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PREDESIGN OF STEEL FRAMES WITH SEMI-RIGID JOINTS

It is well known that real solutions of steel joints in framed structures are far away from the conservative assumption that joints behave like pure hinges and/or full rigid connections. Applying semi-rigid philosophy in the design requires consideration of joint characteristics (M-ϕ relationship) in the global analysis. The main parameters describing M-ϕ curve are the moment resistance $M_{j.Rd}$ and initial stiffness $S_{j.ini}$. In EC3, part 1-8, there are procedures to determinate joint properties, but calculation of them is very troublesome and time consuming. Using regression analysis, simple formulas for $M_{j.Rd}$ and $S_{j.ini}$, possible for hand calculator, were obtained for end-plate bolted as well as welded beam-to-column connection. The distribution of internal forces in the frame depends on, and changes with the changes of joints stiffness, which in turn depend on beam and column sections. To help designers avoid many recalculation and speed up their design work there is a need to supply design tools, like "good guess" assessment, simple formulas, tables, design guidelines, which enable designer to assess preliminary members and joints properties. Based on the wide analysis of many frames with various types of joints, such design tools were developed and are presented in the paper.

Key words: global analysis, design algorithm, semi-rigid joint, conceptual design, predesign, braced frame, unbraced frame, lateral frame drift.

Реальні рішення в сталевих каркасних конструкціях далекі від консервативного припущення, що вузли поводяться як чисті шарніри і/або повністю жорсткі защемлення. Застосування напівжорсткості в проектуванні вимагає розгляду характеристик з'єднання (взаємозв'язку М-ϕ) в глобальному аналізі. Основними параметрами, що описують залежність М-ϕ , є момент опору $M_{j.Rd}$ та початкова жорсткість $S_{j.ini}$. У Єврокоді 3, частині 1-8, передбачено порядок визначення характеристик з'єднання, але їх розрахунок дуже клопітний і забирає багато часу. З використанням регресійного аналізу, прості формули для $M_{j.Rd}$ та $S_{j.ini}$, посильні ручному калькулятору, були отримані для торцевої пластини з болтами, а також зварного з'єднання ригель-колона. Розподіл внутрішніх зусиль в рамі залежить від зміни жорсткості вузла, яка в свою чергу залежить від перерізів ригелів і колон. Щоб допомогти інженерам уникнути багатьох перерахунків і прискорити їхні проектні роботи, необхідно розробити інструменти проектування, такі як "гарна здогадка", прості формули, таблиці, методики, які дозволяють проектанту попередньо оцінити елементи і їх властивості. На основі докладного аналізу багатьох рам з різними типами з'єднань такі інструменти проектування були розроблені і представлені в статті.

Ключові слова: глобальний аналіз, алгоритм проектування, напівжорсткі з'єднання, концептуальне проектування, попередній розрахунок, рама зі зв'язками, рама без зв'язків, поперечні переміщення рами.

Introduction

For many years, when in design of steel structures joints properties were not taken into account in the global analysis, joint safety was checked in the last phase of the design procedure (see Fig. 1).

Applying semi-rigid philosophy in the design requires consideration of joint characteristics (M-ϕ relationship) in the global analysis. In this way design procedure changes to the one shown in the figure 2, where joint parameters should be established in the beginning phase of design, like for members. It is well known that real solutions of steel joints in framed structures are far away from the conservative assumption that joints behave like pure hinges and/or full rigid connections.

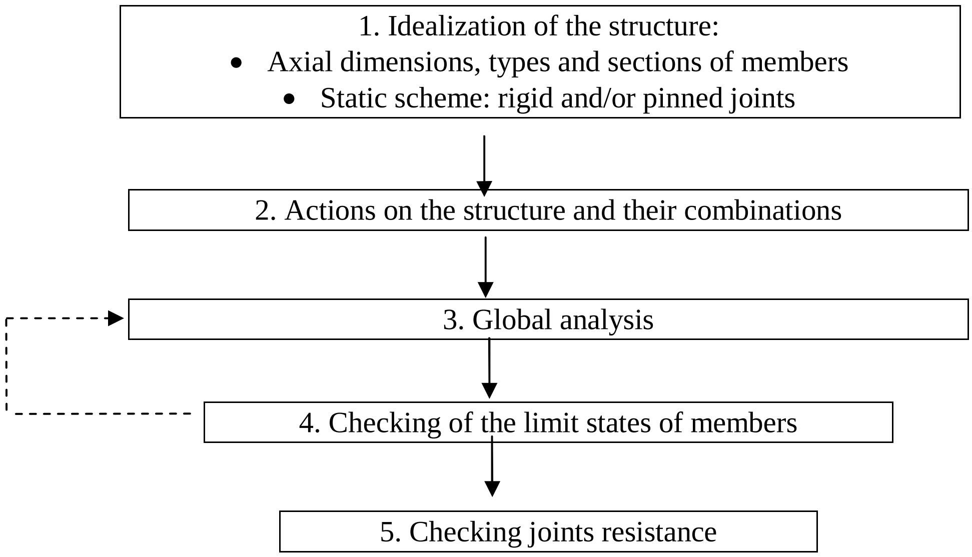

Fig. 1: Traditional algorithm of steel frame design

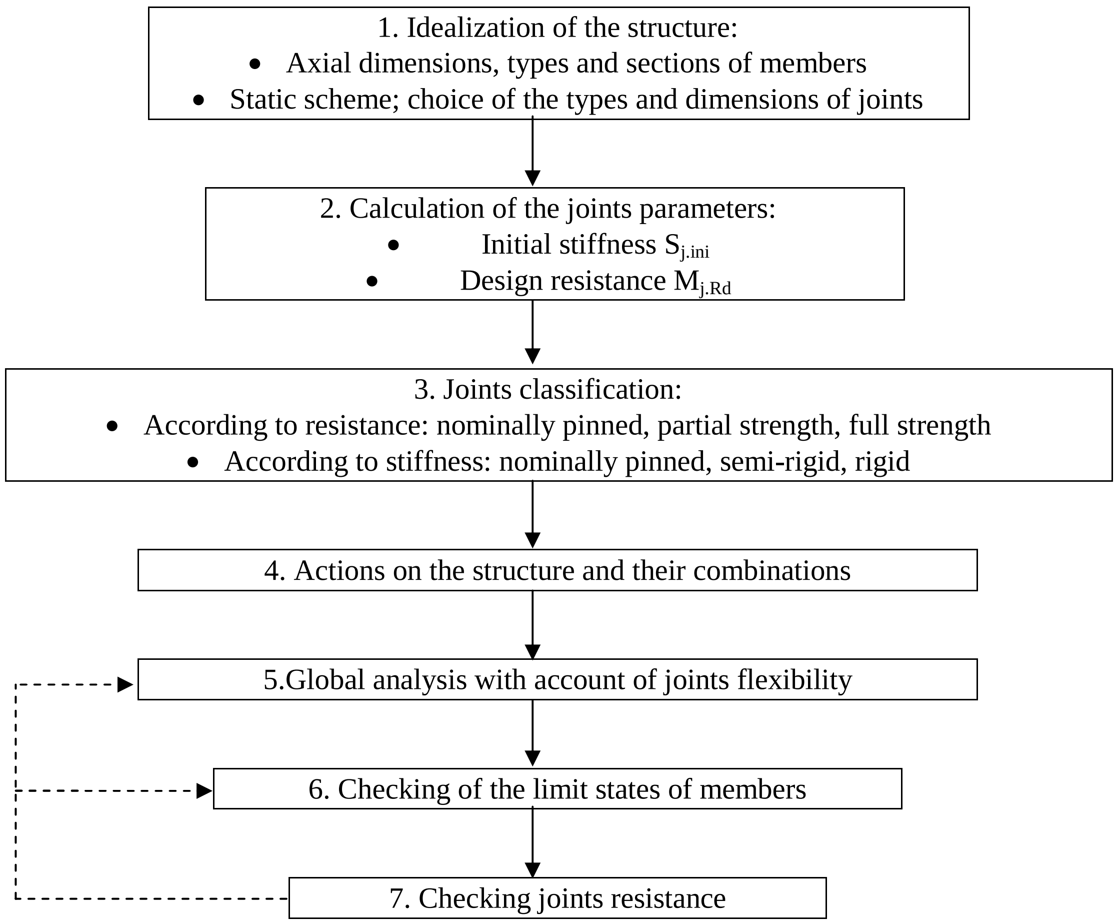

Fig.2: Modern algorithm of steel frame design

To conduct joint classification needed in this procedure and for global analysis, the main joint properties, namely moment resistance $M_{j.Rd}$ and initial stiffnesss $S_{j.ini}$ must be known in advance. Joint characteristics depend not only on joint arrangement and detailing but also on connected beam and column section. In EC3, part 1-8 [1], there are procedures to determinate joint properties, but calculation of them is very troublesome and time consuming, even with the use of available software. Such calculation should be done in the final checking of joint safety. The distribution of internal forces in the frame depends on, and changes with the changes of joints stiffness, which in turn depend on beam and column sections.

To help designers avoid many recalculation and speed up their design work there is a need to supply design tools, like "good guess" assessment, simple formulas, tables, design guidelines, which can be used in predesign (conceptual) phase of design process. The aim of this paper is to propose such solution for steel frames with semi-rigid joints.

Predesign of beam and column section

In the preliminary stage of frame design (predesign) there is a need to estimate beam and column section. Based on the wide analysis of many frames with various types of joints [2], it was possible to indicate values of internal forces in frame members which can be used to estimate preliminary member section. Types of steel joints used in the analysis are shown in figure 3.

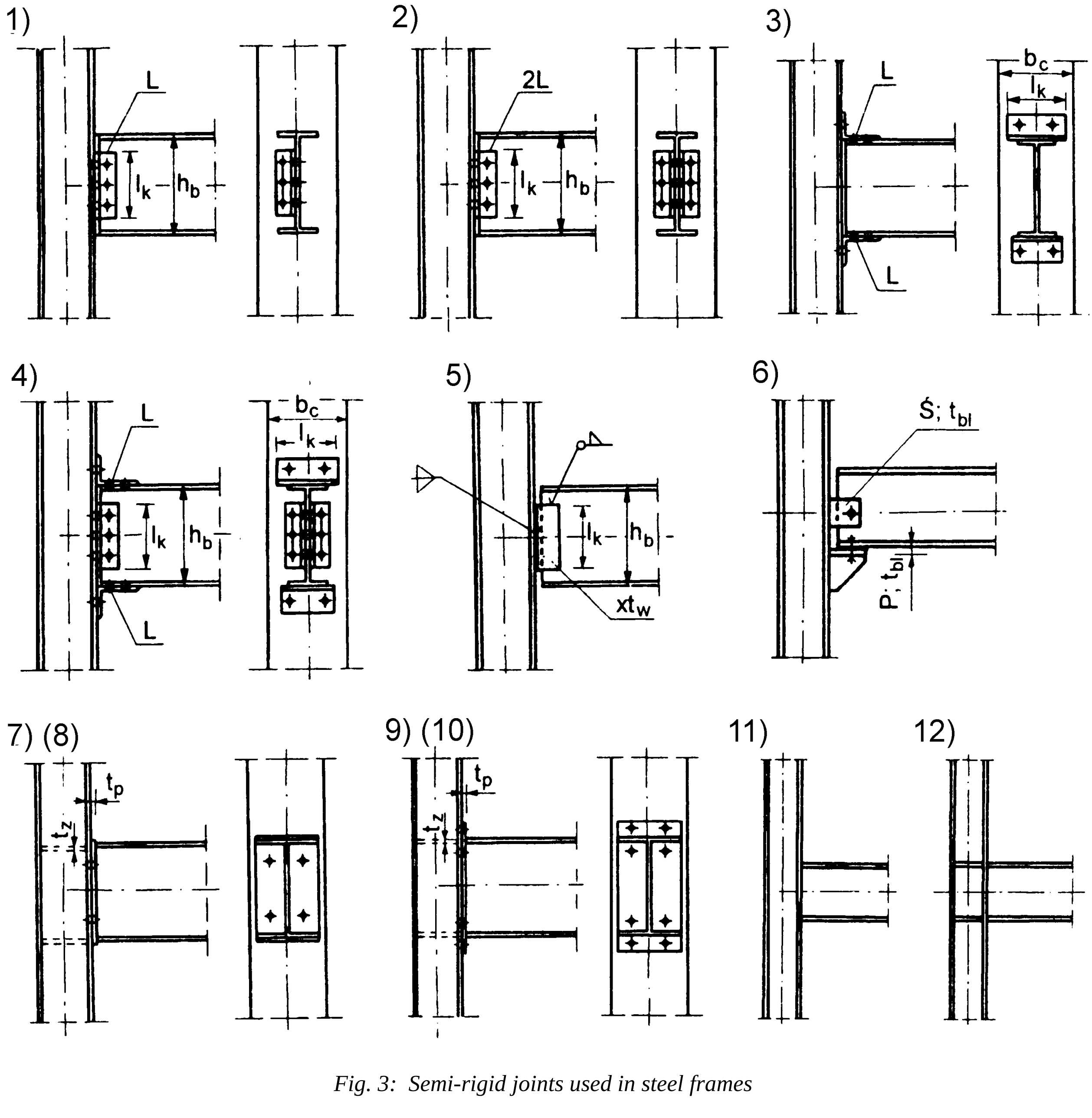

Fig. 3: Semi-rigid joints used in steel frames

In the table 1, geometrical parameters of steel joint used in the analysis are presented. For each type of joint, its lower (L), middle (M) and upper (U) range of parameters were considered. Values of internal forces to predesign of braced frames members are presented in table 2.

Table 1

Geometrical parameters of joints used in steel frames analysis

Nr		geometrical joint parameters	Nr		geometrical joint parameters
1	**L**	L 60 x 6, $l_k = 0{,}5\ h_b$, 3M16	7	**L**	t_p = 15 mm, 4M16
	M	L 90 x 9, $l_k = 0{,}65\ h_b$, 4M16		**M**	t_p = 20 mm, 6M20
	U	L 120 x 12, $l_k = 0{,}8\ h_b$, 5M20		**U**	t_p = 24 mm, 6M4
2	**L**	2 L 60 x 6, $l_k = 0{,}5\ h_b$, 3M16	8	**L**	t_p=15 mm, 4M16, t_z = 15mm
	M	2 L 90 x 9, $l_k = 0{,}65\ h_b$, 4M16		**M**	t_p =20 mm, 6M20, t_z = 15mm
	U	2 L 120 x 12, $l_k = 0{,}8\ h_b$, 5M20		**U**	t_p = 24 mm, 6M24, t_z = 15mm
3	**L**	L 80 x 8, $l_k = 0{,}7\ b_c$, 2M16	9	**L**	t_p = 15 mm, 6M16
	M	L 120 x 12, $l_k = 0{,}85\ b_c$, 3M20		**M**	t_p = 20 mm, 8M20
	U	L 150 x 15, $l_k = b_c$, 4M20		**U**	t_p = 24 mm, 8M24
4	**L**	F; L 80 x 8, $l_k = 0{,}7\ b_c$, 2M16 W; 2L60 x 6, $l_k = 0{,}5\ h_b$, 3M16	10	**L**	t_p = 15 mm, 6M16, t_z=15mm
	M	F; L120 x 12, $l_k = 0{,}8b_c$, 3M20 W; 2L90 x 9, $l_k = 0{,}6h_b$, 4M20		**M**	t_p = 20 mm, 8M20, t_z=15mm
	U	F; L150 x 15, $l_k = b_c$, 4M20 W; 2L120 x 12, $l_k = 0{,}8h_b$, 5M20		**U**	t_p = 24 mm, 8M24, t_z=15mm
5	**L**	t_w = 8 mm, $l_k = 0{,}5\ h_b$	11	**L**	h_c < 300 mm
	M	t_w = 12 mm, $l_k = 0{,}65\ h_b$		**U**	$h_c \geq$ 300 mm
	U	t_w = 16 mm, $l_k = 0{,}8\ h_b$	12	t_z = 20 mm	
6	**L**	P; t_{bl} = 8 mm, 2M16 S; t_{bl} = 6 mm, 2M16			
	M	P; t_{bl} = 10 mm, 4M16 S; t_{bl} = 9 mm, 3M16			
	U	P; t_{bl} = 12 mm, 4M20 S; t_{bl} = 12 mm, 4M20			

Table 2

Internal forces to predesign of braced frames members

Joint label	Beams		Columns	
	M_s [x M_o]	M_j [x M_o]	M_c	N
1L 2L 5L	1,0	0	0	an_sqL_b *
1M	0,97	0,04	0	an_sqL_b *
6L	0,93	0,08	0	an_sqL_b *
5M	0,91	0,1	0	an_sqL_b *
1U 2M	0,89	0,12	0	an_sqL_b *
3L	0,83	0,17	0	an_sqL_b *
6M	0,79	0,22	0	an_sqL_b *
5U 4L	0,78	0,24	0	an_sqL_b *
2U	0,77	0,25	0	an_sqL_b *
6U	0,73	0,31	0	an_sqL_b *
3M	0,69	0,37	0	an_sqL_b *
4M	0,66	0,40	0	an_sqL_b *
7L	0,65	0,42	0	an_sqL_b *
3U	0,62	0,45	0	an_sqL_b *
7M 4U 8L	0,61	0,46	0	an_sqL_b *

[*] a = 1,1 for upper storeys, a = 1,2 for lower storeys.

Values of internal forces to predesign of members in unbraced frames are presented in table 3.

Table 3

Internal forces to predesign of unbraced frames members

Frame configuration	Joint label	Beams		Columns	
		M_s [x M_o]	M_j [x M_o]	M_c [x M_0]	N
$n_s = 2$, $\frac{B}{H} = 1{,}5 - 3{,}0$	4U	0,69	0,52	0,1	$n_s q L_b$
	7U 8M 9L	0,65	0,57	0,1	$n_s q L_b$
	10L	0,61	0,66	0,1	$n_s q L_b$
	8U 9M 11L	0,57	0,71	0,1	$n_s q L_b$
	9U 11U	0,56	0,72	0,1	$n_s q L_b$
	10M 10U 12	0,48	0,82	0,1	$n_s q L_b$
$n_s = 6$, $\frac{B}{H} = 0{,}5$	9M	0,53	0,84	upper: 0,16 lower:0,4	$n_s q L_b$
	9U 11U	0,5	0,92		$n_s q L_b$
	10S 10G 12	0,41	1,1		$n_s q L_b$
$n_s = 6$, $\frac{B}{H} = 1{,}1$	4U	0,62	0,44	upper: 0,12 lower 0,29	$n_s q L_b$
	7U 9L	0,52	0,67		$n_s q L_b$
	8M	0,51	0,71		$n_s q L_b$
	8U	0,5	0,72		$n_s q L_b$
	9M 10L	0,49	0,74		$n_s q L_b$
	11U	0,48	0,77		$n_s q L_b$
	9U	0,46	0,8		$n_s q L_b$
	10M 10U 12	0,44	0,92		$n_s q L_b$
$n_s = 11$, $\frac{B}{H} = 0{,}3$	10M 10U 12	0,32	1,75	*	$n_s q L_b$
$n_s = 11$, $\frac{B}{H} = 0{,}6$	10L	0,55	0,89	upper: 0,12 middle upper: 0,29 middle lower: 0,42 lower: 0,6	$n_s q L_b$
	9M	0,53	0,95		$n_s q L_b$
	11U	0,5	1,05		$n_s q L_b$
	9U	0,48	1,1		$n_s q L_b$
	10M 10U 12	0,34	1,22		$n_s q L_b$

* upper column: 0,16; middle upper: 0,37; middle lower 0,67; lower: 1,1.

Names of the joints in above tables refer to joint which geometrical parameters are shown in figure 3 and in table 1. Joint labels used in tables have the following meaning: digit is the number of joint in the figure 3, letter is the joint parameter. For example, 7L means unstiffened flush end plate bolted joint of lower parameters.

In the table 4 are presented ratios of the beam length Lb to beam section height hb in relation to initial joint stiffness. These values can be used to primary beam section estimation.

Assessment of joint parameters

"Good guess" assessment to estimate preliminary joint parameters was proposed in [3], [4]. These formulas are very simple, but sometimes too unprecise because they are based on many simplified assumptions.

Using computer program CRSJAE [5], which contains full EC3 1-8 procedure for determination of moment resistance and initial stiffness, wide parameter study were performed and main joint geometrical parameters influencing joint characteristics were identified. After regression analysis, simple formulas, possible for hand calculator, were obtained for end-plate bolted as well as welded beam-to-column connection. These formulas are collected in table 5.

Table 4

Preliminary heights of beams in steel frames

range of joint initial stiffness $[x \frac{EJ_y}{L_b}]$	$\frac{L_b}{h_b}$					
	$n_s=2$ $\frac{B}{H}=1{,}5$	$n_s=2$ $\frac{B}{H}=3{,}0$	$n_s=6$ $\frac{B}{H}=0{,}5$	$n_s=6$ $\frac{B}{H}=1{,}1$	$n_s=11$ $\frac{B}{H}=0{,}3$	$n_s=11$ $\frac{B}{H}=0{,}6$
STEEL BRACED FRAMES						
0 – 2,2	15	15	15	15	15	15
2,2 – 3,8	16,5	16,5	16,5	16,5	16,5	16,5
3,8 – 6,0	18	16,5	16,5	16,5	16,5	16,5
6,0 – 10,0	18	18	18	18	18	18
STEEL UNBRACED FRAMES						
8 – 12	18	18	-	18	-	-
12 – 18	18	18	13,5	16,5	-	15
18 – 22	16,5	18	15	16,5	-	15
22 – 25	16,5	16,5	15	16,5	-	15
∞	16,5	16,5	15	15	12	13,5

Table 5

Equations for estimation steel joints parameters

Type of joint	Equations for	
	Design resistance M_{Rd} [kNm]	Initial stiffness $S_{j.ini}$ [kNm/rad]
1	2	3
welded, internal, unstiffened	$M_{Rd} = 8{,}2 \cdot 10^{-7} h_c^{0,9} h_b^{2,3} + 20$	$S_{j.ini} = 0{,}39 h_c^{-0,06} h_b^{2,2} + 2293$
welded, external, unstiffened	$M_{Rd} = 6{,}5 \cdot 10^{-7} h_c^{1,2} h_b^{2,04} + 18$	$S_{j.ini} = 0{,}0251 h_c^{0,82} h_b^{1,7} + 2765$
welded, stiffened	$M_{Rd} = 2{,}5 \cdot 10^{-4} h_b^{2,3} - 12$	$S_{j.ini} = \infty$
bolted, extended end plate, internal, unstiffened	$M_{Rd} = 4{,}8 \cdot 10^{-4} h_c^{0,24} h_b^{1,31} t_p^{0,32} d^{0,9} - 21$	$S_{j.ini} = 0{,}44 h_c^{-0,22} h_b^{2,10} t_p^{0,5} d^{-0,1} - 4896$
bolted, extended end plate, external, unstiffened	$M_{Rd} = 7{,}4 \cdot 10^{-5} h_c^{0,62} h_b^{1,2} t_p^{0,4} d^{0,85}$	$S_{j.ini} = 1{,}5 h_c^{0,44} h_b^{1,2} t_p^{0,35} d^{0,005} - 19211$
bolted, extended end plate, stiffened	$M_{Rd} = 5 \cdot 10^{-5} h_c^{0,16} h_b^{1,6} t_p^{0,36} d^{1,1}$	$S_{j.ini} = 0{,}0563 h_c^{-0,54} h_b^{2,49} t_p^{0,99} d^{0,09} + 12714$
bolted, flush end plate, internal, unstiffened	$M_{Rd} = 1{,}4 \cdot 10^{-5} h_c^{0,09} h_b^{1,7} t_p^{0,63} d^{1,1} + 7$	$S_{j.ini} = 0{,}13 h_c^{-0,32} h_b^{2,3} t_p^{0,51} d^{-0,13} - 6261$
bolted, flush end plate, external, unstiffened	$M_{Rd} = 4{,}6 \cdot 10^{-5} h_c^{0,35} h_b^{1,5} t_p^{0,49} d^{0,81}$	$S_{j.ini} = 0{,}012 h_c^{-0,38} h_b^{2,6} t_p^{0,6} d^{-0,03} + 1074$
bolted, flush end plate, stiffened	$M_{Rd} = 3{,}4 \cdot 10^{-5} h_c^{-0,05} h_b^{1,77} t_p^{0,63} d^{0,98}$	$S_{j.ini} = 0{,}0355 h_c^{-0,4} h_b^{2,5} t_p^{0,75} d^{0,042} - 5377$

The proposed formulas in most cases give much better assessment than “good guess” proposed previously ([3,4]), because they include more joint parameters such as bolts diameter, end-plate thickness and column sizes. They are still simple and can be used for manual calculation. The proposed formulas may be used in predesign phase of design to estimate the initial stiffness and moment resistance of joint to be used in classification process as well as in global frame analysis.

Estimation of lateral drift of unbraced frame

A limitation for using semi-rigid joints in unbraced frames is the requirement to fulfil SLS for lateral frame drift. For preliminary estimation of frame stiffness, the graphs shown in the figure 4 can be used.

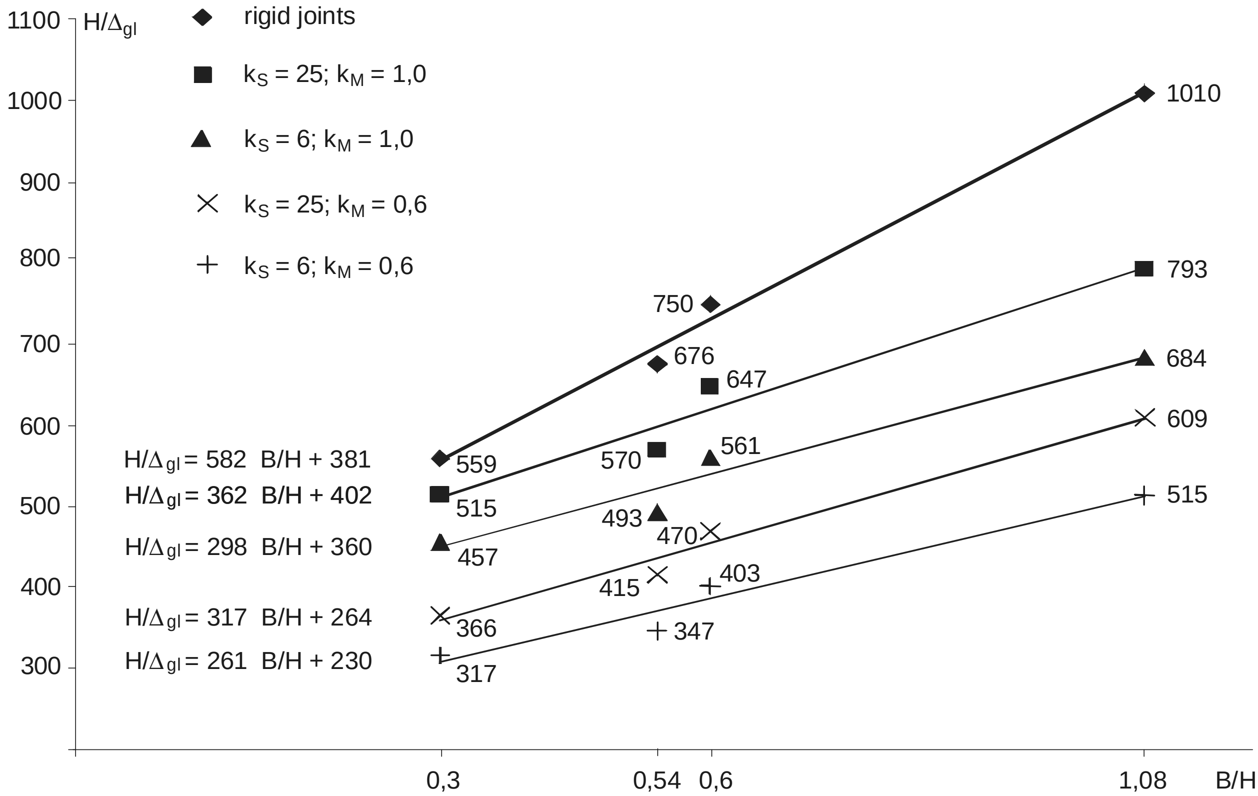

Fig. 4: Diagram for estimation the global frame drift

where: $k_M = \frac{M_{j.Rd}}{M_{b.Rd}}$, $k_S = \frac{S_{j.ini}}{\frac{EJ_y}{L_b}}$.

This diagram allows quick estimation of global frame drift for various joint properties.

Summary

Design of steel frames with semi-rigid joints is nowadays performed with the application of computer programs which enable non-linear joint characteristics to be taken into account. Using these programs requires introduction not only beam and column sections, like in traditional design, but also joints characteristics. These parameters must be known in advance, before global analysis. This is why predesign phase in the design procedure is very important. In this stage, designer using design tools can estimate preliminary members and joints properties to avoid many recalculation. Solutions presented in the paper can be used as such design tools in the predesign of steel frames with semi-rigid joints.

Notations

B, H	width, height of the frame,
E	Young modulus,
J_y	moment of inertia of beam section,
$M_{b.Rd}$	plastic moment resistance of the beam,
M_c	maximum moment in the column,
M_j	maximum moment in the joint,
M_o	span moment, calculated as for simply supported beam,
M_s	maximum moment in the span of the beam,
N	axial force in the column,
d	bold diameter [mm],
h_b	height of the beam section, [mm]
h_c	height of the column section, [mm]
n_s	number of the storeys,
t_p	end plate thickness, [mm]
q	total loading on the beam,
Δgl	maximum frame drift.

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