situations where the joints are subjected to moments and shear forces, but in hogging regions only. Recently, researches have been conducted on the behaviour of composite joints subjected to sagging bending moments and to combined bending moments and axial loads, types of loadings which appear in composite frame further to a column loss *[1]*.
In the present paper, recent developments allowing to extend the EC4 design rules to joints in sagging regions (loading which can occur, for instance, in sway composite frames) are presented and the proposed method is validated through comparisons with experimental test results. Also, an easy-to-apply design software (which will be freely available), applying the rules recommended in Eurocode 4 in a safe and easy way, is described.

## 1 ANALYTICAL PREDICTION OF THE RESPONSE OF COMPOSITE JOINTS SUBJECTED TO SAGGING BENDING MOMENTS

Within the Eurocodes, the analytical method recommended for the joint design is the "component method". This method, as actually proposed, is not yet able to predict the behaviour of composite joints subjected to sagging bending moments. Indeed, no method is available to characterise one of the activated components under such loading which is the concrete slab in compression.
In recent researches, methods to characterise this component in term of « resistance » are proposed. Their aim is to define a rectangular cross section of concrete participating to the joint resistance. The procedure which is described in this section combines two methods proposed respectively by Fabio Ferrario *[2]* and by J.Y. Richard Liew *[3]*. The combination of these two methods permits to reflect in a more appropriate way how the concrete resists to the applied load in the vicinity of the joint.
Also, a formula for the characterisation of this component in terms of "stiffness" is proposed.
The so-defined analytical method is first described and then the validation of the latter is illustrated through a comparison with experimental test results.
In the PhD thesis of Fabio Ferrario *[2]*, a formula is proposed to compute the width of the concrete $b_{eff,conn}$ which has to be taken into account for the joint component "concrete slab in compression":

$$b_{eff,conn} = b_c + 0,7 h_c \le b_{eff}$$

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 in the vicinity of the joint; $b_c$ represents the contribution of the concrete directly in contact with the column flange while $0,7.h_c$ the contribution of the developed concrete rods in the "strut-and-tie" behaviour (see *Fig. 1*).

In the article of J.Y. Richard Liew et al, the width of the concrete is taken as equal to the width of the column flange ($b_{eff,conn} = b_c$) and the development of the concrete rods in compression through the "strut-and-tie" model is neglected.

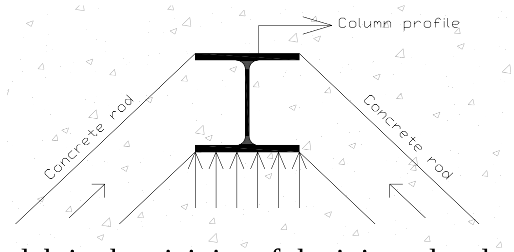


*Fig. 1*. Plane view of the slab in the vicinity of the joint - development of concrete rods in compression under sagging moment

The definition of the width given in *[2]* is used in the developed procedure as this definition reflects in a more appropriate way the mechanism developing in the concrete slab according to the observations reported during experimental tests (*[2]* and *[4]*).
Another difference between the two methods is linked to the definition of the height of concrete to be considered and, accordingly, to the position of the centre of compression within the joint. In *[2]*, the centre of compression is assumed to be at mid-height of the concrete slab while in *[3]*, the following procedure is given to compute the position of this point:

- the characterisation of the components in tension and eventually in shear is performed according to the rules recommended in the Eurocodes;
- then, the height of the concrete/composite slab contributing to the joint behaviour is computed by expressing the equilibrium of the load developing in the concrete/composite slab in compression with the components in tension or in shear and assuming a rectangular stress distribution in the concrete (equal to 0,85 $f_{ck}/\gamma_c$ in a design). For instance, in the example illustrated in *Fig. 2*, the concrete height to be considered is equal to:

$$z = \frac{F_{Rd,1} + F_{Rd,2} + F_{Rd,3}}{b_{eff,conn}.(0,85.f_{ck}/\gamma_c)} \leq h_{concrete}$$

  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);
- finally, the characterisation of the joint is performed assuming that the centre of compression is situated at the middle of the height of the contributing part of the concrete slab (z).

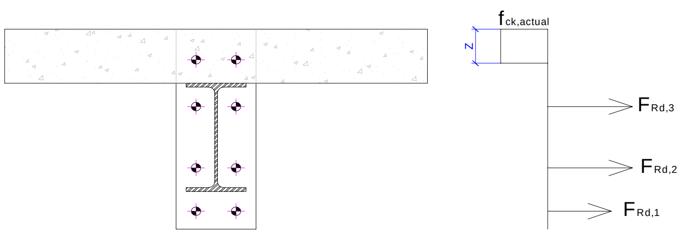


*Fig. 2*. Height of the concrete to be considered in the characterisation of the new component

It is the latter procedure which is considered in the proposed method as it reflects in a more appropriate way the actual behaviour of the joint according to the observations made during experimental tests *[4]*.
So, the resistance of the component "concrete slab in compression" can be computed through the following formula:

$$F_{Rd,CSC} = b_{eff,conn}.z.(0,85.f_{ck}/\gamma_c)$$

The two previously mentioned references only deal with the characterisation of the component "concrete slab in compression" in term of resistance but no formulas are proposed to characterise the latter in term of stiffness; however, the latter is requested in order to be able to predict the initial stiffness of the joint (and to derive the moment-rotation curve).
If reference is made to *[5]* a formula is proposed to predict the stiffness of a concrete block against a rigid plate. In the present case, the steel column encased in the concrete slab can be considered as a rigid plate; so, the formula proposed in *[5]* can be extended to the present situation to compute the stiffness of the component under consideration:

$$k_{csc} = \frac{E_c.\sqrt{b_{eff,conn}.z}}{1,275.E_a}$$

where $E_C$ 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 considered in the component method.
In *[4]*, the so-defined analytical procedure is validated through comparisons with results from experimental tests performed on composite joints in isolation. An example of such comparison is presented in *Fig. 3* where the analytical prediction is compared to results obtained at Trento University *[6]* through experimental tests conducted on external composite joints (see *Fig. 4*) within a European RFCS project called PRECIOUS in which Liège University and ArcelorMittal Long Products were also involved.
Within the analytical computations, the actual material properties (without safety factors), determined through coupon tests for the steel materials and through cylinder compression tests for the concrete, are used. The resistant bending moment $M_{Rd}$ and the initial stiffness $S_{j,ini}$ are computed in full agreement with the component method recommended in the Eurocodes while the ultimate moment $M_u$, the post-limit stiffness $S_{j,post-limit}$ and the rotation capacity $\phi_u$ are computed according to the method proposed in the PhD thesis of Jean-Pierre Jaspart *[7]* (which is in full agreement with the component method), as no methods are actually proposed in the codes to compute these properties.
In *Fig. 3*, it can be observed that two experimental curves are reported. They are distinguished by the configuration of the slab: the TEST 2 joint is composed of a composite slab while the TEST 3 one is composed of a concrete slab.
From the comparison presented in *Fig. 3*, it can be observed that a very good agreement is obtained between the analytical prediction and the experimental results. For TEST 2, a loss of resistance in the joint is observed at a rotation of 29 mrad what is not reflected by the analytical prediction. In fact, this loss of resistance during the test was associated to a lack of ductility of the concrete in the vicinity of the connection, phenomenon not yet covered by the proposed analytical procedure.

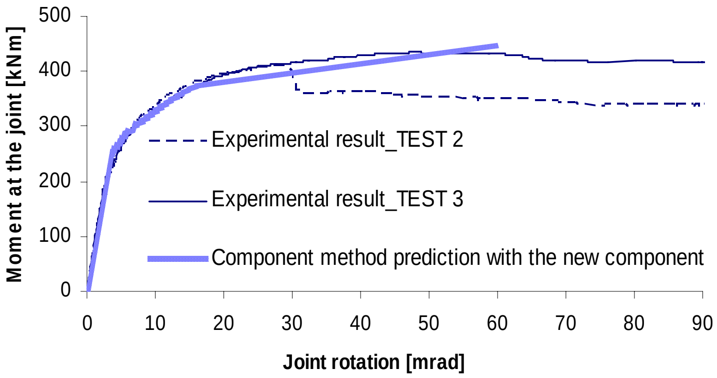


*Fig. 3.* Comparisons analytical prediction vs. experimental results *[4]*

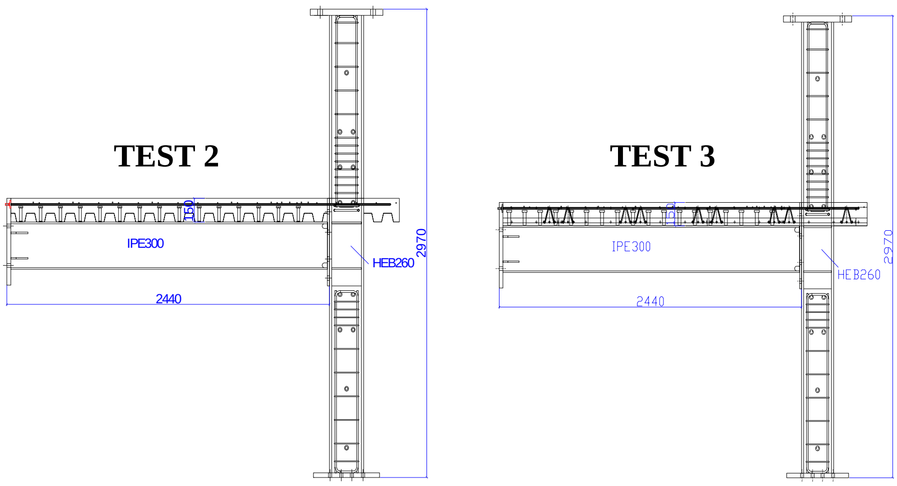


*Fig. 4.* Tested joint configurations at Trento University *[6]*

## 2 DEVELOPED DESIGN DEDICATED SOFTWARE

### 2.1 General information and scope

A user-friendly software tool has been developed in order to make the application of the Eurocode 4 design rules for composite joints more easy for the designer. The software is a special edition of the new version of the well known commercial software CoP (CoP stands for Connection Program). The software is developed by Feldmann + Weynand GmbH in cooperation with the University of Liège. The development has been supported by ArcelorMittal and this special edition is provided free of charge *[8]*. The ArcelorMittal edition of CoP includes also a so-called light version of the CoP steel modules. However this light version is rather limited in scope compared to the full version of CoP. For more information, reference is made to the CoP web site *[9]*. The following paragraphs give a short summary of the scope of the special edition and some screen shots are shown.
CoP is a standard Windows software for the design of joints in steel and steel-concrete composite building frames according to Eurocode 3 (EN 1993) and Eurocode 4 (EN 1994). The ArcelorMittal edition is an unprotected module of CoP which allows the user to design standard joints in composite constructions. A car park for example would be a typical application.

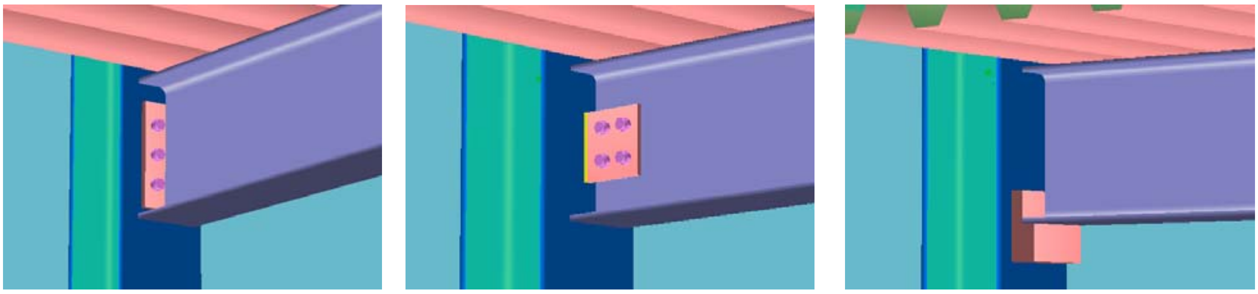

*Fig. 5.* Example of connection types in the CoP ArcelorMittal edition

CoP considers various types of connections (such as bolted end-plate connection, double web cleats, header plates, fin plates) as well as various joint configurations (such as single sided beam-to-column joint configurations, double sided beam-to-column joint configurations, single sided beam-to-beam joint configurations, double sided beam-to-beam joint configurations). Figure 5 shows some examples of connection types of a beam-to-column joint configuration with a composite beam section.
The software consists of three main modules: (a) the user interface, (b) the calculation module and (c) the output processor. These main modules are described more in detail hereafter.

## 2.2 User interface

An easy-to-use and simple user interface is provided in order to input all necessary data to describe the geometry and the material properties of the joints, see Figure 6. The ArcelorMittal edition is available in English, French and German language.

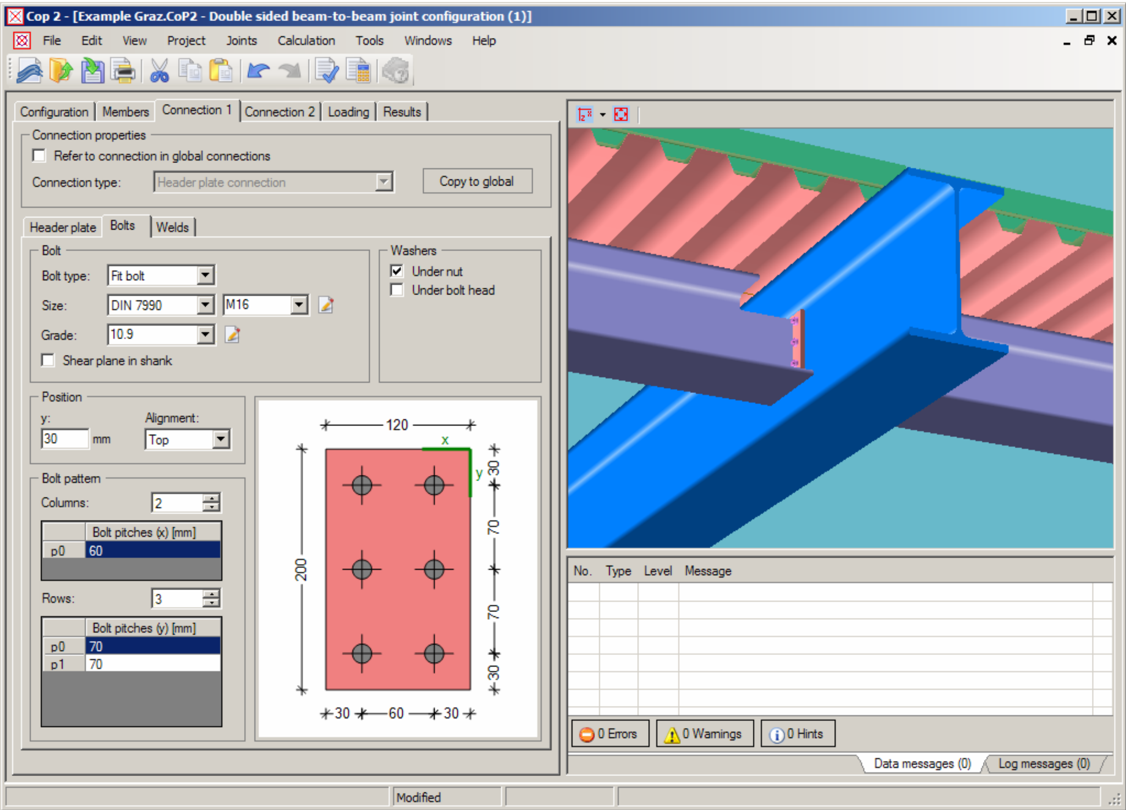


*Fig. 6.* Main screen of CoP

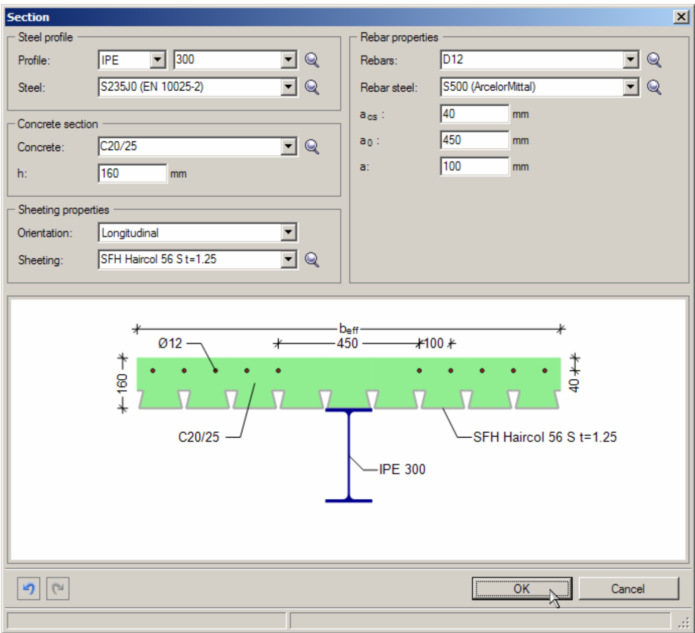


*Fig. 7.* Input screen for composite beam sections

Individual joints may be specified by entering the member and connection data. A complete database containing profile and material characteristics is included in the software in order to

facilitate the data input, see for example the data input screen for a composite beam section in Figure 7.
During the data input, a data check module is observing the consistency and validity of the data and it informs the user immediately about missing or wrong data. Furthermore, scaled 2D drawings and a 3D visualisation give the user an immediate feed-back about the current data input.

### 2.3 Calculation modules

The CoP calculation modules are designed to work with the component method. When the user runs the calculation module, either for the active joint or for all defined joints, the structural properties are calculated and a check of the resistance against the internal forces acting at the joint is made.

### 2.4 Output processor

Finally, CoP will generate a calculation note containing the data input, all results of the calculation of the joint properties and the design checks which are performed if internal loads (effects) are given. The language of the calculation note may be different from that of the user interface.

## 3 CONCLUSIONS

The analytical procedure to characterise the behaviour of composite joints, as actually proposed within the Eurocodes, is not yet able to cover the case of composite joints subjected to sagging bending moments. Within the present paper, an analytical method to predict the response of composite joint subjected to such loadings has been first described.
Furthermore, a software tool for the design of composite joints according to Eurocode 4 is presented. The software is provided free of charge by ArcelorMittal.

## REFERENCES


[1] Demonceau J.F., Luu N.N.H. and Jaspart J.P., Development of membranar effects in frame beams: experimental and analytical investigations, *Eurosteel 2008 conference*, Graz, Austria, 2008.

[2] Ferrario F., Analysis and modelling of the seismic behaviour of high ductility steel-concrete composite structures, *PhD thesis presented at Trento University*, 2004.

[3] Liew R.J.Y., Teo T.H. and Shanmugam N.E., Composite joints subject to reversal of loading – Part 2: analytical assessments, *Journal of Constructional Steel Research*, pp. 247-268, 2004.

[4] Demonceau J.-F., Steel and composite building frames: sway response under conventional loading and development of membranar effects in beams further to an exceptional action, *PhD thesis presented at Liège University*, 2008.

[5] Weynand K., Column bases in steel building frames. COST C1 – Semi-rigid behaviour of civil engineering structural connections, Luxembourg, 1999.

[6] Trento University. Partially reinforced-concrete-encased column joints for severe seismic loadings: tests and main results, *Internal report for the RFCS project RFS-CR-03034 "Prefabricated composite beam-to-column filled tube or partially reinforced-concrete-encased column connections for severe seismic and fire loadings"*, March 2006.

[7] Jaspart J.P.. Study of the semi-rigidity of beam-to-column joints and its influence on the resistance and stability of steel buildings. *PhD thesis, Liège University*, 1991 (in French).

[8] Weynand K., Klinkhammer R., Oerder R. , Jaspart J.-P. , CoP ArcelorMittal Edition, Program for the design of joints according to EN 1994, www.arcelormittal.com/sections, 2008.

[9] Weynand K., Klinkhammer R., Oerder R. , Jaspart J.-P., CoP - The Connection Program, Program for the design of joints according to EN 1993-1-8, www.fw-ing.de/software, 2008.