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APPLICATION RULES FOR STATIC RESISTANCES OF K-GAP JOINTS IN TUBULAR LATTICE STRUCTURES

BY

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Abstract. The particular behaviour of joints with hollow sections is not an easy task, leading to a lack of agility in the design process. The available market profiles of the elements must be chosen judiciously early from the design stage, in order to avoid subsequent problems at the connection design stage. These limitations have given rise to the need to obtain further information on the performance of joints with hollow sections in what concerns resistance, stiffness and deformation capacity. The study of joints with square hollow sections described in the present paper evaluates the differences in design between EN 1993-1-8 and ISO 14346 (2013). The latest norm is based on CIDECT design guide (Packer *et al*., 2009).

Keywords: square hollow sections; lattice structures; Hollow Structural Sections (HSS); Rectangular Hollow Section (RHS); EN 1993-1-8; ISO 14346; K-gap joint; design axial resistance.

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1. Introduction

The past decade has seen a rapid growth of space structures made from tubular profiles. Due to their cross section efficiency, these structural shapes are capable of covering large spans with low material consumption.

Tubular shapes are optimized shapes for compressing and torsion forces. One of the major impediments in designing this type of space structure is the complex prediction of the joints behaviour. Details of the joints for trusses vary, ranging from two- to three-dimensional tube-to-pipe connections. Frequent nodal typologies for space structures are T, K, KT or Y, with space or overlapped.

Most often, Hollow Structural Sections (HSS) connections should be designed to be unreinforced, for economical and aesthetic reasons.

Considerable effort to improve conventional connection designs has been made during the past 5 years to avoid premature failure, varying from analytical approaches to experimental validation or numerical modelling (Rondal *et al*., 1992; Wardenier, 2000; Fleischer *et al*., 2010); studies that indicate the need for further investigations, especially for particular situations of the joints geometry.

Considering this limitations, arises the interest to obtain more information on the performance of joints with hollow sections according to its resistance, stiffness and deformation capacity. The study of joints with square hollow sections described in the present paper evaluates the differences in design between EN 1993-1-8 and ISO 14346 (2013). The latest norm is based on CIDECT design guide (Packer *et al*., 2009).

2. Parameters Included in Design Norms

In order to be able to carry out the preliminary design of the nodes between the elements of the space structures constructed according to the standards in force, among which are SR EN 1993-1-8 (2010), the CIDECT Design Guide (Packer *et al*., 2009) and ISO14346 (2013), different geometric parameters of the node must comply with certain limits imposed by the standard being used.

These parameters are presented in Table 1 and Fig. 1, customized for the case of joints space nodes between square tubular profiles. For this kind of joint, the ratio limit for Rectangular Hollow Section (RHS) recommended by CIDECT is greater than the ratio recommended by EN 1993-1-8.

Table 1
Range of Validity for Gapped Connections with Square Hollow Sections

	EN 1993-1-8 (2010)	ISO 14346 (2013)
Brace-to chord ratio	$b_1/b_0 \geq 0.1 + 0.01b_0/t_0$ but $b_1/b_0 \geq 0.35$	$b_1/b_0 \geq 0.1 + 0.01b_0/t_0$ but $b_1/b_0 \geq 0.25$
RHS chord	class 2 and $2\gamma = b_0/t_0 \leq 35$	***Compression*:** class 1 or 2 and $2\gamma = b_0/t_0 \leq 40$ ***Tension:*** $\gamma = b_0/t_0 \leq 40$
RHS Brace	***Compression*:** class 2 and $b_i/t_i \leq 35$ ***Tension:*** $b_i/t_i \leq 35$	***Compression*:** class 1 or 2 and $b_i/t_i \leq 40$ ***Tension:*** $b_i/t_i \leq 40$
Gap	$0.5 (1 - \beta) \leq g/b_0 \leq 1.5 (1 - \beta)$ but $g \geq t_1 + t_2$	
SHS brace-to chords ratio	$0.6 \leq \dfrac{b_1 + b_2}{2b_1} \leq 1.3$	*N/A*

where the following notations are used:

$$\beta = \frac{b_1 + b_2}{2b_0}, \qquad \gamma = \frac{b_0}{2t_0}, \tag{1}$$

b_0, t_0, b_i and t_i denote the widths and the thickness of the chord and respectively, of the braces members, and g is the gap between brace members, according to Fig. 1.

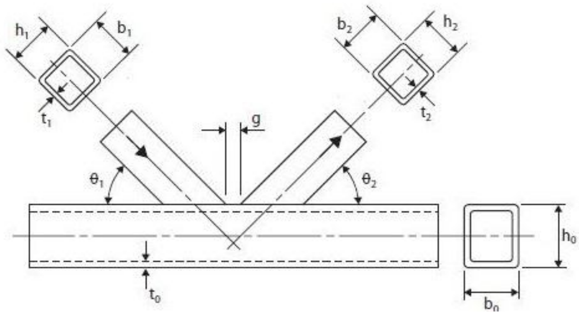

Fig. 1 – Gap joint: notations.

3. Failure Modes for RHS to RHS Connections

In the last five years, a series of experimental studies demonstrated the influence of the stresses in the flange on the diagonal strength. The results have shown that stresses in the compressed flange significantly reduce joint resistance (Nizer *et al.*, 2015). The new edition of standards, i.e. the second version of the CIDECT design guide, based on which the international standard ISO 14346 (2013) is being developed, predict a certain reduction in the joints resistance for both flange and tension and compression (Table 2). These two editions incorporate the latest studies of the International Welding Institute IIW, obtained on extensive and rigorous analyses that led to a reformulation of the joints resistance between the tubular profiles. The European design standard EN 1993-1-8 (Jaspart *et al.*, 2005) has not yet been updated, still retaining the recommendations prescribed by the first version of CIDECT, as can be seen in Table 3.

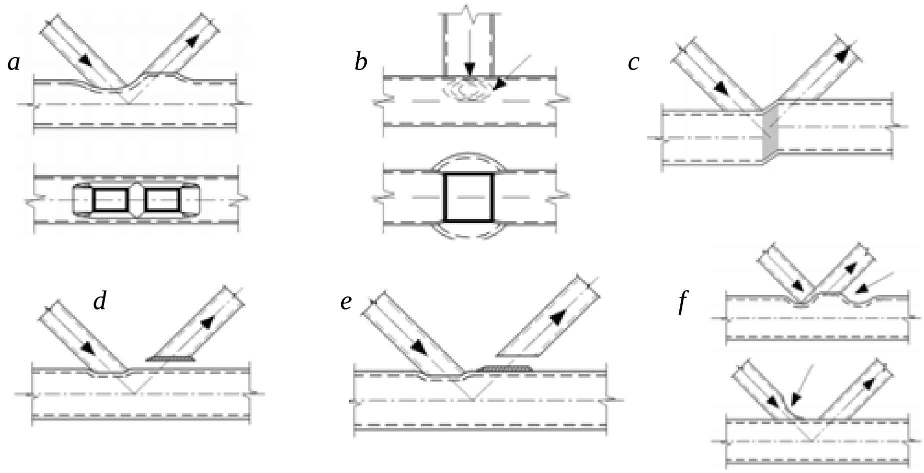

Fig. 2 – Failure modes in K-Connections according to EN 1993-1-8: *a* – chord face failure; *b* – chord side wall failure; *c* – Chord shear failure; *d* – Punching shear; *e* – brace failure; *f* – local buckling.

Table 2 presents the computational relationships Eurocod 3, EN 1993-1-8 (2005) and ISO 14346 (2013), but also the design methodology of the tubular joints due to relevant failure modes (Fig. 2).

The value of *n* can be estimated with:

$$n = \frac{N_{0,\mathrm{Ed}}}{A_0 f_{y0}} + \frac{M_{0,\mathrm{Ed}}}{W_{\mathrm{el},0} f_{y0}}, \tag{2}$$

where $N_{0,\mathrm{Ed}}$ and $M_{0,\mathrm{Ed}}$ are the design compression force and bending moment, respectively, f_{y0} is the yield stress of the chord member, A_0 and $W_{\mathrm{el},0}$ are area and respectively, the elastic modulus of the chord section.

Table 2
Design Resistances of SHS Brace to RHS Chord K Gap Joints-Chord Resistance

EN 1993-1-8 (2006)	$N_{1,Rd} = 8.9\beta\gamma^{0,5}k_n \frac{f_{yo}t_0^2}{\sin\theta_i}/\gamma_{M2}$ $k_n = 1.3 - \frac{0.4}{\beta}n$ if n >0 (chord in compression) $k = 1$ if $n \le 0$ (chord in tension)
ISO 14346 (2013) CIDECT 2009	$F_1^* = Q_u Q_f \frac{f_{yo}t_0^2}{\sin\theta_i}$ $Q_u = 14\beta\gamma^{0,3}$; $Q_f = (1-\lvert n\rvert)^{C_1}$ with $C_1 = 0.5 - 0.5\beta$ if n >0 (chord in compression) $C_1 = 1$ if $n \le 0$ (chord in tension)

Table 3
Design Resistances of SHS Brace to RHS Chord K Gap Joints Chord Punching Shear and Brace Failure Resistance

Chord punching shear	
EN 1993-1-8 (2006)	$F_i^* = \frac{f_{yo}t_0}{\sqrt{3}\sin\theta_i}l_{p,\text{eff}}/\gamma_{M5}$
ISO 14346 (2013) CIDECT 2009	$F_i^* = \frac{0.588 f_{yo}t_0}{\sin\theta_i}l_{p,\text{eff}}$
$l_{\text{p,eff}} = \frac{2h_i}{\sin\theta_i} + b_i + b_{e,p}$, $b_{e,p} = \frac{10}{b_0/t_0}b_i \le b_i$	
Brace failure	
EN 1993-1-8 (2006)	$F_i^* = f_{yi}t_i l_{b,\text{eff}}/\gamma_{M5}$
ISO 14346 (2013) CIDECT 2009	$F_i^* = f_{yi}t_i l_{b,\text{eff}}$
$l_{b,\text{eff}} = 2h_i + b_i + b_e - 4t_i$, $b_e = \frac{10}{b_0/t_0}\frac{f_{y0}t_0}{f_{yi}t_i}b_i \le b_i$	

4. Numerical study - Parameter effects and comparison between standards

The chord face failure by plasticisation is the most common failure mode for joints with a single bracing and for gapped *K*- and *N*-connections. This mode of failure is sensitive to bracing-to-chord width ratio β. If β is bigger than 0.85, the joint resistance can exceed the resistance of the bracing, as can be observed from Fig. 3. Slender chords with large width to thickness ratio, *i.e.* large γ, are sensitive to chord face failure.

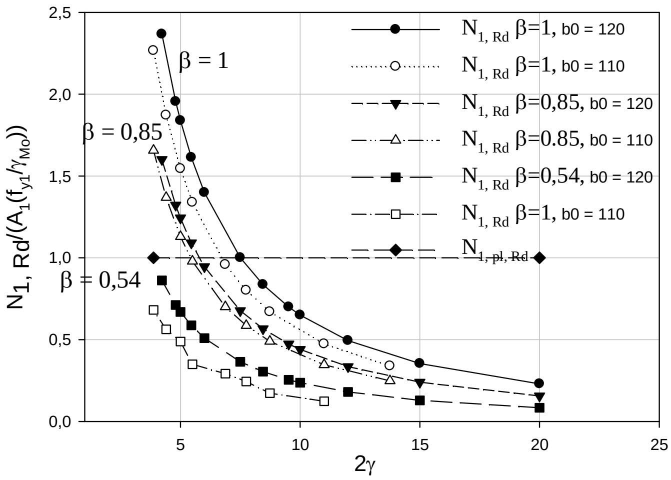

Fig. 3 – Chord plasticization failure for different *β*.

Due to the geometric characteristics and difference of stiffness between members, the concept of effective width based on the non-uniform stresses and strains in the joint is introduced. Such a failure (Fig. 2 *e*) can occur when the effective width decreases and is mainly associated with rectangular chord gap joints with large *b* ratios and thin chords. Procedures that can be made to increase the effective width require the use of reinforcements.

Fig. 4 shows that the effective width of a transverse element highly depends on the slenderness of the chord member – if the chord connecting face is thin and flexible (high $2\gamma = b_0/t_0$), the effective width will be low.

A significant number of studies based on experimental and numerical results indicate that this failure mode may also occur in tension, by the local yielding and then premature failure of the transverse element. This trend is reflected by CIDECT and respectively, ISO 14346, with both reducing the joint resistance for both cases, *i.e.*, tensile and compression, while the European norm EN 1993-1-8 mentions the resistance reduction only for compression.

The chord punching shear can be caused by a crack initiation in the chord face, causing a patch of chord material to pull out (or punch in) around the footprint of a branch member, at the toe of the weld to the chord. (Fig. 2 *d*). This failure mechanism is not usually critical, but can happen when the chord width to thickness ratio (2γ) is small or when chord- to brace width ratio β less that 0.85 (Fig. 5).

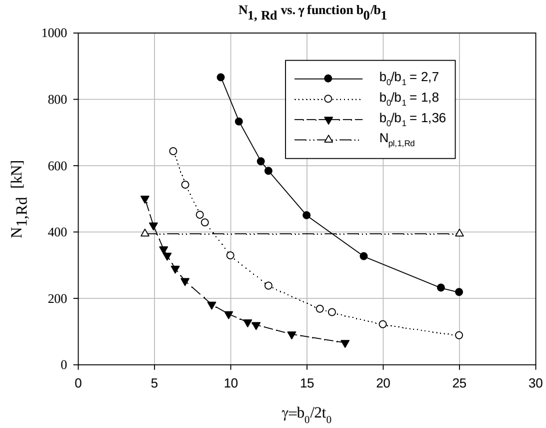

Fig. 4 – Effective width failure function of bracing to cord ratio.

This failure is frequently found in various HSS connections, particularly for medium to high branch-to-chord width ratios, as shown in Fig. 5. It can also be found in the case of slender braces, as depicted in Fig. 6.

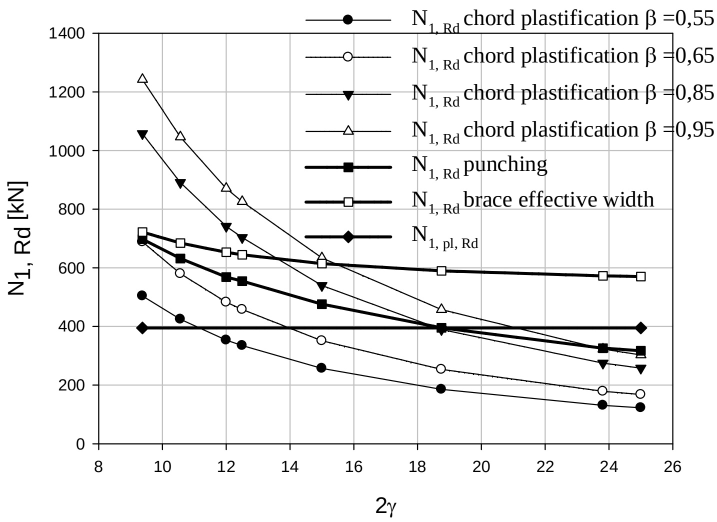

Fig. 5 – Comparison between chord plasticisation, punching shear and effective with resistance.

Comparison diagrams for the failure mechanism by chord plasticization obtained by following European norm EN 1993-1-8 and ISO 14346 are shown in Fig. 7. The results are obtained for a load factor coefficient *n* =0.8 (see eq. 2). The influence of bracing to chord width ratio is also investigated, by means of varying the chord section for a constant brace section. Small brace to chord ratio significantly reduces the levels of the brace connection, as can be seen in Fig. 7.

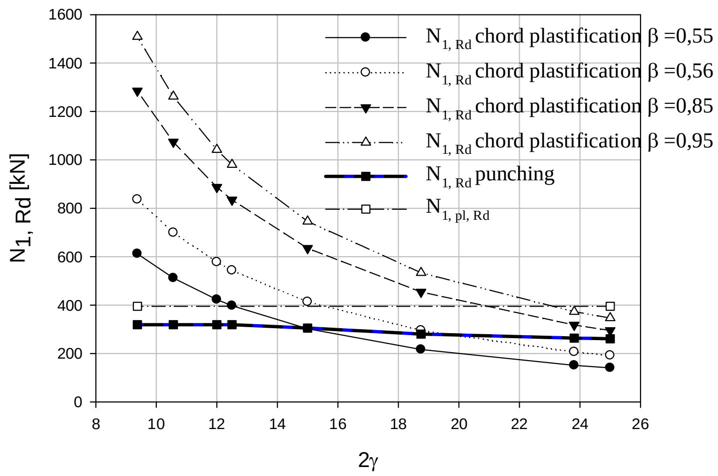

Fig. 6 – $N_{1,\,Rd}$ chord plasticisation, punching shear and effective with resistance for slender braces.

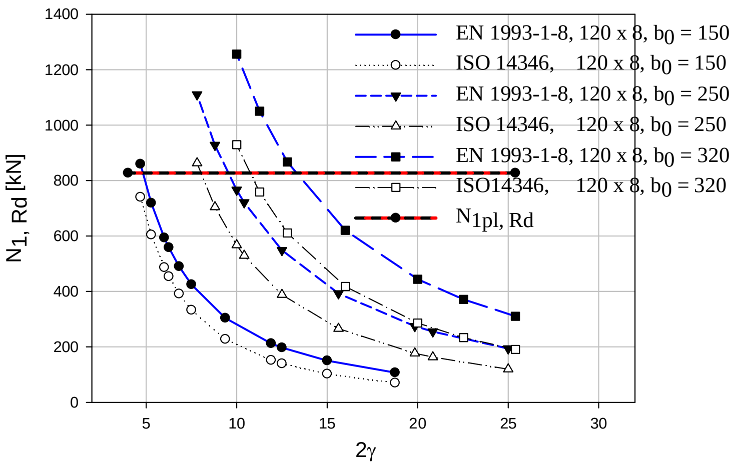

Fig. 7 – $N_{1,\,Rd}$ chord plasticisation, comparison EN 1993-1-8 (2006) with ISO 14346 (2013)

5. Conclusions

Due to its complex design and detailing compared to other structural elements, the design of tubular lattice is not a trivial task. The particular behaviour of joints with hollow sections causes a certain discrimination in using these kind of sections. The behaviour of joints with hollow sections leads to a lack of agility in the design process, when the design engineer must choose the available profiles for the elements early in the design stage, in order to avoid subsequent problems at the connection design stage.

The particular behaviour of joints with hollow sections is slightly different in the main design norms, such as European norm EN 1993-1-8, the CIDECT design guide for RHS joints (Packer *et al*., 2009) and ISO 14346 (2013). In spite of the above, due to their properties, the demand for hollow sections is on the rise.

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APLICAREA STANDARDELOR PENTRU EVALUAREA REZISTENȚEI NODURILOR ÎN K CU SPAȚIU LA STRUCTURILE RETICULARE

(Rezumat)

Studiul comportării nodurilor secțiunilor tubulare nu este o sarcină uşoară, ceea ce duce la o viteză redusă în procesul de proiectare. Pofilele disponibile ale elementelor structurale trebuie alese în mod judicios la începutul etapei de proiectare, pentru a evita problemele ulterioare din etapa de proiectare a nodurilor. Având în vedere aceste limitări, se manifestă interesul pentru obținerea mai multor informații despre performanțele îmbinărilor cu secțiuni tubulare în ceea ce priveşte rezistența, rigiditatea şi capacitatea de deformare. În această lucrare, studiul nodurilor secțiunilor tubulare în conformitate cu EN 1993-1-8 şi ISO 14346 (213) care se bazează pe ghidul de proiectare CIDECT este realizat într-un mod facil pentru a cunoaşte şi înțelege proiectarea pe baza acestor norme principale.