EXTENSION OF THE COMPONENT METHOD TO JOINTS IN TUBULAR CONSTRUCTION

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Abstract

In the Eurocode 3 Annex J, reference is made to the so-called "component method" for the design of structural joints in building frames. Application rules for the evaluation of the mechanical properties of beam-to-column joints and beam splices are provided as long as H or I hot-rolled or built-up sections are used for the connected members. In this paper, the extension of the component approach and the development of appropriate design rules are discussed and a preliminary application to a particular example is described.

1. INTRODUCTION

Plenty of analytical models for the evaluation of the mechanical properties of structural joints (rotational stiffness, moment resistance, rotation capacity) are available in the literature for different types of joint configurations and connection types. But progressively one of these models, because of the advantages it offers in comparison to the others, slowly became the reference and is now considered as such by most of the researchers. In particular it has been followed in Eurocode 3 Revised Annex J on "Joints in Building Frames [1]. It is known as the component method.

Roughly speaking the component method may be presented as the application of the well-known finite element method to the calculation of structural joints.

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 (joint between H or I profiles with an extended end-plate connection subject to bending), 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;
- in shear zone :
  - column web panel in shear.

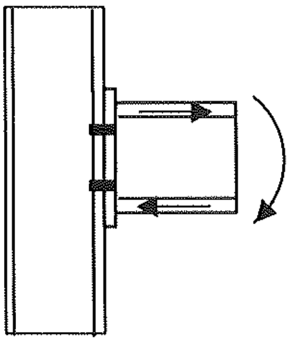


Figure 1 Joint with end-plate in bending

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 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 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 moment-rotation curve).

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

As specified here above, the parallelism with the finite element method is obvious. To "component" and "joint" may then be substituted the words "finite element" and "structure".

The application of the component method requires a sufficient knowledge of the behaviour of the basic components. Those which are active in the traditional steel joints (with welded, end-plate or cleated connections) have been deeply studied and recommendations for their characterisation are given in the Revised Annex J of Eurocode 3 [1] . 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.

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 [2].

However the field of application of Eurocode 3 Annex J is limited to structural joints between H or I hot-rolled and built-up welded profiles. In this paper, the extension of the scope of Annex J to joints made of beam-to-column joints between H or I beams and column profiles made with rectangular hollow sections (R.H.S.) filled with concrete (Figure 3) is discussed. In these joints, the connection is realised by means of a flush end-plate welded to the beam end and bolted to the column. Different techniques are available on the market to connect the end-plate to the column face. Amongst them, blind bolting, flowdrill or welded studs techniques are rather common ones.

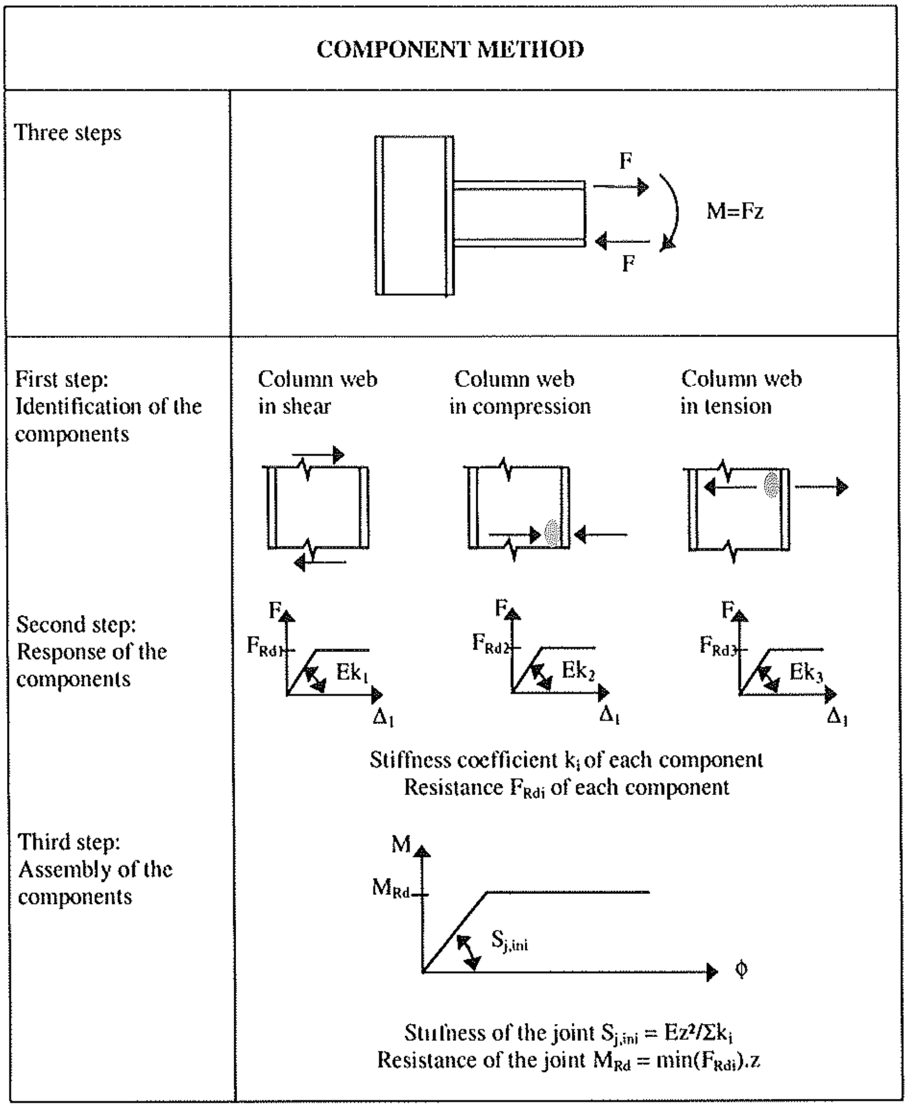


Figure 2 Application of the component method to a welded steel joint (simplified bi-linear component and joint deformability curves)

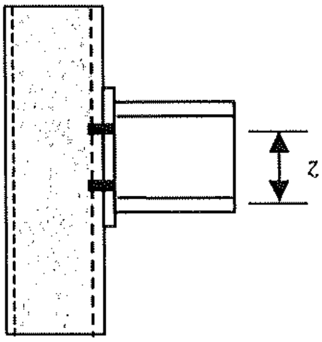


Figure 3 Joint configuration and connection type under consideration (tubular column with in-filled concrete)

2. RELEVANT COMPONENTS IN JOINTS WITH R.H.S. COLUMNS

As mentioned earlier the first main step in the application of the component method is the identification of the relevant constitutive components. In Table 1, all the components to be considered in the particular situation studied in this paper are listed. For each of them it is indicated whether application rules for the evaluation of their mechanical properties are available or not in Eurocode 3 Annex J. A quick look on Table 1 allows to draw the following conclusions:

- most of the constitutive components are already covered by Annex J and no further investigations is required;
- the components indicated in *italic* are not relevant for the joint considered in the present paper as the concrete in the column is stiffening and strengthening the compression zone of the column;
- the only new components to be considered are the following:
  - the "connectors in tension", i.e. the connecting devices (welded studs, blind bolts, ...);
  - the "column face in bending" which is subjected to tension transverse forces transferred by the connectors and compression transverse forces carried over mainly by the lower flange of the beam.

As a result, the required investigations are seen to be limited to the development of design rules for two components only while good profit is made of already available rules for all the other components. This is one of the reasons why the component method is widely recognised now as a general procedure for joint characterisation in the scientific community and in the European codes (Eurocodes 3 "Steel structures" and 4 "Composite structures".

Components	Availability in EC3 Annex J
• Compression zone	
▪ *Column face in compression*	*No*
▪ *Lateral column faces in compression*	*Yes, with some adaptation*
▪ Beam flange and web in compression	Yes
• Tension zone	
▪ Lateral column faces in tension	Yes, with some adaptation
▪ Column face in bending	No
▪ End-plate in bending	Yes
▪ Connectors in tension	No
▪ Beam web in tension	Yes
• Shear zone	
▪ Column web panel in shear	Yes, with some adaptation

Table 1 Availability of components in Eurocode 3 Annex J

3. INVESTIGATIONS ON NEW COMPONENTS

To fix the ideas, a specific type of connector is selected: the welded stud. For non concrete-filled columns, the flowdrill, welded stud or blind bolting techniques may be equally used while only the stud technique is easily applied for concrete-filled columns. The stud technique consists in welding with the help of a special gun a threaded stud on the face of the section on which the connection is to be realised. The other elements of the connection are fixed at the studs with nuts, as done for classical bolts. The studs are then subjected to tension forces when the joint is subjected to bending moments, as for usual joints. The studs to be used are threaded studs with a reduced base section. So, the welds have approximately the same diameter than the threaded part of the studs (Figure 4).

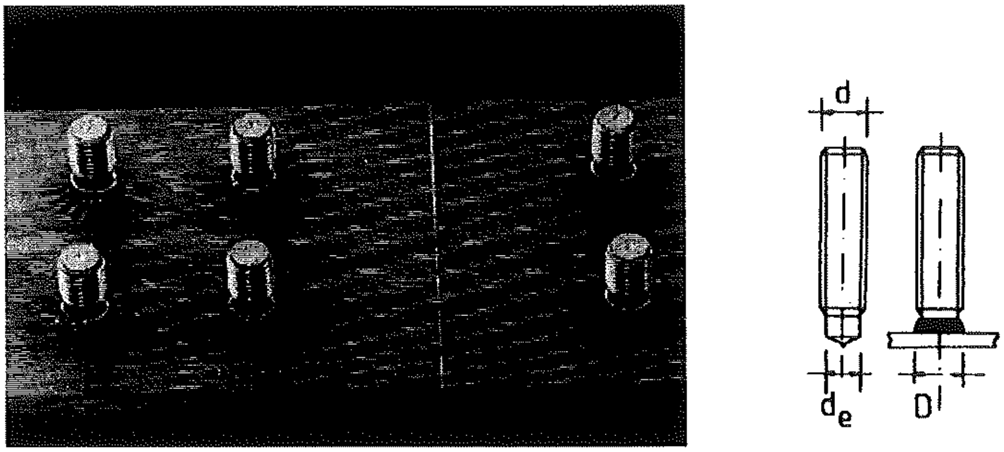


Figure 4 The stud technique

3.1 "Connector in tension" component

In the welded stud technique, the studs themselves may be considered as bolts in tension and the design rules available in Eurocode 3 apply accordingly. The stiffness factor and the tension design resistance are respectively expressed as follows:

$$k_c = 1{,}6 A_s / L_b \qquad (1)$$

$$F_{t.Rd,1} = 0{,}9 A_s f_{ub} / \gamma_{Mb} \qquad (2)$$

In these formulae, A_s designates the area of the connector in its threaded part, f_{ub} the ultimate strength of the connector and γ_{Mb} the partial safety factor. L_b is the sum of the thickness of the end-plate and of the washer, if any, and half the thickness of the nut.

3.2 "Column face in bending" component

Three different failure modes are identified as far as the behaviour of the face of the column is concerned:

- punching shear failure in the column face along the stud weld;
- lamellar tearing in the plate at the connector's location;
- failure of the face in bending though progressive yielding (development of a plastic plate mechanism in the column face).

"Column face in bending" may therefore appear as a too restrictive component denomination as it only refers to one of the possible collapse modes. Nevertheless this component name will be used in the next paragraphs.

As long as welded studs are concerned, design rules covering the two first above-mentioned failure modes for the face of a rectangular hollow section have been suggested by MAQUOI, NAVEAU and RONDAL [3] some years ago:

- punching shear failure

$$F_{t.Rd,2} = 0{,}95 \pi d t \frac{f_y}{\sqrt{3}} / \gamma_{M0} \qquad (3)$$

- lamellar tearing

$$F_{t.Rd,3} = 0{,}95 \frac{\pi d^2}{4} f_y / \gamma_{M0} \qquad (4)$$

where f_y is the yield stress of the column face, t its thickness, d is the nominal diameter of the studs and γ_{M0} a partial safety factor.

No significant elastic deformation is associated to these two failure modes; as a consequence the value of the related stiffness coefficients k is taken as infinite.

In order to evaluate the design resistance of the face of the R.H.S. column, reference is made to the work of GOMES [4] where formulae are given for the evaluation of the design resistance of column webs subjected to transverse forces in minor axis beam-to-column joints between H or I profiles. In this work, illustrated in Figure 5, a plastic yield mechanism (Figure 5.a) is assumed to develop in the web subject to bolt forces. These ones are assumed to act on a sort of rigid equivalent rectangular zone with bxc dimensions (Figure 5.b). The failure by plastic mechanism which occurs for low values of the b_0/L ratio tends progressively to be replaced by a punching shear failure of the web along the radius of fillet when b_0/L tends to 1.0. This aspect which is explicitly covered by the model is not addressed here.

The formulae to apply is the following one (Figure 5):

$$F_{t.Rd,4} = m_{pl,Rd}\alpha k \tag{5}$$

with:

$$m_{pl,Rd} = 0{,}25t^2 f_y / \gamma_{M0} \tag{6.a}$$

$$\alpha = \frac{1}{1-b/L}(\pi\sqrt{1-b/L} + 2c/L) \tag{6.b}$$

$$k = \begin{cases} 1 & if\ (b+c)/L \geq 0{,}5 \\ 0{,}7 + 0{,}6(b+c)/L & if\ (b+c)/L \leq 0{,}5 \end{cases} \tag{6.c}$$

$$\begin{cases} b = b_0 + 0{,}9d_m \\ c = 0{,}9d_m \end{cases} \tag{6.d}$$

$$d_m = \frac{d_1 + d_2}{2} \tag{6.e}$$

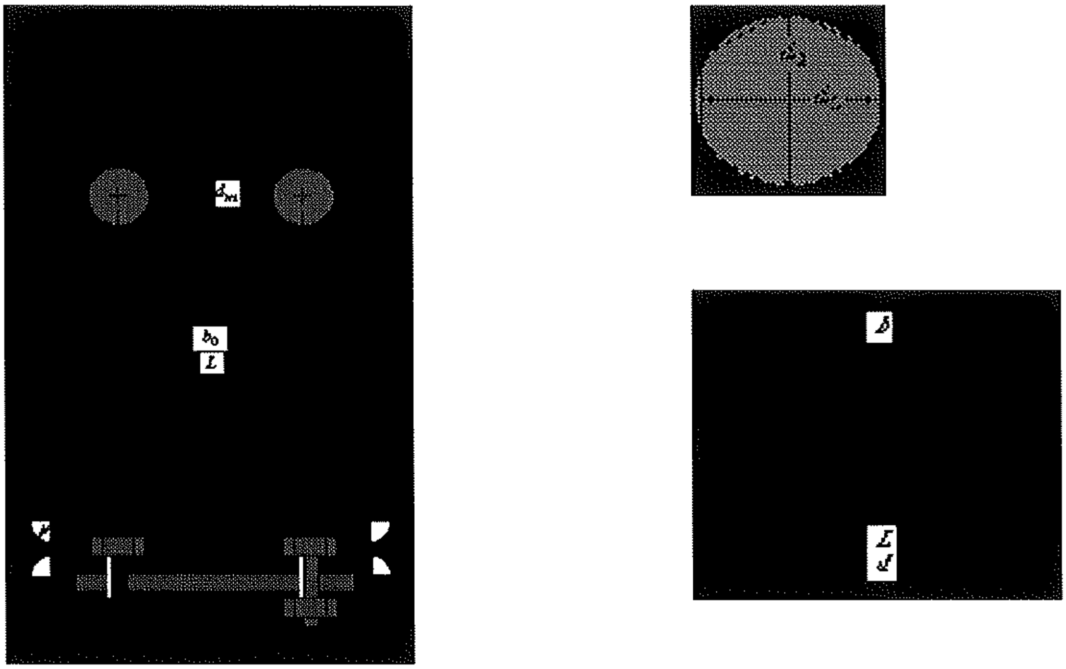
The domain of validity of this approach is as follows:

$$b \leq 0{,}8L \tag{7.a}$$

$$0{,}7 \leq h/(L-b) \leq 10 \tag{7.b}$$

Finally the design resistance of the "column face in bending" component is expressed as:

$$F_{Rd} = \min(F_{Rd,2}; F_{Rd,3}; F_{Rd,4}) \tag{8}$$



a. Plastic yield mechanism b. Equivalent rectangle for loading and bolt property

Figure 5 Failure modes in a column web [4]
(minor axis beam-to-column joint)

The straight extension of the GOMES' model to faces of R.H.S. columns appears at first sight as quite reasonable and such an assumption is made in this preliminary study.

To complete the information on the "column face in bending" component, a stiffness model is required to predict the level of deformation of the face under transverse forces in the elastic domain. Some attempts to derive such a model have been made in Portugal by NEVES [5] but the rules seemed not to be sufficiently developed to be used in the present study. The NEVES' model is still in development and more reliable models could be made available in the future. In order to overcome this lack of information, it has been decided in Liège, in collaboration with the CRIF research centre [6], to perform numerical simulations with the aim to evaluate, for a limited number of geometrical joint configurations, the initial elastic stiffness of the column face subject to transverse bolt forces. These simulations and their results are briefly described in the next paragraph.

3.3 Numerical simulations of R.H.S. faces under transverse forces

The numerical simulations have been carried out with the non-linear FEM program FINELG developed at the University of Liège [7]. Shell finite elements are used to simulate the elastic response of the column face. The computations are based on the following assumptions:

- The concrete in the column is assumed to strongly reduce the deformation of the joint in its compression zone, i.e. at the level of the lower beam flange. No stiffness coefficient is therefore attached to this zone which is roughly assumed to be fully rigid. The whole column face is meshed but only tension forces are applied in the simulations.
- The lateral faces of the R.H.S. profiles are subjected to tension forces over a so-called "diffusion length" (transfer from the bolts to the lateral faces through the column face where the connection is realised). Their own deformation contributes to the global deformation of the joint but in a way which is considered here as rather limited, and which is therefore neglected in comparison to the flexural deformation of the main column face.

- Under tension forces, the face of the column deforms out of its plane and the column cross-section tends to deform as shown on the Figure 6. The concrete inside the column somewhat prevents this deformation from developing freely, what results in a stiffening of the face subject to tension forces. In order to try to cover this specific aspect, and for sake of simplicity, the numerical simulations are performed by assuming the main column face as a infinitely long plate (along the column axis) subjected to transverse bolt forces and laterally clamped.

The simulation has been performed for the particular joint configuration and connection type which is presented in Section 4 and is used later in Section 5 as reference to validate the application of the component method to structural joints between beams with open sections and R.H.S. columns.

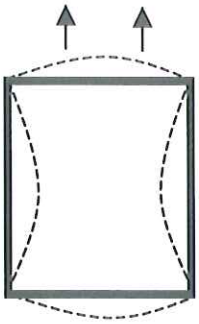


Figure 6 Transverse deformation of the column cross-section

4. EXPERIMENTAL EVIDENCE FOR JOINT BEHAVIOUR.

Tests on two identical single-sided beam-to-column joints with a flush end-plate (Figure 3) have been performed in laboratory [6] with the aim to derive their moment-rotation characteristic. They belong to a series of eight laboratory tests on similar joint configurations with web cleats, flange cleats and extended end-plates.

The column profile is made of a 200x200x6,3 tubular square section while the beam is an IPE240 one. The end-plate has the following dimensions: 270x150x10 mm. Four M20 4.8 studs are used to connect the end-plate to the column.

All the geometrical and mechanical properties of the column, beam and end-plate elements as well as details about the testing arrangement and the measurements made during the test are reported in [6].

5. CONFRONTATION MODEL - EXPERIMENTS

The Eurocode 3 Annex J assembly models allow an easy evaluation of the stiffness and resistance characteristics of the joints on the basis of the components properties (see Figure 2). From these characteristics a joint moment-rotation curve may be derived. As already said, in the present case, these properties are analytically derived from the Annex J rules when they exist or from the formulae presented in Sections 3.1 and 3.2. The only exception is the "column face in bending" for which no good reliable stiffness model is available, what explains that a numerical simulation has been carried out.

In Figure 7 comparisons between analytically and experimentally derived moment-rotation curves are shown. The initial elastic stiffness of the joint is reasonably well predicted by the model; the plastic resistance of the joint which results from the yielding of the column face in bending is also seen to be evaluated in a rather accurate way. On the other hand the membrane effect which develops in the column face further to its plastic yielding and which leads to a significant increase of the resistance beyond the yielding point is not covered by the model. This post-limit stiffness is also increased by the steel strain-hardening which is also not predicted by the *design* model inspired by Eurocode 3 rules. A rough estimation of this post-limit stiffness may be easily derived [8], but the first question to raise would probably be the following: should the extra-resistance resulting from membrane effects be considered in the definition of the *design* resistance of the joint? No definitive answer to this difficult question is presently available, even if some aspects of the problem have already been discussed in [9].

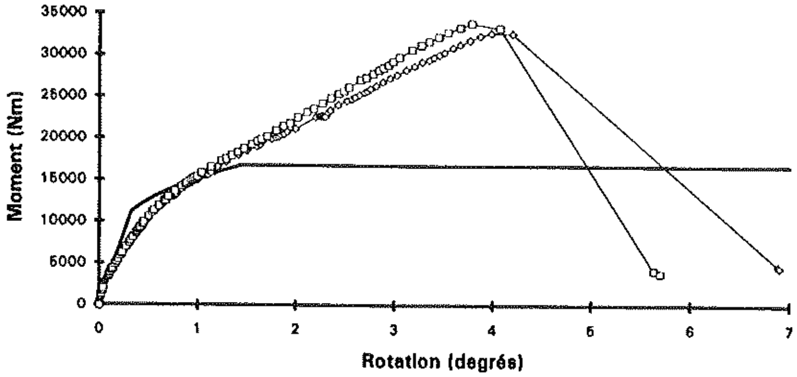


Figure 7 Comparisons between experimental tests and model

6. PERSPECTIVES AND CONCLUSIONS

The component method which is applied in the present paper to a single-sided joint between an IPE beam and a R.H.S. column is nowadays considered as a reference for the design of structural joints in steel and composite structures made of H or I profiles. In Eurocodes 3 and 4, its principles have been adopted and applications rules enabling its practical applications have been implemented.

The present paper has therefore to be seen as a first step towards its application to tubular construction. The development of such a consistent approach for all joints, independently of their cross-sectional shapes, would obviously present several advantages:

- *Scientific aspects*
  The component method is now well agreed at the European level for joints with open sections. Its extension to hollow section joints would allow to unify the design concepts by anyway keeping most of the valuable design models presented in Eurocode 3 Annex K "Joints in tubular construction" (the latter being based on another "philosophy").
- *Aspects of normalisation*
  A consistent design approach for all joints would simplify the related normative documents which represent a main part of Eurocode 3.
- *Practical aspects*
  The designer would no more be faced to different design philosophies according to the type joint and profiles. This approach would facilitate his daily work, all the practical design tools available making reference to an unique design philosophy (simplified design procedure, tables of standardised joints, software, ...).

From this point of view, the successful application of the component method to a joint with a R.H.S. column appears as rather promising even if further investigations will be required before the final goal is reached. The CIDECT Committees are sensitive to the problem and as a result, a one-and-a-half year project involving the French steel producer Usinor (Tubeurop) and the Universities of Aachen (Germany) and Liège (Belgium) has been funded with an aim to develop further the concept, derive analytical expressions for the stiffness of the column face and see which kind of practical design tools for daily work could be proposed to designers.

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