First practical implementation of the component method for joints in tubular construction

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ABSTRACT: The extension of the component method, recommended in Eurocode 3 and 4 for steel and composite joints between H or I profiles, to the design of steel joints in tubular construction has been already discussed in a paper presented at the 9^{th} ISTS in Düsseldorf in 2001. In the meantime further investigations have been undertaken in order to develop rules for specific components. Some have been presented at the 10^{th} ISTS in Madrid in 2003; others have been derived in various CIDECT research projects. Furthermore existing rules published in the CIDECT Design Guides and in EN 1993 Part 1.8 have been "converted" into a component format. As a result of these works, this paper presents a survey on the application of the component method to "tubular" joints and a first practical implementation of the component method by referring to so-called "design sheets" particularly useful for the day-to-day design.

1 INTRODUCTION

In a paper presented at the Ninth International Symposium on Tubular Structures (Jaspart & Weynand 2001), the extension of the component method, as recommended in Eurocode 3 and 4 for steel and composite joints between H or I profiles, to the design of steel joints in tubular construction was discussed. First related design rules for bolted beam-to-column joints between RHS columns and H or I beams were also briefly described. At the end of the paper, the following conclusions were drawn:

- the successful application of the component method to joints with RHS columns appears as promising even if further investigations are required;
- the CIDECT committee is supporting further developments;
- a wider implementation of this method would lead to simplifications in view of the standardisation and hence, it would help to facilitate the daily work of designers.

In the meantime several further investigations have been undertaken on the scientific level in order to develop more rules for components specific to joints in tubular construction. Some have been for instance presented during the tenth Symposium on Tubular Structures (Bortolotti & al 2003, Pietrapertosa & Jaspart 2003). Others have been derived in the framework of different CIDECT research projects; they are all referenced in (Jaspart & al 2005). Furthermore, existing rules published in the CIDECT Design Guides and in EN 1993 Part 1.8 have been "converted" into a component format.

As a result of these recent works, a survey on the application of the component method for the design of joints used in tubular construction is first presented in this paper. Then a full design procedure for one specific one is detailed, as an example, by referring to so-called "practical design sheets" particularly useful for the day-to-day design.

2 THE COMPONENT METHOD AS A BASIS FOR THE UNIFIED APPROACH

The component method is a three step procedure which requires successively:

- to identify the constitutive individual components of the joint;
- to evaluate the stiffness/resistance/ductility properties of all these components by using appropriate design formulae;
- to combine or "assemble" these individual components so as to derive the stiffness/resistance/ductility properties of the complete joint.

The properties of joints to be evaluated in practice strongly depend on the type of global frame analysis and design process which is followed by the designer; for instance:

- for an elastic analysis combined with an elastic verification of the member sections and joints, the

stiffness and the elastic resistance of the joints should be derived;
- for an elastic analysis combined with a plastic verification of the most heavily loaded member section or joint, the stiffness and the plastic resistance are required;
- for a rigid-plastic analysis, only the plastic resistance and the ductility of the joints will have to be evaluated;

This approach which is recommended in Eurocode 3 and 4, respectively for steel and composite joints between I or H sections, is very comprehensive. As already said, the objective of the authors was to extend it to joints involving other types of member cross-sections and, in particular, hollow sections. Practically speaking, this requires:
- to extend the list of available components to those met in joints between hollow sections;
- to verify that the available "assembly" procedures (which are based on general principles like equilibrium, compatibility of displacements, ...) are general enough to be considered as independent of the actual nature of the constitutive components and are therefore still relevant.

It has again to be stated that this approach is in full agreement with all the principles and rules stated in Eurocode 3, and especially in its Part 1-8.

3 FIELD OF APPLICATION

Basically the field of application of the "component based" unified design approach is rather wide. The only limitations to its use may be expressed as follows:
- design rules for the evaluation of the stiffness/resistance/ductility properties would not be available for some or all the constitutive individual components;
- these rules would have a limited range of application;
- an appropriate assembly procedure would not be available.

In practice, the main limitation may come from the lack of information on a specific component (unknown or with a limited field of application). But as stated in Eurocode 3, any validated component design rule which would be found in the literature or result from specific investigations by the user (experiments, numerical simulations, ...) may be adopted and combined with those provided by the code. From that point of view, all the results of past, ongoing and future research projects (referring or not to the component approach) are and will remain adequate and useful pieces of information.

In Table 1 the reader will find a schematic view of the general field of application of the here-promoted unified design procedure for joints. And in Figure 1 few examples of joints to which the unified design approach applies are shown.

Table 1. Field of application of the unified design approach.

Parameters	Values, range or field
Joint configurations	In-plane joints in trusses : T-joints, X joints, ... In-plane joints in frames : beam-to-column joints, beam splices, column splices, column bases Others
Loading situations	Axial forces (tension or compression) Shear forces Bending moments Any combination of these forces
Cross-sections of the connected members	Hollow sections : RHS, SHS, CHS, EHS Hot-rolled or built-up I or H sections Others (L or U sections, ...)
Connectors	Bolted connections (with preloaded or non-preloaded bolts, injection bolts, studs, anchors, ...) Welded connections Combination of welding and bolting
Connection elements	End-plates: partial-depth, flush or extended Cleats: web or flange cleats Fin plates Inserted plates Splices Diaphragms Contact plates
Stiffening elements	Transverse and diagonal web stiffeners (I or H sections) Web plates Haunches Backing plates
Steel grades for members and connection elements	S235 to S460

A wide range of possible joint configurations may in fact nowadays be covered, as detailed knowledge is available for 37 hereafter-listed components.

1 Web panel in shear
2 I or H section web in transverse compression
3 I or H section web in transverse tension
4 I or H section flange in out of plane bending
5 End-plate in out of plane bending
6 Flange cleat in out of plane bending
7 I or H section flange and web in compression
8 I or H section web in longitudinal tension
9 Plate in tension or compression
10 Bolts (studs) in tension
11 Bolts (studs) in shear
12 Plate in bearing(plate in general, beam flange or web, column flange or face, end-plate, cleat or base plate)
13 Concrete in compression including grout
14 Base plate in bending under compression

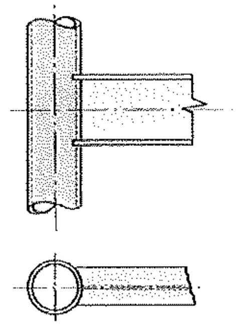
15 Base plate in bending under tension
16 Anchor bolts in tension
17 Anchor bolts in shear
18 Welds
19 Haunch
20 Longitudinal steel reinforcement in tension
21 Steel contact plate in compression
22 Partial depth end plate or fin plate in shear: Gross section
23 Partial depth end plate or fin plate in shear: Net section
24 Partial depth end plate or fin plate in shear: shear block
25 Partial depth end plate or fin plate in in-plane bending
26 Web in shear in partial depth end plate connection
27 Buckling of the fin plate
28 Web in shear in fin plate connection: net section
29 Web in shear in fin plate connection: shear block
30 CHS in transverse compression or tension: chord face failure
31 CHS in transverse compression or tension: Punching shear failure
32 RHS in transverse compression or tension: chord face failure
33 RHS in transverse compression or tension: brace failure
34 RHS in transverse compression or tension: chord side wall crushing
35 RHS in transverse compression or tension: punching shear failure
36 Inserted Plate in shear in CHS/RHS
37 Diaphragm in tension or compression

In (Jaspart & al 2005), detailed rules are provided for the evaluation of the stiffness and resistance properties of all these 37 components. Additionally assembly procedures are given that cover the usual loading situations met in steel construction.

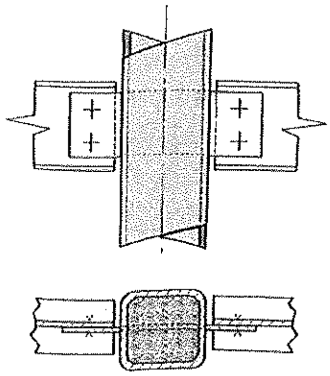
"To assemble the components" means to express the fact that the forces acting on the whole joint distribute amongst the constitutive components in such a way that:
- the internal forces in the components are in equilibrium with the external forces applied to the joint;
- the resistance of a component is nowhere exceeded;
- the deformation capacity of a component is nowhere exceeded.

As far as the resistance of the whole joint to external forces is concerned, the fulfilment of these three rules is enough to ensure that the evaluated design resistance is smaller than the actual joint resistance.

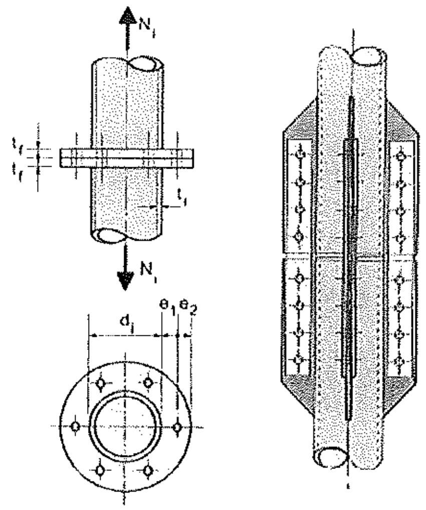
For stiffness calculation, the elastic distribution of internal forces in the joint is requested to fulfil one more condition:
- the compatibility of displacements amongst the constitutive components.



I-to-CHS beam-to-column joint (moment resistant joint)



I-to-composite RHS beam-to-column joint (simple joint)



Splices

Figure 1. Examples of joint configurations covered by the unified design procedure

4 DESIGN SHEET FOR PRACTICAL APPLICATION

4.1 *General*

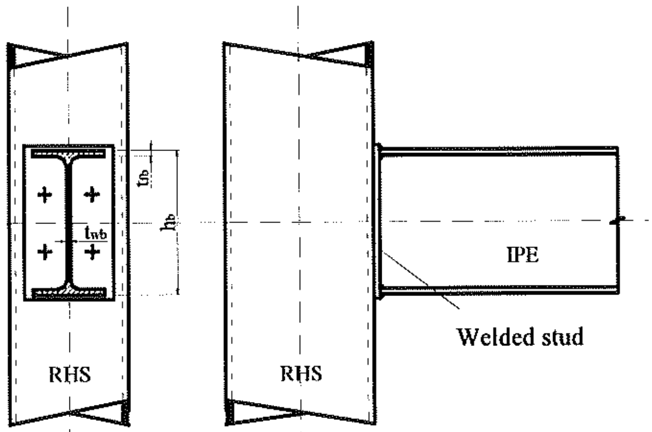
The component based unified design approach is a quite powerful tool for the evaluation of the stiffness and/or resistance properties of structural steel and composite joints under several loading situations. Amongst its advantages the user will express the ability, through a unique concept:
- to study all the joints of the considered structure, whatever their configurations and the member cross-sections (open or hollow);
- to characterise joints made of other materials or of a combination of different materials;
- to follow with the same approach the evolution of the properties of the composite joints, for instance, during the erection time (bare steel joints before and during concreting, composite joints after concrete drying);

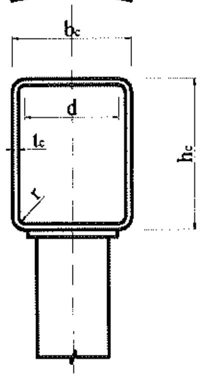
– to take easily into consideration all the loading situations resulting from the several structural load cases.

For people who are acquainted to the use of the component approach, the advantages that it brings in comparison to more traditional approaches will much more than compensate the sometimes heavier requested calculation time. That is why, in parallel to the development of the component method, various practical design tools have to be developed and disseminated throughout the construction community. For steel and composite joints connecting members with open sections, a huge work has been achieved which led to the publication of design tables of standardised joints, simple design sheets, etc. Dedicated software are also available on the market.

For tubular construction or "mixed open/hollow sections" joints, such an effort will have to be achieved too. Hereafter, a simple calculation design sheet is presented just as an example for a specific joint configuration (moment resistant I beam-to-RHS column joint with flush end plate and one row of studs in tension).

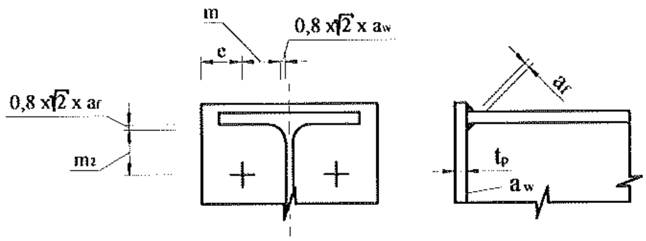
4.2 *Joint layout, notations*





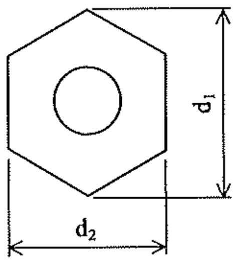
h_c Height of the column
b_c Width of the column
t_c Thickness of the RHS section
r Root radius
d Clear depth of the column face $[d = b_c - 2t_c - 2r]$
f_{yc} Yield strength of the column
f_{uc} Ultimate strength of the column
h_b Height of the beam
t_{wb} Thickness of the beam web
t_{wb} Thickness of the beam flange
f_{yb} Yield strength of the beam
f_{ub} Ultimate strength of the beam

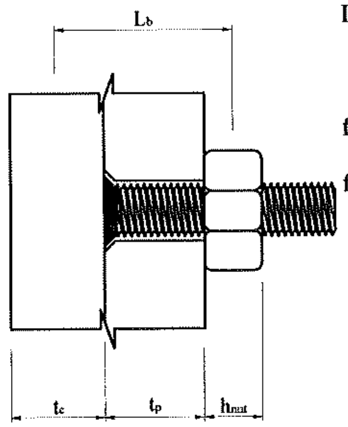
Figure 1. Notations for column and beam



a_f Throat thickness of the weld adjacent to the beam flange
a_w Throat thickness of the weld adjacent to the beam web
e Edge to bolt row distance
m Distance as indicated
m_2 Distance as indicated
t_p Thickness of the end plate
f_{yp} Yield strength of the end plate
f_{up} Ultimate strength of the end plate

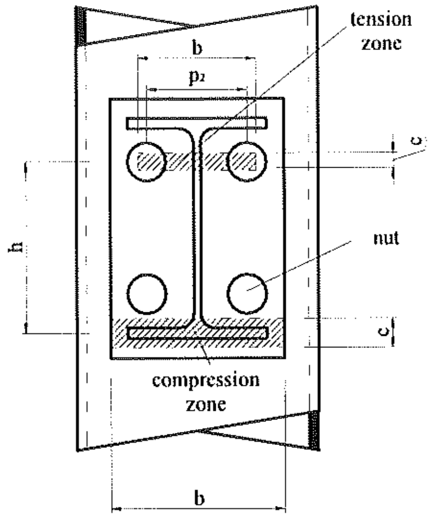
Figure 2. Notations for end plate





d_1 Largest diameter of the nut
d_2 Smallest diameter of the nut
d_m Mean diameter of the nut $[d_m = (d_1 + d_2)/2]$
h_{nut} Height of the nut
A_s Resistant area of the stud
L_b Stud elongation length $[L_b = 0,5t_c + t_p + 0,5h_{nut}]$
f_{yb} Yield strength of the stud
f_{ub} Ultimate strength stud

Figure 3. Notations for studs



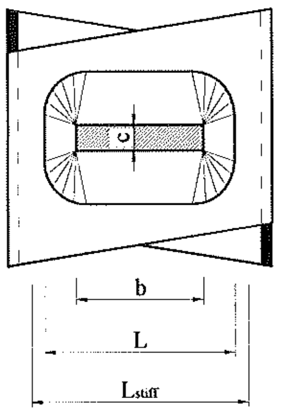
Tension zone:

- p_2 Horizontal distance between the studs
- b Width of the tension zone *[$b = p_2 + 0,9d_m$]*
- c Height of the tension zone *[$c = 0,9d_m$]*

Compression zone:

- b Width of the compression zone
  [For the determination of b in the compression zone, a dispersion of the load under 45° from the edges of the welds can be assumed. b is limited by the dimensions of the end plate]
- c Height of the compression zone
  [For the determination of c in the compression zone a dispersion of the load under 45° from the edges of the welds can be assumed. b is limited by the dimensions of the end plate]
- h Distance between the centre of the tension zone and the compression zone

Figure 4. Notations for studs



- L Width of the yield area *[$L = b_c - 2t_c - 1,5r$]*
- L_{stiff} Equivalent yield length for stiffness determination *[$L_{stiff} = d + r = b_c - 2t_c + r$]*

Figure 5. Notations for the yield area (tension or compression)

4.3 *Design moment resistance*

4.3.1 *Beam flange in compression:*

$$F_{Rd,1} = M_{b,Rd} / (h_b - t_{fb})$$

with:

$M_{b,Rd}$ is the design moment resistance, depending on the class of the cross section (M_{pl}, M_{el} or M_{eff})

4.3.2 *Studs in tension:*

$$F_{Rd,2} = n \times \min[F_{t,Rd}; B_{p,Rd}]$$

with:

n is the number of studs in the tension zone of the joint

$$F_{t,Rd} = \frac{k_2\ f_{ub}\ A_s}{\gamma_{M2}}$$

where:

$k_2 = 0,63$ for countersunk bolt,

$k_2 = 0,9$ otherwise

$$B_{p,Rd} = 0,6\,\pi\, d_m\, t_p f_{up} / \gamma_{M2}$$

4.3.3 *End-Plate in bending:*

$$F_{Rd,3} = \min[F_{T,Rd,1}; F_{T,Rd,2}]$$

with:

$$F_{T,Rd,1} = \frac{(8n - 2e_w) M_{pl,1,Rd}}{2mn - e_w(m+n)}$$

where:

$$n = \min[e; 1,25 \times m]$$

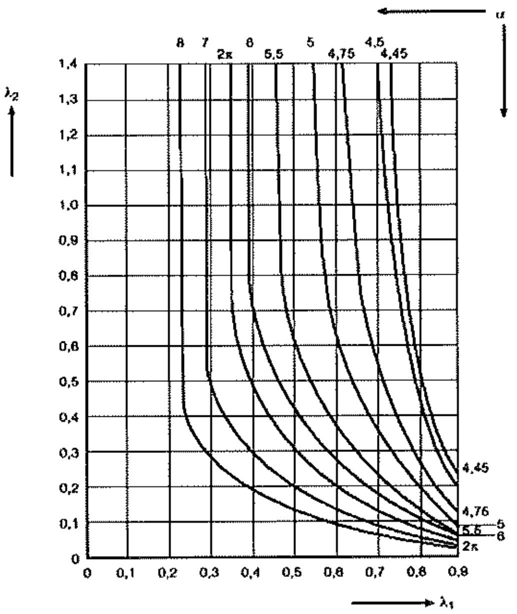
$$e_w = \frac{d_1}{4}$$

$$M_{pl,1,Rd} = 0,25 \sum l_{eff,1} t_p^2 f_{yp} / \gamma_{M0}$$

and:

$$\sum l_{eff,1} = l_{eff,1} \text{ (only 1 row)}$$

$$= \min[2\pi m; \alpha \times m]$$



α is based on the pre-evaluation of:

$$\lambda_1 = \frac{m}{m+e} \text{ and } \lambda_2 = \frac{m_2}{m+e}$$

$$F_{T.Rd,2} = \frac{2M_{pl,2,Rd} + n\sum F_{t,Rd}}{m+n}$$

where:

$$M_{pl,2,Rd} = 0{,}25\sum l_{eff,2} t_p^2 f_{yp} / \gamma_{M0}$$

and:

$$\sum l_{eff,2} = l_{eff,2}(only 1 row) = \alpha \times m$$

4.3.4 *Beam web in tension:*

$$F_{Rd,4} = b_{eff,t,wb} t_{wb} f_{yb} / \gamma_{M0}$$

with

$$b_{eff,t,wb} = l_{eff,1}$$

4.3.5 *RHS in transverse compression and tension: Chord face failure:*

$$F_{Rd,5 and 6} = \min[F_{pl,loc}; F_{pl,glob}]$$

for determination of $F_{pl,loc}$:

if b> $b_m = L\left[1 - 0{,}82\frac{t_c^2}{c^2}\left(1+\sqrt{1+2{,}8\frac{c^2}{t_c L}}\right)^2\right]$

$$\Rightarrow F_{pl,loc} = \beta 4 m_{pl,Rd}\left[\frac{\pi\sqrt{L(a+x)}+2c}{a+x} + \frac{1{,}5cx + x^2}{\sqrt{3}t_c(a+x)}\right]$$

where:

$\beta = 1$ if $\frac{b+c}{L} \geq 0{,}5$

$\beta = 0{,}7 + 0{,}6\frac{b+c}{L}$ if $\frac{b+c}{L} \leq 0{,}5$

$$m_{pl,Rd} = \frac{1}{4} t_c^2 f_{yc} / \gamma_{M0}$$

$$a = L - b$$

$$x = -a + \sqrt{a^2 - 1{,}5ac + \frac{\sqrt{3}t_c}{2}\left[\pi\sqrt{L(a+x_0)} + 4c\right]}$$

and:

$$x_0 = L\left[\left(\frac{t_c}{L}\right)^{\frac{2}{3}} + 0{,}23\frac{c}{L}\left(\frac{t_c}{L}\right)^{\frac{1}{3}}\right]\left(\frac{b-b_m}{L-b_m}\right)$$

if b $\leq b_m = L\left[1 - 0{,}82\frac{t_c^2}{c^2}\left(1+\sqrt{1+2{,}8\frac{c^2}{t_c L}}\right)^2\right]$

$$\Rightarrow F_{pl,loc} = \beta\frac{4\pi m_{pl,Rd}}{1-\frac{b}{L}}\left(\sqrt{1-\frac{b}{L}} + \frac{2c}{\pi L}\right)$$

for determination of $F_{pl,glob}$:

$$F_{pl,glob} = \frac{F_{pl,loc}}{2} + m_{pl,Rd}\left(\frac{2b}{h} + \pi + 2\rho\right)$$

where:

$\rho = 1$ if $0{,}7 \leq \frac{h}{L-b} \leq 1$

$\rho = \frac{h}{L-b}$ if $1 \leq \frac{h}{L-b} \leq 10$

if $\frac{h}{L-b}$ smaller than 0,7 or greater than 10, the formula for $F_{pl,glob}$ is not valid.

4.3.6 *RHS in transverse tension: Punching shear failure*

$$F_{Rd,7} = \min[F_{punch,nc}; F_{punch,cp}]$$

with

$$F_{punch,nc} = 2(b+c)v_{pl,Rd}$$

where:

$$v_{pl,Rd} = \frac{t_c f_{yc}}{\sqrt{3}\gamma_{M0}}$$

$$F_{punch,cp} = n\pi d_m v_{pl,Rd}$$

4.3.7 *RHS in transverse compression: Punching shear failure*

$$F_{Rd,8} = F_{punch,nc}$$

with

$$F_{punch,nc} = 2(b+c)v_{pl,Rd}$$

where:

$$v_{pl,Rd} = \frac{t_c f_{yc}}{\sqrt{3}\gamma_{M0}}$$

4.3.8 *Resistance of the weakest component*

$$F_{Rd} = \min_{i=1}^{8} F_{Rd,i}$$

4.3.9 *Plastic design moment resistance*

$$M_{Rd} = F_{Rd} \times h$$

4.3.10 *Elastic moment resistance*

$$M_e = \frac{2}{3} M_{Rd}$$

4.4 *Initial joint stiffness*

4.4.1 *Beam flange in compression*

$$k_1 = \infty$$

4.4.2 *Studs in tension*

$$k_2 = 1{,}6\frac{A_s}{L_b}$$

4.4.3 *End-plate in bending*

$$k_3 = \frac{0{,}9 l_{eff} t_p^3}{m^3}$$

4.4.4 *Beam web in tension*

$k_4 = \infty$

4.4.5 *RHS in transverse compression and tension: Chord face failure*

$$k_{5\,and\,6} = \frac{t_c^3}{14{,}4\beta L_{stiff}^2}\left(\frac{L_{stiff}^2}{bt_c}\right)^{1,25} \frac{\dfrac{c}{L_{stiff}} + \left(1-\dfrac{b}{L_{stiff}}\right)\tan\theta}{\left(1-\dfrac{b}{L_{stiff}}\right)^3 + \dfrac{10{,}4\left(k_1 - k_2\dfrac{b}{L_{stiff}}\right)}{\left(\dfrac{L_{stiff}}{t_c}\right)^2}}$$

with:

$\theta = 35 - 10\dfrac{b}{L_{stiff}}$ if $\dfrac{b}{L_{stiff}} < 0{,}7$

$\theta = 49 - 30\dfrac{b}{L_{stiff}}$ if $\dfrac{b}{L_{stiff}} \geq 0{,}7$

$k_1 = 1{,}5$

$k_2 = 1{,}6$

the formula for $k_{5\ \text{and}\ 6}$ is only valid if these requirements are fulfilled:

$10 \leq L_{stiff} / t_c \leq 50$

$0{,}08 \leq b / L_{stiff} \leq 0{,}75$

$0{,}05 \leq c / L_{stiff} \leq 0{,}20$

4.4.6 *RHS in transverse tension: Punching shear failure*

$k_7 = \infty$

4.4.7 *RHS in transverse compression: Punching shear failure*

$k_8 = \infty$

4.4.8 *Initial stiffness*

$$S_{joint,init} = Eh^2 / \sum_{i=1}^{8} 1/k_i$$

5 CONCLUSIONS

The component approach is nowadays considered as the general procedure for the evaluation of the design properties of structural joints made of a single construction material or of a combination of different materials and subjected to various loading situations (moments, shear and/or axial forces, ...) and loading conditions (static, seismic, fire, ...). It is explicitly referred to in Eurocodes 3 and 4, respectively for steel and steel-concrete joints between I or H profiles. Since few years, the authors investigate, with the help of CIDECT, its extension to steel joints between members made of tubular profiles or of tubular and open profiles. The steps to cross are the following ones:

- derivation of design formulae for still-unknown components;
- validation of design procedures for whole joints by comparisons with tests and numerical simulations;
- proposal of practical guidelines for the day-to-day application of the component method.

Progress is regularly made on the two first steps through appropriate scientific works; it consists either in the reformatting of existing design formulae or the derivation of new ones. A review of the today available material is proposed in (Jaspart & al 2005).

In the present paper a first practical design tool, with a so-called "design sheet" format, is suggested. Its application is rather simple and a reliable programming (EXCEL sheet for instance) may be easily contemplated. In order to simplify further the work of the designer, tables of standardised joints may even be produced in which the properties of the joints, evaluated by means of the "design sheets" are directly listed (moment resistance, rotational stiffness, failure mode, ...).

Such design tools (software, design sheets, tables of standardised joints) are now widely available and used in Europe for joints between members with I and H sections and the authors hope that the work presented in this paper will be the trigger of a similar evolution process for the tubular construction.

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