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Component method model for predicting the moment resistance, stiffness and rotation capacity of minor axis composite seat and web site plate joints

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Abstract. Codes EN 1993 and EN 1994 require to take into account actual joint characteristics in the global analysis. In order to implement the semi-rigid connection effects in frame design, knowledge of joint rotation characteristics (M-ϕ relationship), or at least three basic joint properties, namely the moment resistance M_R, the rotational stiffness S_j and rotation capacity, is required. To avoid expensive experimental tests many methods for predicting joint parameters were developed. The paper presents a comprehensive analytical model that has been developed for predicting the moment resistance M_R, initial stiffness $S_{j.ini}$ and rotation capacity of the minor axis, composite, semi-rigid joint. This model is based on so-called component method included in EN 1993 and EN 1994. Comparison with experimental test results shows that a quite good agreement was achieved. A computer program POWZ containing proposed procedure were created. Based on the numerical simulation made with the use of this program and applying regression analysis, simplified equations for main joint properties were also developed.

Keywords: connections; composite joint; semi-rigid; component method; analytical model; initial stiffness; moment resistance; rotation capacity

1. Introduction

Composite steel-concrete construction is very effective and attractive to designers because of its greater stiffness and resistance capacity compared to non-composite construction. This enables to reach less depth of used beams and reducing the height of floor structure. Further decrease in composite beam section can be obtained by appropriate design of beam to column connections. In so-called “composite connection”, resistance to hogging moment is provided by properly anchored tension reinforcement, placed in concrete slab, together with steel part of beam-to-column joints. Efficiency of such composite joints is specially high for joints, where steelwork details is customary associated with “simple” construction, e.g., web cleats with seating cleats, partial depth end plates and so on.

In flooring system, where the composite beams are used, there is often a need to join the secondary beam to column in weak axis plane (joint “A”) or to main beam (joint “B”). Example of such floor layout is shown in Fig. 1. By appropriate ratio of main beams to secondary beams spans,

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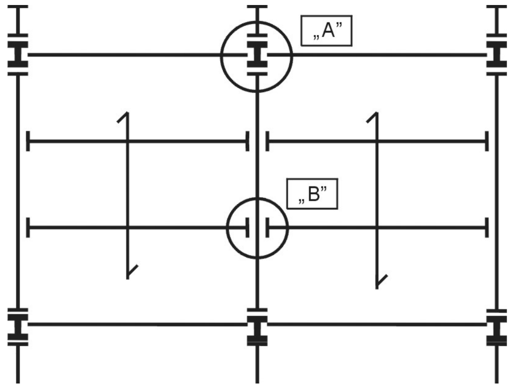

Fig. 1 Example of composite floor layout

it is possible to get the same depth of both beams, what gives lower floor structure depth and smaller global storey height.

Shaping of joints connecting beams to column in the weak axis plane can make difficulties. One of the joint used in such situation is a joint which steelwork part consists of a seating Tee section bracket bolted to lower beam flange and finplate welded to column web and bolted to beam web, Fig. 2. Such joint has some advantages. In the construction stage, joint produces certain rotation restraint, what results in lower beam size and smaller beam deflection. In the working phase, by introduction of a reinforced concrete slab over the steel beam, the lever arm is increased, reinforcement bars take tension force and bolts connecting lower beam flange to the bracket transmit compression. Amount of reinforcement and the number of bolts in lower flange beam connection are the main variable allowing designers to get joint of required capacity and stiffness. The use of described joints does not require holes to be drilled in the column and can lead to an increased construction speed. Next advantage is presence of some tolerance in the bolt holes what makes that requirements for beam length are not so strict as for other joints.

Application of the semi-rigid philosophy in global analysis of steel and composite structure requires knowledge of joint rotation characteristic (M-ϕ relationship). This characteristic is described by three basic joint parameters: the moment resistance $M_{R,}$ the rotational stiffness S_j and rotation capacity. The best way to obtain these parameters is experimental tests (e.g., Han *et al*. 2015, Katula and Dunai 2015), but such tests are very expensive and time taking. Many analytical methods for predicting joint characteristics have been proposed worldwide in the last decades (Anderson 1996, Li *et al*. 1996, Ahmed and Nethercot 1997, Ahmed *et al*. 1997, Brown and Anderson 2001, Silva 2008, Nogueiro *et al*. 2009, Diaz *et al*. 2011, Asha and Sundararajan 2014). One of the most effective methods to analyse and predict the rotational behaviour of different types and different configurations of connections is so-called component method, based on mechanical modelling (Huber and Tchemmernegg 1998, Faella *et al*. 2000, Liew *et al*. 2004, Rassati *et al*. 2004, Lemonis and Gantes 2009, Savio *et al*. 2009, Pilso *et al*. 2012, Pitrakkos and Tizani 2015). This method is widely incorporated in European specifications EN 1993 (EN 1993-1-8 2005) in case of steel joints and in EN 1994 (EN 1994-1-1 2004) for composite joints.

The aim of this paper is to present analytical, based on component method, model for composite, minor axis joint which steelwork part consisted of a seating Tee section bracket bolted to lower beam flange and finplate welded to column web and bolted to beam web, Fig. 2. Experimental tests of this joint has been presented elsewhere (e.g., Kozlowski and Sleczka 2007).

2. Determination of the moment resistance

Moment resistance of the analyzed joint was calculated on the base of a simple force transfer mechanism at failure (Fig. 2).

Resistance of the basic joint components were established as follows:

- reinforcement in tension F_r

$$F_r = A_r n_r \frac{f_{yr}}{\gamma_{Mr}} \tag{1}$$

where:

A_r – cross section of one reinforcement bar ,
f_{yr} – yield stress of the reinforcement bars,
n_r – number of reinforcement bars in the effective width,
γ_{Mr} – partial safety factor for reinforcement steel.

- bolted connection of the beam web to fin plate (F_b)

$$F_b = \min \begin{cases} F_{bs} \\ F_{bd} \\ F_{bb} \\ F_{bw} \end{cases} \tag{2a}$$

when connection is in tension, and

$$F_b = \min \begin{cases} F_{bs} \\ F_{bd} \end{cases} \tag{2b}$$

when connection is in compression,

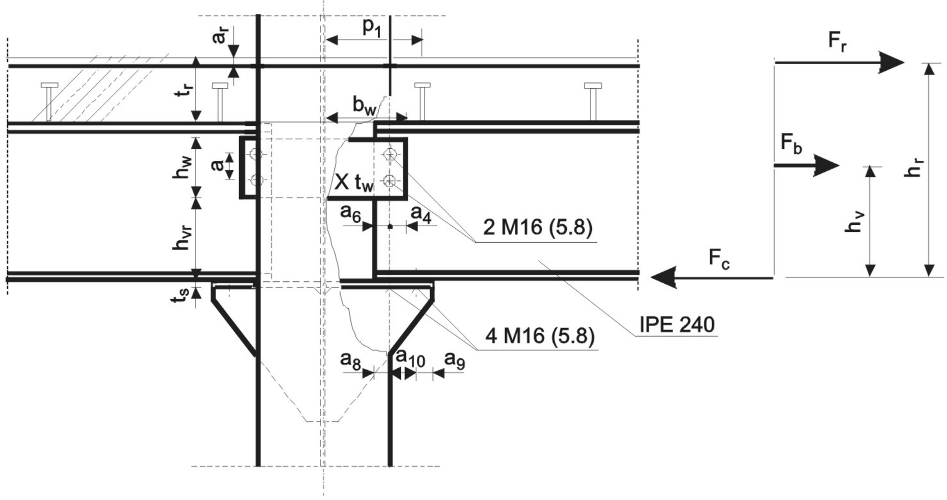

Fig. 2 Force transfer mechanism in analyzed joint

where: F_{bs} – shear bolt resistance,
F_{bd} – bearing resistance,
F_{bb} – resistance of fin plate in the net area,
F_{bw} – beam web resistance in the net area.

Resistance of each of above mentioned components can be obtained as follows:

- shear resistance of the bolts (EN 1993-1-8 2005)

$$F_{bs} = \frac{\alpha_v f_{ub} A}{\gamma_{M2}} m \cdot n_2 \tag{3}$$

when connection is in compression,
where: F_{bs} – shear bolt resistance,
F_{bd} – bearing resistance,
F_{bb} – resistance of fin plate in the net area,
F_{bw} – beam web resistance in the net area.

Resistance of each of above mentioned components can be obtained as follows:

- shear resistance of the bolts (EN 1993-1-8 2005)

$$F_{bd} = \min(F_{bd \cdot p}, F_{bd \cdot w}) \tag{4}$$

where: $F_{bd.p}$ – bearing resistance of fin plate,
$F_{bd.w}$ – bearing resistance of beam web

$$F_{bd \cdot p} = \frac{k_1 \alpha_b f_{uf} d t_w}{\gamma_{M2}} n_2 \tag{5a}$$

$$F_{bd \cdot w} = \frac{k_1 \alpha_b f_{uw} d t_{wb}}{\gamma_{M2}} n_2 \tag{5b}$$

where:

k_1 is the smallest of $2{,}8\frac{e_2}{d_o} - 1{,}7$ or 2,5,

α_b is the smallest of: $\frac{f_{ub}}{f_{ui}}$; $\frac{a_4}{3d_o}$; 1,0

$f_{ui} = f_{uf}$ or f_{uw} respectively,
f_{uf} – ultimate tensile strength of fin plate,
f_{uw} – ultimate tensile strength of beam web,
d – bolt diameter,
t_w – thickness of fin plate,
t_{wb} – thickness of beam web,
e_2 – distance from the centre of the bolt to the edge perpendicular to force transfer, see Fig. 3,
a_4 – distance from the centre of the bolt to the edge in the direction of load transfer, see Fig. 2,
d_o – the hole diameter.

- resistance of the fin plate

$$F_{bb} = \min\left(\frac{f_{yf} A_{nt,f}}{\gamma_{M0}}; \frac{0{,}9 t_w h_w f_{uf}}{\gamma_{M2}}\right) \tag{6}$$

where: $A_{nt.f}$ – net area of the fin plate: $A_{nt.f} = t_w \cdot h_w - n_2 \cdot d_o$,
f_{yf}, f_{uf} – yield stress, ultimate tensile strength of the fin plate steel,

- beam web resistance

$$F_{bw} = \min\left(\frac{f_{yw} A_{nb}}{\gamma_{M0}}; \frac{0{,}9 f_{uw} A_b}{\gamma_{M2}}\right) \tag{7}$$

where: A_{nb} – tension net area of the beam web, according to Fig. 3:
$A_{nb} = t_{wb} \cdot (a + 2\sqrt{2} \cdot a_6 - n_2 \cdot d_o)$, $A_b = t_{wb} \cdot (a + 2\sqrt{2} \cdot a_6)$,
a – spacing between centers of bolts,
f_{yw} – yield stress of the beam web.

It was assumed that the resistance of the welds connecting fin plate to the column web is bigger than fin plate resistance.

- connection of the lower beam flange to the seat (F_c)

$$F_c = \min(F_{cs},\ F_{cd}) \tag{8}$$

where: F_{cs} – shear resistance of the bolts,
F_{cd} – bearing resistance.

- shear resistance

$$F_{cs} = \frac{\alpha_v f_{ub} A}{\gamma_{M2}} m \cdot n_1 \tag{9}$$

where: n_1 – number of the bolts connecting beam flange to the seat,

- bearing resistance

$$F_{cd} = \min(F_{cd \cdot b},\ F_{cd \cdot s}) \tag{10}$$

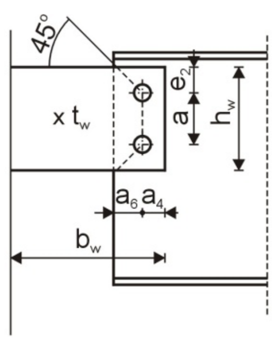

Fig. 3 Notation of steel joint geometrical dimensions

Fig. 4 Force arrangement: (a) in load Case 1; (b) in load Case 2

where: $F_{cd.b}$ – bearing resistance for beam flange,
$F_{cd.s}$ – bearing resistance for seat plate.

$$F_{cd \cdot b} = \frac{k_1 \alpha_b f_{up} \; d t_f}{\gamma_{M2}} n_1 \tag{11a}$$

$$F_{cd \cdot s} = \frac{k_1 \alpha_b f_{us} \; d t_s}{\gamma_{M2}} n_1 \tag{11b}$$

where: f_{up} – ultimate tensile strength of beam flange,
f_{us} – ultimate tensile strength of seat plate,
k_1 and α_b as in Eq. (5) for relevant bolt spacing.

In order to determinate joint resistance, two loading cases should be considered:

Case 1: $F_r > F_c$; reinforcement resistance bigger than the resistance of the beam flange to the seat connection (Fig. 4(a)).

Effective force in the connection of the beam web to the fin plate can be find as

$$F_b' = \min \; (F_b, \; F_r - F_c) \tag{12}$$

where F_b is the bolt resistance given by Eq. (2b).

Effective force in the reinforcement

$$F_r' = \min \; (F_r, \; F_c + F_b' \;) \tag{13}$$

F_r is the reinforcement resistance taken from Eq. (1)

Moment resistance is calculated as

$$M_R = \; F_r' \cdot h_r - F_b' \cdot \; h_v \tag{14}$$

Case 2: $F_r < F_c$; reinforcement resistance smaller than the resistance of the beam flange to the seat connection (Fig. 4(b)).

Effective force in the connection of the beam web to the fin plate can be found as

$$F_b' = \min \; (F_b, \; F_c - F_r) \tag{15}$$

where F_b is the resistance given by Eq. (2a).

Moment resistance of the joint is

$$M_R = F_r \cdot h_r + F_b' \cdot h_v \tag{16}$$

3. Stiffness of the joint

Mechanical model shown in Fig. 5 was created to determinate joint stiffness. The basic joint components were simulated by a spring system. The following assumptions were accepted:

- in the initial stage of the loading internal forces are low, so components behavior remain in the elastic stage modeled by springs with constant stiffness,
- after deflection, section of the steel beam and concrete slabs remain plane having the same rotation,
- the following components are considered:
  - connection of the lower beam flange to the seat, modeled by the spring k_c,
  - bolted connection of the beam web to the fin plate, modeled by spring k_b,
  - reinforcement bars, modeled by spring k_r,
  - slip at the interface of concrete slab and steel beam top flange was also taken into account; shear connectors were modeled by spring k_t

Considering the equilibrium condition of forces in the elastic stage

$$F_r + F_b = F_c, \qquad F_t = F_r,$$

it was obtained

$$M = F_r \cdot h_r + F_b \cdot h_v. \tag{17}$$

The compatibility condition gives

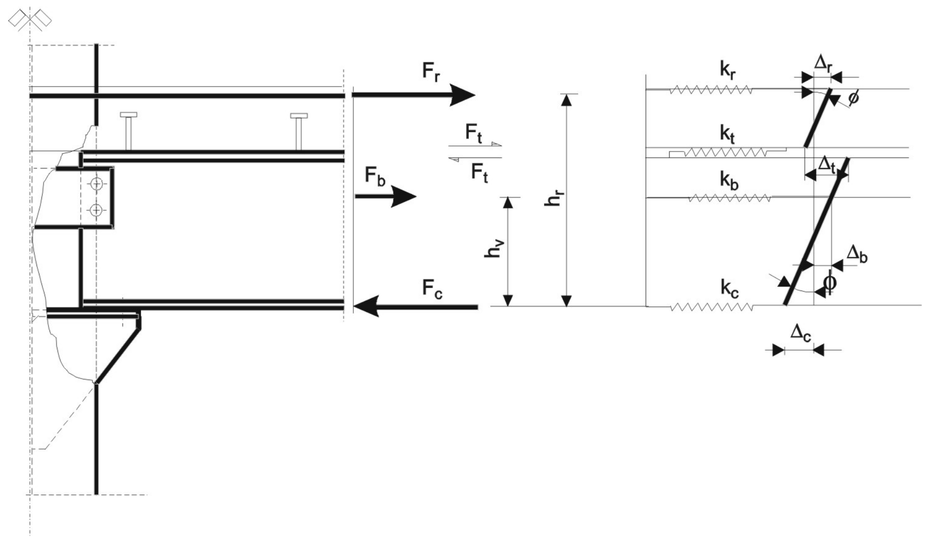

Fig. 5 Mechanical, spring model of composite joint

$$\frac{\Delta_t + \Delta_r + \Delta_c}{h_r} = \frac{\Delta_b + \Delta_c}{h_v} = \phi \tag{18}$$

knowing that

$$F_r = k_r \cdot \Delta_r \cdot E, \quad F_b = k_b \cdot \Delta_b \cdot E, \quad F_c = k_c \cdot \Delta_c \cdot E, \quad F_t = k_t \cdot \Delta_t \cdot E, \tag{19}$$

and substituting Eqs. (19) to (18) one can obtain set of equations

$$\begin{cases} \dfrac{F_t}{k_t} + \dfrac{F_r}{k_r} + \dfrac{F_c}{k_c} = h_r \cdot \phi \cdot E \\ \dfrac{F_b}{k_b} + \dfrac{F_c}{k_c} = h_v \cdot \phi \cdot E \end{cases} \tag{20}$$

solving for F_z and F_b, gives

$$F_r = \frac{h_r\left(\dfrac{1}{k_b} + \dfrac{1}{k_c}\right) - h_v \cdot \dfrac{1}{k_c}}{\left(\dfrac{1}{k_t} + \dfrac{1}{k_r} + \dfrac{1}{k_c}\right)\left(\dfrac{1}{k_b} + \dfrac{1}{k_c}\right) - \dfrac{1}{k_c^2}} \cdot \phi \cdot E \tag{21}$$

$$F_b = \frac{h_v\left(\dfrac{1}{k_t} + \dfrac{1}{k_c} + \dfrac{1}{k_r}\right) - h_r \cdot \dfrac{1}{k_c}}{\left(\dfrac{1}{k_t} + \dfrac{1}{k_r} + \dfrac{1}{k_c}\right)\left(\dfrac{1}{k_b} + \dfrac{1}{k_c}\right) - \dfrac{1}{k_c^2}} \cdot \phi \cdot E \tag{22}$$

Substituting to Eq. (17) and taking into account that

$$S_{j.\mathrm{ini}} = \frac{M}{\phi} \tag{23}$$

formula for initial stiffness is obtained in the form

$$S_{j.ini} = \frac{h_r^2\left(\dfrac{1}{k_b} + \dfrac{1}{k_c}\right) - 2h_r h_v \dfrac{1}{k_c} + h_v^2\left(\dfrac{1}{k_t} + \dfrac{1}{k_c} + \dfrac{1}{k_b}\right)}{\left(\dfrac{1}{k_t} + \dfrac{1}{k_r} + \dfrac{1}{k_c}\right)\left(\dfrac{1}{k_b} + \dfrac{1}{k_c}\right) - \dfrac{1}{k_c^2}} \cdot E \tag{24}$$

Stiffness coefficients for the particular components were predicted as follows:

- reinforcement in tension

from Eq. (19) $k_r = \dfrac{F_r}{\Delta_r \cdot E}$, remembering that $\Delta_r = \dfrac{F_r \cdot l_r}{E \cdot A_r \cdot n_r}$

We obtain

$$k_r = \frac{A_r n_r}{l_r} \tag{25}$$

where: $A_r n_r$ – reinforcement bars area,
l_r – reinforcement bars elongation length, taken as: $l_r = p_1$
p_1 – distance from column axis to the first shear connector,

- slip of shear connectors: stiffness of the single connector can be expressed as

$$k_{t1} = \frac{0{,}6 \cdot F_t}{\Delta_t} \tag{26}$$

where:
F_t – shear force in the connectors,
Δ_t – slip in the connection plane.

During experimental tests of the joints, slip in the plane of the beam to concrete slab connection as well as forces in reinforcement bars were measured (Kozlowski and Sleczka 2007). Assuming that in the initial stage of loading: $F_t = F_r$, single connector stiffness was obtained: k_{t1} = 87 kN/mm.

Stiffness coefficient of the shear connectors is given by

$$k_t = \frac{k_{t1} \cdot n_t}{E} \tag{27}$$

n_t – number of connectors.

- beam web to fin plate bolted connection:

Deformation of the fin plate in tension (k_{b1}), bolts in shear (k_{b2}) and bearing between bolts and beam web and fin plate were taken into account:

- fin plate in tension

$$k_{b1} = \frac{A_w}{b_w} \tag{28}$$

A_w – cross section of fin plate = $t_w h_w$,
b_w – fin plate length,

- bolts in shear (EN 1993-1-8 2005)

$$k_{b2} = \frac{16 \cdot n_b \cdot d^2 \cdot f_{ub}}{E \cdot d_{M16}} \tag{29}$$

where: n_b – number of bolt rows connecting fin plate to beam web,
f_{ub} – ultimate tensile strength of bolts,
d – bolt diameter,
d_{M16} – M16 bolt diameter.

- bearing between bolts and beam web (or fin plate)

$$k_{b3} = \frac{24 \cdot n_b \cdot k_b \cdot k_t \cdot d \cdot f_u}{E} \tag{30}$$

where

$$k_b = \frac{0.25 \cdot a_4}{d} + 0.5 \leq 1.25; \qquad k_t = \frac{1.5 \cdot t_j}{d_{M16}} \leq 2{,}5$$

a_4 – the distance from the bolt-row to the free edge of the fin plate in the direction of load transfer,
f_u – the ultimate tensile strength of the steel on which the bolt bears,
t_j – thickness of the relevant component (fin plate or beam web).

Finally, the total stiffness of fin plate to beam web connection, calculated taking account in line springs, can be obtained from formula

$$k_b = \frac{1}{\frac{1}{k_{b1}} + \frac{1}{k_{b2}} + \frac{1}{\Sigma k_{b3}}} \tag{31}$$

- bolted connection of beam lower flange to the seat:

Deformation of the bolts in shear and bearing between bolts and beam flange and seat plate were taken into account, deformation of the seat plate was neglected because of the applied stiffener.

Stiffness coefficients were obtained as follows:

- bolts in shear

$$k_{c1} = \frac{16\, n_c \cdot d^2 \cdot f_{ub}}{E \cdot d_{M16}} \tag{32}$$

- bolts in bearing

$$k_{c2} = \frac{24 \cdot n_c \cdot k_c \cdot k_t \cdot d \cdot f_u}{E} \tag{33}$$

where: n_c – number of bolt rows connecting seat plate to beam flange,
$k_c = k_{c1}$ but $k_c \leq k_{c2}$,

$$k_{c1} = \frac{0{,}25 a_9}{d} + 0{,}5 \leq 1{,}25,$$

$$k_{c2} = \frac{0{,}25 a_{10}}{d} + 0{,}375 \leq 1{,}25,$$

k_t as above,
a_9 – the distance from the bolt-row to the free edge of the seat plate in the direction of load transfer,
a_{10} – the spacing of the bolt-rows in the direction of load transfer,

Resultant stiffness of the beam flange to seat plate connection

$$k_c = \frac{1}{\frac{1}{k_{c1}} + \frac{1}{\Sigma k_{c2}}} \tag{34}$$

Finally, the overall behaviour, i.e., M-ϕ relationship was expressed adopting Chen power model (Chen 2000)

$$M = \frac{S_{j,ini} \cdot \phi}{\left\{1 + \left(\frac{S_{j,ini} \cdot \phi}{M_R}\right)^{1,5}\right\}^{\frac{1}{1,5}}} \tag{35}$$

4. Rotation capacity of the joint

Composite joint attains the available rotation capacity in the state close to failure, thus the value of the forces in each component of the joint were estimated for stage of full plastification. Only components having the greatest influence on the rotation capacity were taken into account i.e., the extension of reinforcement bars Δ_{ur} and slip in the steel-concrete plane Δ_{ut} (Fig. 6).

$$\phi_u = \frac{\Delta_{ru}}{h_r} + \frac{\Delta_{tu}}{h_b} \tag{36}$$

Elongation of reinforcement bars was calculated taking into account "tension stiffening" effect according to (CEB-FIP Model Code 1993).

Effective reinforcement ratio

$$\rho_{eff} = \frac{2 A_r n_r}{A_c} \tag{37}$$

Stresses in reinforcement bars in the stage of first plastification

$$\sigma_{r,t} = \frac{f_{ct}}{\rho_{eff}}\left(1 + \frac{E_r}{E_c}\rho_{eff}\right) \tag{38}$$

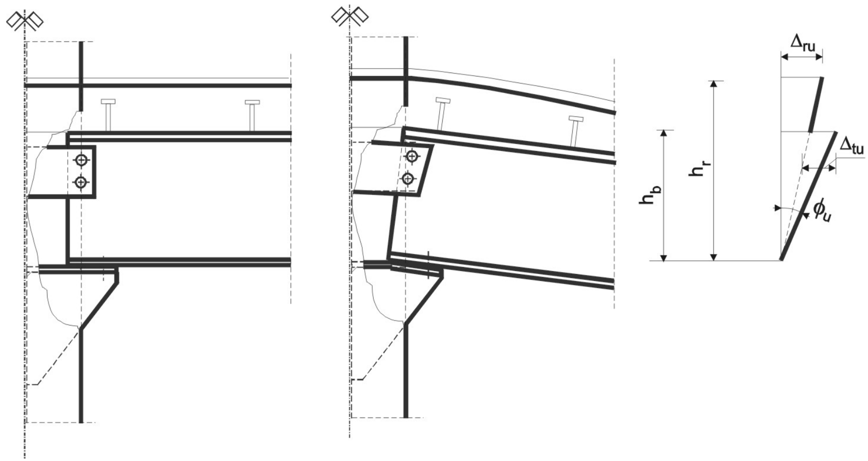

Fig. 6 Composite joint rotation capacity model

where: A_c – concrete slab cross section,
f_{ct} – tensile resistance of concrete,
E_r, E_c – Young modulus of reinforcement steel, concrete.

Strains in rebars in the stage of plastification

$$\varepsilon_{ry} = \frac{f_{yr}}{E_r} - \beta_t \Delta_\varepsilon + \delta (1 - \frac{\sigma_{r,t}}{f_{yr}})(\varepsilon_{ru} - \frac{f_{yr}}{E_r}) \tag{39}$$

where

$$\Delta_\varepsilon = \frac{\sigma_{r,t}}{E_r} - \frac{f_{ct}}{E_c} \tag{40}$$

ε_{ru} – ultimate steel strain calculated as

$$\varepsilon_{ru} = \frac{f_{yr}}{E_{ru}} \tag{41}$$

where

$$E_{ru} = \frac{E_r}{50}, \tag{42}$$

$\beta_t = 0.4$, $\delta = 0.8$ according to (CEB-FIP Model Code 1993)

$$\Delta_{ru} = \varepsilon_{ry} \, l_r \tag{43}$$

where: $l_r = p_1$ = distance from column axis to the first shear connector

Slip in the steel-concrete interface

$$\Delta_{tu} = \frac{F_t}{n_t \, k_{s1}} \tag{44}$$

where: k_{s1} – secant stiffness of separated stud (k_{s1} = 87/3 = 29 kN/mm)

$$F_t = F_r = A_r n_r f_y \tag{45}$$

Rotation capacity of composite joint

$$\phi_u = \frac{\varepsilon_{ry} \, l_r}{h_r} + \frac{A_r n_r f_y}{n_t k_{s1} h_b} \tag{46}$$

5. Comparison of prediction with test results

Experimental tests were conducted in the Faculty Laboratory of Civil Eng. Department Rzeszow University of Technology. All specimens were of the cruciform arrangement as shown in Fig. 2. The cantilever beams are made of IPE 240 and columns of HEB 200 sections. Collection of tested composite specimens is shown in Table 1.

Table 1 Details of the specimens

Specimen	Column	Beam	Reinforcement	No. of specimens
CP-1	HEB200	IPE240	6ϕ10; ρ = 0,5 %	1
CP-2.1	HEB200	IPE240	10ϕ10; ρ = 0,8 %	1
CP-2.2*	HEB200	IPE240	10ϕ10; ρ = 0,8 %	1
CP-3	HEB200	IPE240	14ϕ10; ρ = 1,1 %	1

* specimens CP-2.1 and CP-2.2 were nominally identical, but specimen CP-2.2 was loaded non-symmetrical

Table 2 Mechanical properties of steel components

Element	Yield strength [MPa]	Ultimate strength [MPa]	Elongation [%]
IPE 240, beam flange	328	495	28
IPE 240, beam web	342	513	30
HEB 200, column flange	298	441	30
HEB 200, column web	336	472	23
Plate t_w = 6 mm	293	401	26
Plate t_s = 10 mm	339	479	34
Rebar ϕ10	385	598	15

Grade S235 steel was used for all beams, columns and plates. Before the tests, all parts of joints were measured to obtain their actual geometric dimensions. Tensile test were carried out on coupon samples of structural steel used for beams, columns and plates, in accordance with standard methods. The steel coupon test results are summarized in Table 2.

Connection of lower beam flange to seat was made with the use of four bolts and connection of beam web to side plate by two bolts. M16 grade 5.8 bolts were used in all connections. Bolts were only hand tightened. From tensile testing of bolts it was obtained that f_{yb} = 601 MPa, f_{ub} = 762 MPa.

Longitudinal reinforcement was made of ϕ10 bars. The number of bars was varied from 6 to 14 providing reinforcement varying from 0,5% to 1,1%. Transverse reinforcement in the form of 10 mm diameter bars with a spacing equal to 150 mm was supplied. Results of tensile tests of reinforcement bars were included in Table 2.

Headed studs of 12 mm diameter, spacing 188 mm, were used as shear connections. They were fixed to the beam flange at the fabrication shop, using stud-welding equipment. Experimental tests results of this joint has been presented elsewhere (e.g., Kozlowski and Sleczka 2007).

The comparison of results of calculations obtained according to proposed model with experimental test results is presented in the Table 3. Calculations were executed for actual, measured dimensions of elements and actual parameters of materials. Additionally, in the Table 3 were given results of the calculations according to the method included in (EN 1994-1-1 2004). Moment resistance M_R and initial stiffness $S_{j.ini.}$ of the joint according to EN 1994 were calculated using characteristics of steel part of the joint obtained by method presented in (Pisarek 2002) and taking into account reinforcement bar as a additional bolt row, like in end-plate connections. Values presented in that table indicate that good agreement between proposed component model and test results was achieved.

Table 3 Comparison of prediction and test results

Specimen		Moment resistance M_R [kNm]			Initial stiffness $S_{j.ini.}$ [kNm/mrad]			Rotation capacity ϕ_u [mrad]	
		test *	model	EN 1994	test	model	EN 1994	test	model
CP-1	L	69,89	75,15	74,15	12,9	12,15	11,14	37,4	32,4
	P	66,77			13,5			43,2	
CP-2	L	81,78	94,67	89,9	13,9	13,59	12,97	46,4	44,27
	P	77,12			14,15			54,2	
CP-3	L	108,0	101,64	89,8	14,1	14,08	14,06	56,7	52,6
	P	109,08			15,3			53,1	

* - maximum moment obtained during tests

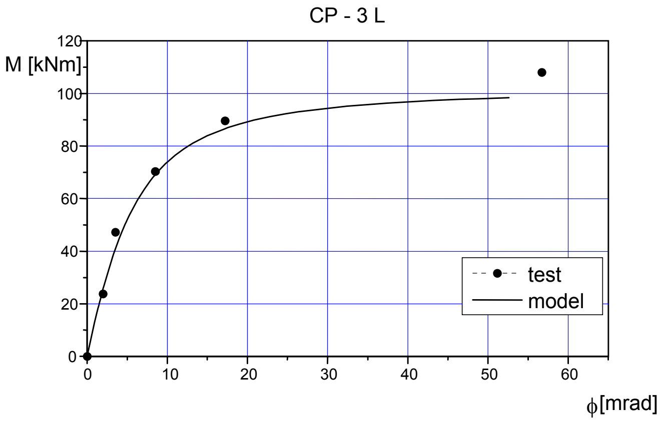

Fig. 7 Comparison of prediction with test results for specimen CP-3L

A typical comparison between predicted and experimental results is shown in Fig. 7 for specimen CP-3L.

6. Simplified formulas for estimation of moment resistance, stiffness and rotation capacity of composite joint

After positive validation of proposed prediction and joint model, a computer program POWZ was developed in the format of spreadsheet EXCEL, containing full procedure. In order to facilitate designers calculation of joint properties and speed up their work a simplified formulas were created. They are especially useful in predesign phase of design work. To limit number of factors influencing joint behaviour some of them were established as constant, basing on practical design recommendation. The following factors were taken as constant:

(1) $t_w > t_{wb}$; thickness of fin plate bigger than thickness of beam web,
(2) $t_s > t_{fb}$; thickness of seat plate bigger than beam flange thickness,
(3) $n_2 = 2$; 2 bolts M16grade 5.8,
(4) minimum values of bolt spacing acc. to EN 1993,

(5) stiffness of one stud: k_{t1} = 100 kN/mm,
(6) concrete class C25,
(7) steel grade S235,
(8) beams of IPE profiles.

As a variable parameters were taken:
for moment resistance and stiffness assessment:

x_1: n_1 d (number of bolts connecting seat plate to beam flange × bolt diameter),
x_2: t_r (thickness of concrete slab [mm]),
x_3: ρ (reinforcement ratio [%]),
x_4: h_b (height of the beam IPE [mm]),

Boundaries of variable factors were taken as:

$x_1 \in$ (64-120) 4 or 6 bolts M16 or M20,
$x_2 \in$ (80-120) [mm],
$x_3 \in$ (0,5-1,1) [%],
$x_4 \in$ (200-300) [mm],

for rotation capacity:

x_1: $\rho \in$ (0,5-1,1) [%]
x_2: $h_b \in$ (200-300) [mm].

Theory of experiment design was applied and adopted for numerical simulation. The following function was applied to represent joint parameters

$$P_i = A\prod_{1}^{n} x_i^{\alpha_i} \tag{47}$$

where: P_i – resistance, stiffness or rotation capacity of the joint,
A – constant,
x_i – variable factors,
α_i – exponent.

Experiment plan PS/DK-2^4 shown in Table 4 was used to estimate resistance and stiffness of the joint. Values of M_R and $S_{j.ini}$ were obtained using program POWZ.
Using regression analysis it was obtained

$$M_R = 0.00068(n_1 d)^{0.71} t_r^{0.69} \rho^{0.5} h_b^{0.98} \tag{48}$$

$$S_{j.ini} = 0.0054(n_1 d)^{0.61} t_r^{0.79} \rho^{0.21} h_b^{1.54} \tag{49}$$

where: M_R – moment resistance of the joint [kN·m],
$S_{j.ini}$ – initial stiffness [kN·m/rad],

Experiment plan for rotation capacity is presented in Table 3.
From regression analysis

$$\phi_u = 1.210 \rho^{0.39} h_b^{-0.6} \tag{50}$$

Table 4 Experiment plan to estimate resistance and stiffness of the joint

Lp.	$\hat{x}$				x				M_R [kN·m]	$S_{j.ini}$ [kN·m/mrad]
	$\hat{x}_1$	$\hat{x}_2$	$\hat{x}_3$	$\hat{x}_4$	x_1: $n_1\, d$	x_2: t_r	x_3: ρ	x_4: h_b		
1	- 1	- 1	- 1	- 1	64	80	0,5	200	40,8	6,48
2	+1	- 1	- 1	- 1	120	80	0,5	200	43,46	8,99
3	- 1	+1	- 1	- 1	64	120	0,5	200	60,41	9,71
4	+1	+1	-1	- 1	120	12	0,5	200	73,87	13,84
5	- 1	- 1	+1	- 1	64	80	1,1	200	53,13	7,67
6	+1	- 1	+1	- 1	120	80	1,1	200	83,89	11,28
7	- 1	+1	+1	- 1	64	120	1,1	200	62,46	10,88
8	+1	+1	+1	- 1	120	120	1,1	200	108,51	16,20
9	- 1	- 1	- 1	+1	64	80	0,5	300	61,23	12,72
10	+1	- 1	- 1	+1	120	80	0,5	300	66,62	17,89
11	- 1	+1	- 1	+1	64	120	0,5	300	80,87	17,45
12	+1	+1	- 1	+1	120	120	0,5	300	105,33	25,29
13	- 1	- 1	+1	+1	64	80	1,1	300	77,24	14,94
14	+1	- 1	+1	+1	120	80	1,1	300	130,14	22,32
15	- 1	+1	+1	+1	64	120	1,1	300	87,7	19,51
16	+1	+1	+1	+1	120	120	1,1	300	167,26	29,56

Table 5 Experiment plan for rotation capacity

Lp.	$\hat{x}$		x		ϕ_u
	$\hat{x}_1$	$\hat{x}_2$	x_1: ρ	x_2: h_b	
1	-1	-1	0,5	200	39,7
2	+1	-1	1,1	200	54,1
3	-1	+1	0,5	300	29,3
4	+1	+1	1,1	300	39,6

Proposed simple formulas allow estimating of main composite joint parameters with accuracy of 20 %.

7. Conclusions

Based on experimental data and component method taken from EN 1993 and EN 1994, a comprehensive model of semi-rigid composite steel-concrete, weak axis joint, has been developed for predicting the moment capacity, initial stiffness and rotation capacity. The design equations are presented in the style that facilities the necessary calculations. Comparison with test results showed that good agreement was achieved. Basing on proposed prediction a computer program POWZ was developed. This program was used to create simplified formulas to quick assess of join resistance, initial stiffness and rotation capacity. These formulas can be used by designers in the predesign phase of design procedure.

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