Study on Stiffness of Composite Beam-to-Column Joints

Jaroslav Odrobiňák*, Róbert Idunka, Tomáš Bačinskýa

a Faculty of Civil Engineering, University of Žilina, 01026 Žilina, Slovakia

Abstract

Safe and economical design of new steel-concrete composite structures, as well as assessment of existing ones, depends not only on a load-carrying capacity of individual beams and columns, but it is greatly influenced by their mutual connection in joints. Stiffness of two types of composite joints is analyzed in the paper. The presented study is focused on the influence of reinforcement and slab thickness on the stiffness of composite joints. Fourteen variants of horizontal beams, several slab thickness, and appropriate modification of reinforcement ratios were performed in the study. Calculation procedures have been performed in accordance with the Component Method implemented into the current standards.

Keywords: Composite steel and concrete structures; composite joint; the Component Method; semi-rigid connections; stiffness of joint.

1. Introduction

Typically, common models of a beam-to-column connections in structural analysis of building structures do not reflect the actual joint behaviour and its influence on the analyzed structure. Traditional models are usually represented either by the perfectly rigid connection transmitting all internal forces from one element to another or by the perfect hinge joint without any ability to carry bending moments. In order to avoid inequality between the calculation model and the real provisions of structural joints, there are techniques for more relevant description of the joint behaviour. The "semi-rigid" joint can transfer a part of bending moment as result from partial restraint of rotation in the connection. Nowadays, the implementation of such joints into the global analysis of structures represents no difficulties. Especially, FEM-based software represents powerful tool for solving complicated structural systems with semi-rigid joints without any serious problems. However, the problem remains in approximation of the joint element that should be easily described. When omitting finite elements methods, the "Component Method" specified in [1] represents the most widely used alternative for the steel structures.

In the case of steel and concrete composite joints, some specifications are given in [2]. Tens of documents, e.g. [3, 4, 5,], and hundreds of articles, e.g. [6, 7, 8], were already published on the topic of semi-rigid joints or on their
2. Description of the parametric study

In the following, the parametric study focused on the influence of the reinforcement amount and the thickness of slab on initial stiffness of joint, when the two composite beams (e.g. bearers or joists) are symmetrically connected to a steel column. The Component Method was applied for estimation of the initial stiffness of joints $S_{j,ini}$.

2.1. Joints and their variation

The two types of standard composite joints for connections in composite steel and concrete structure:
- Joint with small contact plate (shear saddle + contact pad for compression) - Type "A" - see Fig. 1a
- Joint with steelwork connection effective in tension (end-plate + bolts in tension) - Type "B" - see Fig. 1b

![Fig. 1. Composite joints considered in the study: (a) the Type A; (b) the Type B.](image)

The bending moments from the beams were considered equal and opposite. The steel grade of S235 was adopted for both the column and the beams. The fourteen variants of hot rolled IPE cross-sections in the range from 160 mm to 600 mm were considered for the beams, while the hot rolled profile HEB 260 for the column remained the same. For each alternative, the six different thicknesses $h_c$ of the reinforced concrete slabs were considered; from 100 mm to 200 mm in steps of 20 mm. Moreover, the reinforcement ratio $\rho$ varied from 0.2% to 1.0% in 0.1% steps in each case. Thus, 756 alternatives for each type of the joint arose from the variation of above mentioned parameters. Due to the fact that the calculation is not realized for certain spacing and length of the beams, these additional premises were taken into account in the study:
- Centrum of gravity of the reinforcement was in the middle of slab thickness
- Minimum amount of the reinforcement was based on the effective width of reinforced concrete slabs which was considered equal to three times the beam height
- No slip between the slab and the steel beam was taken into account

Because of each type of the joint had some particularities, supplementary assumptions had to be taken into account. For the Type A joint they were:
- The contact plate was 20 mm high and as long as the width of flange of IPE beam section
- Contact plate and shear saddle are made of steel S235.

In the case of the joints of Type B these additional rules were given:
- Bolts M16, M20, M24 of quality 8.8 were designed
- The number of bolts came from shear resistance of the web of steel beam; it varied from 4 to 10, with dependence on the beam height and the diameter of applied bolts
- Minimum spacing in accordance with [1] were applied for bolts taking into account the necessary manipulating areas
- The top and bottom overhang of the end plate made of steel S235 was 20 mm
The thickness of the end plate was determined from possible failure mode of the equivalent T-stub; the mode of failure 1 and 2 in accordance with [1] were preferred.

The effective throat thickness of fillet welds was 4 mm.

Due to the limited space of the paper more details, concerning joints and their characteristics, are not given.

2.2. Determination of stiffness

To determine the rotational stiffness of a joint, three basic steps are usually needed. Firstly, identification of relevant basic components of each type of joint should be done. Then the stiffness of each component can be calculated on the basis of recommendation in the codes [1] and [2]. Finally, the overall initial rotational stiffness of the joint can be derived.

In the case of the joints of Type A, following components were identified:

- Column web panel in shear - stiffness coefficient $k_1$
- Column web in compression - stiffness coefficient $k_2$
- Beam flange and web in compression - stiffness coefficient $k_7$
- Longitudinal steel reinforcement in tension - stiffness coefficient $k_{s,r}$
- Contact plate under compression - stiffness coefficient $k_{14}$

For joints of Type B, valid components taken into the analysis were:

- Column web panel in shear - stiffness coefficient $k_1$
- Column web in compression - stiffness coefficient $k_2$
- Column web in tension - stiffness coefficient $k_3$
- Column flange in bending (for each bolt-row in tension) - stiffness coefficients $k_4$
- End-plate in bending (for each bolt-row in tension)- stiffness coefficients $k_5$
- Bolts in tension (for each bolt-row) - stiffness coefficients $k_{10}$
- Longitudinal steel reinforcement in tension - stiffness coefficient $k_{s,r}$

Corresponding formula and calculation methods can be found in [1] and [2], respectively. Concerning assumptions given before, values of the component stiffness coefficient $k_1$ were taken as zero. Moreover, the component stiffness coefficient $k_7$ and $k_{14}$ could be taken as infinite, in the case of the joint of Type A.

Transformation of joints in the form of the component models of both types of joints can be seen in Fig. 2. In the case of the Type B joint, see Fig. 2b, the alternative with two rows of bolts in tension zone is shown as an example.

In accordance with Fig. 2a, initial rotational stiffness of the joint of Type A can be calculated form formula (1).
Equation (2), valid for the Type B given in Fig. 2b, is a little bit different, as the single equivalent stiffness coefficient \( k_{eq} \) and the equivalent lever arm \( z_{eq} \) should be determined. For this purpose, the effective stiffness coefficient \( k_{eff,r} \) shall be obtained for each level \( h_r \) of the components in the tension zone, see [1, 2].

\[
S_{j,ini,Type\ B} = \frac{E_u \cdot z_{eq}^2}{\mu \sum_i \frac{1}{k_i}} = \frac{E_u \cdot z_{eq}^2}{\mu \left( \frac{1}{k_2} + \frac{1}{k_{eq}} \right)},
\]

\[
k_{eq} = \frac{\sum_r \left( k_{eff,r} \cdot h_r \right)}{z_{eq}}.
\]

\[
z_{eq} = \frac{\sum_r \left( k_{eff,r} \cdot h_r^2 \right)}{\sum_r \left( k_{eff,r} \cdot h_r \right)}.
\]

3. Results of the study

The graphs given in Fig. 3 show calculated values of the initial stiffness \( S_{j,ini} \) for both types of joints with dependence on the beam alternatives and the reinforcement ratios in the case of 100 mm thick slab. It is evident that in addition to changing the cross-sections of the beam, the stiffness of the composite joint can be enhanced by increase of the reinforcement ratio, as well. For the other slab thicknesses, similar tendencies were obtained.

Fig. 3. Stiffness of both types of joints for different beam alternatives and various reinforcement ratios in the case of 100 mm thick slab.
From Fig. 4 it is evident, how big the influence of the reinforcement ratio on the joint stiffness was determined. Relative growth of initial stiffness of both joint types in dependence on reinforcement ratio in the case of 200 mm thick slab is shown there. The relationships given in Fig. 4 declare that, for instance, if IPE 300 cross-section is applied, the increment of reinforcement ratio from 0.2 to 0.5 % can lead to 51% and 45% higher initial stiffness of the composite joint in case of the Type A and the Type B, respectively. In the case of the lower beam cross sections, modification of the initial stiffness is even more noticeable.

Almost similar or little bit smaller values of the relative growth of initial stiffness were also calculated for the concrete slabs thinner than one, covered by Fig. 4.

To validate the influence of thickness of concrete slab on the initial joint stiffness, curves given in Fig. 5 can be used. Relative growth of initial stiffness of the Type A joint in the case of two selected reinforcement ratios is presented on the graphs. Almost linear relationship can be stated in all variants covered by the study. In fact, the slab thickness affects the stiffness only through the increase of lever arm, as concrete in tension was not taken into account.

4. Conclusions

Analysis of the initial stiffness of composite joint confirmed that the growth of reinforcement ratio can be very significant for both types of joints. In the case of the Type B joint, the influence is slightly smaller due to the larger number of components involved in the overall stiffness of the joint.
Basically, the initial stiffness can be used for the classification of a joint in structural system, see [1]. Then, decision whether the semi-rigid joint should be allowed for the global analysis, or the joint can be more or less approximated by either rigid or hinge behaviour, can be adopted.

Moreover, the classification of real joints takes into account the actual length and spacing of joists or bearers. It is also possible to consider the fact, if structural system can be thought braced or unbraced.

Acknowledgements

The paper presents results of works supported by the Slovak Research and Development Agency under the contract No. APVV-0106-11 and by the Scientific Grant Agency of the Slovak Republic under the project No. 1/0583/14.

References

[1] EN 1993-1-8: Eurocode 3: Design of steel structures - Part 1-8: Design of joints. CEN, Brussels 2005.
[2] EN 1994-1-1: Eurocode 4: Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings. CEN, Brussels 2004.
[3] Semi-rigid behaviour of civil engineering structural connections: COST C1 - Composite steel-concrete joints in braced frames for buildings. European Commission, Brussels - Luxembourg 1996.
[4] Wald, F. Answers to questions about the structural connections of steel structures in accordance with European codes. ČVUT, Praha, 2003 (In Czech)
[5] Bitar D. et al.: Applicability of composite structures to sway frames. Final report, Report EUR 212913 en, Science Research Development, European Commission, Brussels 2006.
[6] Pisarek, Z., Kozlowski, A., Slezka, L.: Mechanical model of steel-concrete composite joint. In: Eurosteel 2011 - 6th European Conference on Steel and Composite Structures, Budapest, Hungary. ECCS Brussels 2011. Vol. A, pp. 459-464.
[7] AJ. Wang: Studies on composite joints under gravity and lateral Loads. Australian Journal of Structural Engineering, Vol. 12, Issue 1. Engineers Australia 2011, pp. 69-85.
[8] JF. Demonceau, JP. Jaspart: A new simplified analytical design method for steel and composite sway frames. Journal of Constructional Steel Research, Vol. 84, Elsevier 2013, pp. 27-35.