DESIGN HANBOOK FOR FRAME DESIGN

INCLUDING JOINT BEHAVIOUR

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Summary

In this paper, a design handbook for designers of steel building frames is presented. This handbook gives a quite complete overview of the design procedures for frame design - including joint behaviour - which are included in Eurocode 3 Part 1-1[1]. In its first part, a background information is given. The second part focuses on application rules for daily practice and a particular attention is paid to structural joints. Finally, worked examples for complete frame design are presented in the third part.

1. Introduction

Traditionally the analysis and the design of steel frame structures is based on the assumption that the constitutive beam-to-column joints, splices and column bases are perfectly pinned or perfectly rigid.

However studies performed in the last decade have clearly shown that:

- Most of the joints used in daily practice are not fulfulling the requirements so to be characterized by such idealized responses; they are said «*semi-rigid*» and «partial strength» when their resistance is lower than that of the connected members.
- The fulfillment of these requirements is often involving extra fabrication or erection costs .

Through economical investigations, it has also been progressively demonstrated that:

- The traditional rules for design of joints are rather conservative.
- The use of semi-rigid joints instead of pinned ones results in a decrease of the weight of the structure, and therefore of their total cost (5 to 10 %) including fabrication, transportation and erection costs.
- The use of semi-rigid joints instead of rigid ones sometimes results in an increase of the amount of steel needed, but also to a strong decrease of the fabrication costs through a simplified detailling of the joints (less stiffening for instance). The benefits varies here from 10 to 25 %.

To profit from these potential benefits requires new design methodologies for what regards design assumptions,frame analysis and verification of the ultimate and serviceability limit states.

This need is now widely expressed by designers, what has engendered, at the european level, different actions in the last years . Among these ones, let us mention:

- The full revision of the Annex J of Eurocode 3 on "Steel Joints in Building Frames" [2].
- The SPRINT european project where simplified design procedures for joint design and tables of standardized joints, all in agreement with EC3 Annex J, have been suggested [3].

The first one provides a legal frame for the use of the new design techniques for joints while the second focuses more on the practical aspects to which the designer is likely to be faced in his daily practice.

In the frame of a recent ECSC project (contracts 7210-SA/212 and 320), the SPRINT action has been prolonged so to cover also the implications of the joint behaviour on the structural frame analysis and design. The guide for users resulting from this action is briefly presented in the following pages.

The partners in this project are: University of Liège in Belgium as coordinator (R. MAQUOI and J.P. JASPART), CTICM in France (B. CHABROLIN, I. RYAN and A. SOUA), CRIF in Belgium (D. VANDEGANS), TNO Delft in The Netherlands (M. STEENHUIS) and RWTH Aachen in Germany (K. WEYNAND).

2. Content of the design handbook

The ECSC user's manual covers the following three main aspects :

- The design of commonly used beam-to-column joint configurations such as welded ones or bolted end plate and flange cleated ones. Beam splices are also covered.
- Guidelines on how to incorporate joint behaviour in the structural analysis (both 1st order and 2nd order, elastic and plastic).
- Design checks for the ultimate limit states (frame and member resistance and stability, member and joint section checks, ...)

It is structured into three main parts which all deal with all the three different aspects mentioned here above:

- *Part 1-Technical Background*

  A primary objective of the manual is to facilitate the use of Eurocode 3 and it has so been thought that this was requiring explanations about the general design philososophy to adopt in particular cases, the successive steps to follow, the assumptions to follow and the formulae to use.

- *Part 2-Application Rules*

  In this section, practical guidelines are given in a straigthforward manner. The designer should find there the recommendations he needs to perform frame analysis, joint design and structural verifications. All the formulae are expressed together with their limitations and their implications on further steps. For joints, three different design approaches are expressed, as described in section 3 of the present paper.

- *Part 3-Worked Examples.*

  Three different worked examples are included in the manual. They cover the whole frame and joint design procedure and not only some specific aspects as the joint characterization or the frame analysis. They should help the designer in understanding the different steps of a semi-rigid frame design, and the sequence of these steps according to the practical situation to which he is faced : engineer or constructor responsible for both frame and joint design or share of the responsibilities between the engineer (frame design) and the constructor (joint design).

All the scientific aspects have been disregarded and the content of all the chapters has been limited to the minimum but sufficient information which appears to be strictly useful to practitioners.

3. Design of the structural joints

An important step in the design process is the determination of the mechanical properties of the joints in terms of rotational stiffness, moment and shear resistances and rotation capacity.

For what regards this characterization, three approaches are followed :

- *design sheets*

  These are short documents containing very simple rules allowing to calculate in an easy and quick way the stiffness and resistance properties of some well-defined types of joints:

– beam-to column joints with extended endplates;
– beam-to column joints with flush endplates (2 types);
– beam splices with flush endplates (2 types);
– beam-to column joints with angle flange cleats.

These simplified procedures strongly reduce the amount of calculation in comparaison with the application of EC3 Annex J but are anyway in agreement with the EC3 design philosophy. An example of such a design sheet is shown in Annex 1 of the present paper.

- *design tables*

  These are tables covering standardized joints and providing the user with joint detailing and stiffness / resistance properties (see Annex 2); information allowing to classify the joints as pinned, semi-rigid or rigid, partial strength or full strength is also given.

- *software*

  This PC software called DESIMAN is able to characterize the mechanical properties of a wide range of usual or non-usual types of joints subjected to bending moments and shear forces. It includes graphical pre- and post-processors (see Annex 3). The pre-processor allows a user's friendly introduction of the data. It is connected to bolt, plate, material and profile databases, so allowing a decrease of the time required to introduce the data. It is also connected to another database in which all the calculations made can be stored, in order to be used further if needed.

  The post-processor of DESIMAN produces four main files :

  – A short one just giving the main results of the computation : design resistances in bending and shear, initial stiffness, collapse mode, ductility, class for frame analysis (1/2 page).
  – The previous one to which the resistance and the stiffness of all the constitutive joint components are added. Such a file allows the designer to modify in an optimum way its joint when the design requirements are not fulfilled (1 page).
  – A calculation note (± 5 pages) presenting more detailed results of the calculations, for each component and for the joint. This note is useful when, for instance, the design has to be checked by a control office.
  – A full calculation note just like that which could be produced by hand, and in which the results of all the intermediate calculations are given.

4. References

[1] Eurocode 3: Design of Steel Structures, Part 1-1; General Rules and Rules for Buildings, ENV 1993-1-1, 1992.

[2] New revised Annex J of Eurocode 3 "Joints in Building Frames", Doc. CEN/TC250/SC3-N419E, Brussels, June 1994.

[3] SPRINT Contract RA351 on "Steel Moment Connections according to Eurocode 3. Simple Design Aids for Rigid and Semi-Rigid Joints", 1992-1996.

Annex 1: Example of simplified design procedure

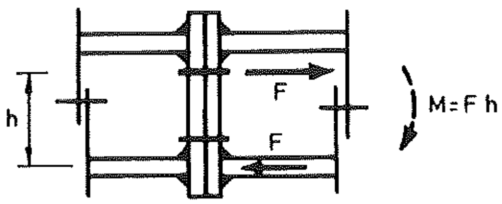
Mechanical characteristics

	Yield stresses	Ultimate stresses
Beam webs	f_{ywb}	-
Beam flanges	f_{yfb}	-
End-plates	f_{yp}	f_{up}
Bolts	-	f_{ub}

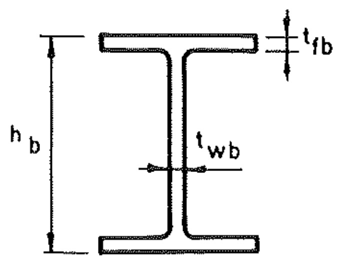
If hot-rolled profiles : $f_{ywb} = f_{yfb}$

Geometrical characteristics

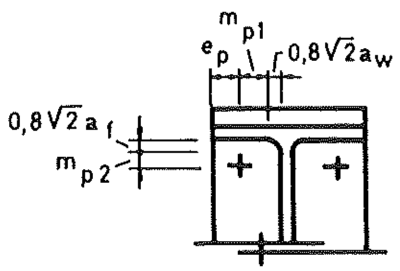
Joint

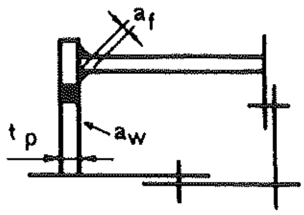


Beams



End-plates



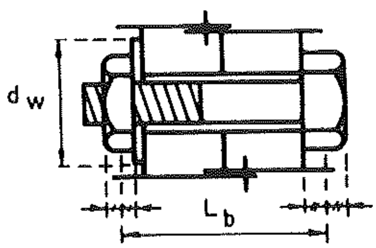


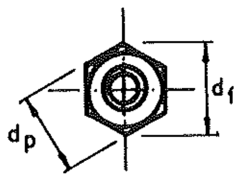
Bolts

d_w : see figure or = d_p if no washer*

A_s : resistance area of the bolt

* d_f is recommended in EC3 Annex J, and not d_p. As d_f is not given in all the catalogs for bolts, d_p is chosen here (safe assumption).

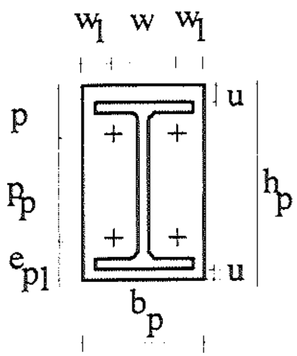


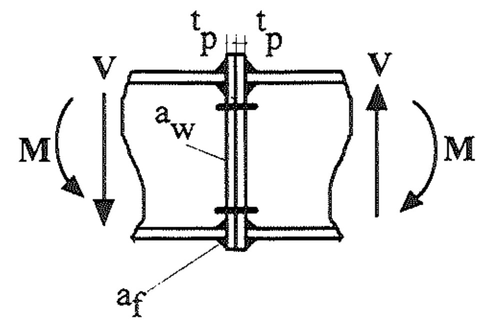


	STIFFNESS	RESISTANCE
Beam flanges in compression	$k_3 = \infty$	$F_{Rd,3} = M_{c.Rd} / (h_b - t_{fb})$ $M_{c.Rd}$: beam design moment resistance
Bolts in tension	$k_4 = 1{,}6 \dfrac{A_s}{L_b}$	$F_{Rd,4} = 2\ B_{t.Rd}$ with $B_{t.Rd} = F_{t.Rd}$ $F_{t.Rd} = \dfrac{0{,}9\ f_{ub}\ A_s}{\gamma_{Mb}}$
End-plates in bending	$k_7 = \dfrac{0{,}85\ l_{eff.p,t}\ t_p^3}{2\ m_{p1}^3}$	$F_{Rd,7} = \min\ [\ F_{ep.Rd,1}\ ;\ F_{ep.Rd,2}\ ]$ $F_{ep.Rd,1} = \dfrac{(8n_p - 2e_w)\ l_{eff.p,t}\ m_{pl.p}}{2m_{p1}\ n_p - e_w(m_{p1} + n_p)}$ $F_{ep.Rd,2} = \dfrac{2\ l_{eff.p,t}\ m_{pl.p} + 2\ B_{t.Rd}\ n_p}{m_{p1} + n_p}$ $n_p = \min\ [\ e_p\ ;\ 1{,}25 m_{p1}\ ]$ $m_{pl.p} = 0{,}25\ t_p^2\ f_{yp} / \gamma_{Mo}$ $e_w = d_w / 4$
	$l_{eff.p,t} = \min\ [\ 2\pi m_{p1}\ ;\ \alpha m_{p1}\ ]$ where α is defined in EC3 Annex J	
Beam web in tension	$k_8 = \infty$	$F_{Rd,8} = b_{eff.wb,t}\ t_{wb}\ f_{ywb} / \gamma_{Mo}$
	$b_{eff.wb,t} = l_{eff.p,t}$	
JOINT	Initial stiffness : $S_{j,ini} = E\ h^2 / \sum_{i=3,4,7,8} 1/k_i$ Nominal stiffness : $S_j = S_{j,ini} / 3$	$F_{Rd} = \min\ [\ F_{Rd,i}\ ]$ Plastic design moment resistance : $M_{Rd} = F_{Rd}\ h$ Elastic moment resistance : $\dfrac{2}{3} M_{Rd}$

Annex 2: Example of design table for standardized joints

Poutre — S235 — **Boulons hr8.8**





Mode de rupture	Code
Semelle de la poutre en compression	BFC
Boulons en traction	BT
Plat d'about soumis à flexion	EPT
Ame de la poutre en traction	BWT

$\gamma_{M0} = 1.10$

$\gamma_{Mb} = 1.25$

Poutre S235	Boulons hr8.8	Plat d'about: S235 (mm)			Détail du noeud (mm)						Soudures (mm)		Rigidité du noeud (kNm/rad)		Résistance: Moment (kNm)		Résistance: Cisaillement (kN)	Mode de rupture	Longueur de référence(m)	
		t_p	b_p	h_p	p	p_p	e_{p1}	w	w_1	u	a_w	a_f	$S_{j,ini}$	$S_{j,ini}/3$	M_{Rd}	$2/3M_{Rd}$	V_{Rd}	Code	L_{bb}	L_{bu}
IPE220	M16	15	140	240	60	120	60	90	25	10	3	5	15433	5144	24.1	16.1	157	EPT	3.0-R	S
IPE240	M16	15	140	260	60	140	60	90	25	10	4	5	20098	6699	27.2	18.1	157	EPT	3.3-R	S
IPE270	M16	15	154	290	65	160	65	90	32	10	4	6	26826	8942	32.4	21.6	157	EPT	3.6-R	S
	M20	20	154	290	65	160	65	90	32	10	4	6	42892	14297	53.8	35.9	245	EPT	R	7.1-R
IPE300	M16	15	170	320	65	190	65	90	40	10	4	6	36564	12188	38.9	25.9	157	EPT	3.8-R	12.0-R
	M20	20	170	320	65	190	65	90	40	10	4	6	57607	19202	64.3	42.8	245	EPT	R	7.6-R
IPE330	M16	15	180	350	65	220	65	90	45	10	4	6	47398	15799	44.8	29.9	157	EPT	4.2-R	13.0-R
	M20	20	180	350	65	220	65	90	45	10	4	6	74007	24669	73.8	49.2	245	EPT	2.7-R	8.3-R
	M24	20	180	350	75	200	75	110	35	10	4	6	62600	20867	78.5	52.3	352	EPT	3.2-R	9.9-R
IPE360	M16	15	210	400	75	250	75	90	60	20	5	7	60854	20285	50.1	33.4	157	EPT	4.5-R	14.0-R
	M20	20	210	400	75	250	75	90	60	20	5	7	93626	31209	82.5	55.0	245	EPT	2.9-R	9.1-R
	M24	20	210	400	85	230	85	110	50	20	5	7	85645	28548	96.8	64.5	352	EPT	3.2-R	10.0-R
IPE400	M16	15	220	440	75	290	75	90	65	20	5	7	78661	26220	56.7	37.8	157	EPT	4.9-R	15.4-R
	M20	20	220	440	75	290	75	90	65	20	5	7	120698	40233	93.4	62.3	245	EPT	3.2-R	10.1-R
	M24	20	220	440	85	270	85	110	55	20	5	7	113428	37809	112.7	75.1	352	EPT	3.4-R	10.7-R
	M27	25	220	440	95	250	95	130	45	20	5	7	118284	39428	139.3	92.9	458	EPT	3.3-R	10.3-R
IPE450	M16	15	230	490	75	340	75	90	70	20	5	8	104399	34800	65.0	43.3	157	EPT	5.4-R	17.0-R
	M20	20	230	490	75	340	75	90	70	20	5	8	159614	53205	107.1	71.4	245	EPT	3.6-R	11.1-R
	M24	20	230	490	85	320	85	110	60	20	5	8	152172	50724	130.4	86.9	352	EPT	3.7-R	11.6-R
	M27	25	230	490	95	300	95	130	50	20	5	8	162176	54059	165.8	110.5	458	EPT	3.5-R	10.9-R
IPE500	M16	15	240	540	80	380	80	100	70	20	6	9	118633	39544	72.4	48.3	157	EPT	6.8-R	S

Annex 3: Input and output screens of DESIMAN software