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A new method to assess the stiffness and rotation capacity of composite joints

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Abstract

Composite beam-to-column joints in buildings are mostly modelled as pinned joints in order to facilitate the design of the structure. In reality, due to the required reinforcement in the concrete slab, a certain joint rigidity and bending resistance is always available. The real joint behaviour corresponds therefore more to that of a semi-continuous joint. This is not only beneficial for the serviceability limit state but can also be advantageous at ultimate limit state. However, due to the lack of analytical design rules in EN 1994 to verify the rotation capacity of semi-continuous joints, these are commonly modelled as pinned joints, which impedes an efficient design of composite structures.
In this context, a research program on the behaviour of composite joints, focusing on the ultimate rotation capacity, was initiated at the University of Luxembourg [1]. The aim was to identify the influence of two major joint components – the reinforced concrete slab and the steelwork connection – on the moment-rotation curves of composite joints under hogging bending moment. An experimental campaign comprising 8 tests on beam-to-column joints was conducted to determine the response of composite joints with variable reinforcement ratio and diameter of reinforcing bars. In addition to the experimental part, an FE model was developed with the software ABAQUS aiming to simulate the behaviour of internal beam-to-column composite joints.
In this paper, the 3D finite element model and results of analyses are presented. The FE model has been defined by 3D solid elements with realistic contact definitions and non-linear material laws. The results of the numerical simulations presented a good agreement with the experimental data. Based on the experimental and numerical investigations, the influence of reinforcement and steelwork connection on the structural properties of composite joints is derived. A new analytical method to determine the stiffness and rotation capacity of composite joints is proposed. The accuracy of this new method is confirmed by existing experimental and numerical results.

Keywords: *Composite joints; semi-continuous; rotation capacity; joint stiffness; numerical simulations; Abaqus*

1. Introduction

Composite beams can be designed according to different methods, for example, the elastic and the plastic global analysis, which provide at the same time different levels of design efficiency. For a continuous composite beam, the elastic analysis provides a lower load bearing capacity due to the smaller bending resistance at the support, while a plastic analysis allows to fully exploit the beam's bending capacity at support and mid-span. This leads to a greater load bearing capacity and thus to a more efficient design.

However, a plastic global analysis is not always applicable. In order to allow for a plastic redistribution of the bending moments, a certain rotation capacity must be ensured by the weakest structural member. For a composite beam supported by semi-continuous beam-to-column composite joints, the weakest member is the joint. In order to take advantage of the more efficient plastic analysis method, sufficient rotation capacity must be verified.

Currently, no analytical method for the rotation capacity of composite joints is provided by EN 1994 [2] and only a reference to experimental evidence is made. As a consequence of this lack of analytical guidance, the use of semi-continuous composite joints finds nearly no application in practice. This constitutes an obvious bottleneck in composite construction since the semi-continuous modelling strategy represents the most realistic approach for composite joints. It is a fact that most of the joints regarded as pinned possess some rigidity and resistance of which advantage can be taken in the design of composite beams.

In this context, a research project was performed at the University of Luxembourg [1] with the objective to study the structural properties of composite joints, namely **stiffness, resistance and rotation capacity**. The principal aim of this study was the development of an **analytical method** for the stiffness and rotation capacity of composite joints.

In order to fulfil these objectives, an experimental test campaign was conducted in the laboratory of the University of Luxembourg. Furthermore, an FE model was developed with the software ABAQUS intending to simulate the behaviour of composite joints.

2. Experimental analysis

2.1. Test program

The experimental test program consisted of 7 tests on composite and 1 test on steel beam-to-column joints, see Fig. 1. The tests were performed on a slim-floor type of composite beams, commonly known as CoSFB [3]. In comparison to traditional composite beams, the major difference of CoSFB consists in the CoSFB dowels ensuring the shear connection between steel and concrete.

A symmetrical cruciform type of set-up was adopted in order to simulate the behaviour of internal major axis joints in a structural frame [3]. With this testing configuration, no bending moment was transferred to the column. The main parameters investigated were:

(i) the longitudinal reinforcement ratio ρ

(ii) the diameter of the longitudinal rebars Ø

(iii) the steelwork connection

According to this, the test program was subdivided into 3 series as illustrated in Fig. 1. The **first series B** was focused on the two first parameters (i) and (ii). Thus, a steelwork connection between the beams and the column was intentionally omitted in order to restrict the joint's load bearing behaviour to the sole reinforcement component. The comparison of tests with equal reinforcement ratio (B21 – B31 and B22 – B32) allowed to deduce the influence of different rebar diameters, whereas the comparison of tests with equal rebar diameter (B22 – B31) allows to conclude on the effect of larger reinforcement ratio on the structural properties of composite joints.

In contrast to the first series, the **second test series C** was only focused on the third parameter (iii). Hence, a bolted flush endplate connection was provided between the beams and the column. To ensure that the isolated behaviour of the steelwork connection was reproduced realistically, no concrete was cast in test specimen C14.

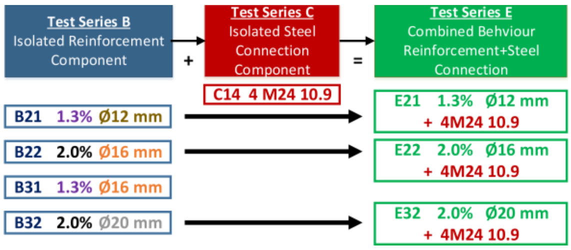

Fig. 1. Experimental test program

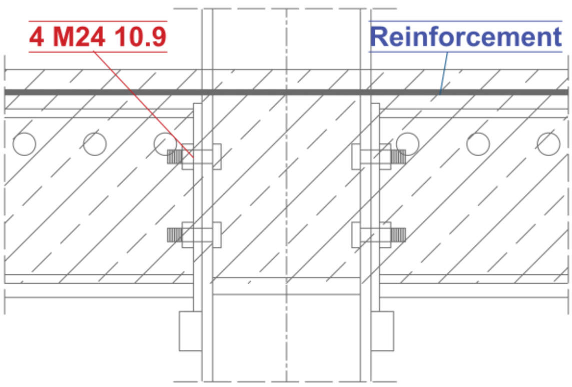

Fig. 2. Detail of composite joint in test series E

In the **third test series E**, 3 tests on composite joints were performed. These tests consisted of the 2 components, which have been tested previously in isolation in series B and C, see Fig. 2. The purpose was to analyse the influence of a flushed endplate connection on the overall composite joints' behaviour [1, 3].

2.2. Experimental results

In conjunction with the ductile endplate connection, the large reinforcement ratio and rebar diameter used in the present test campaign provided a large ductility to all the tested joint configurations. Rotation capacities above 95 mrad were achieved for composite joints. Only 2 tests failed through the fracture of a longitudinal reinforcement bar (B21 and B22). The other tests have been stopped due to excessive specimen deformation before any sign of failure could be identified. An overview of all the moment-rotation curves is illustrated in Fig. 3.

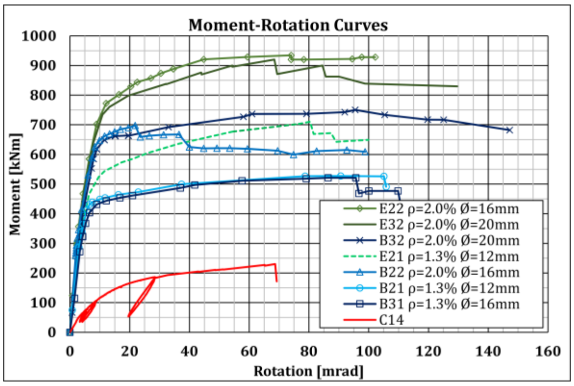

Fig. 3. Experimental moment-rotation curves

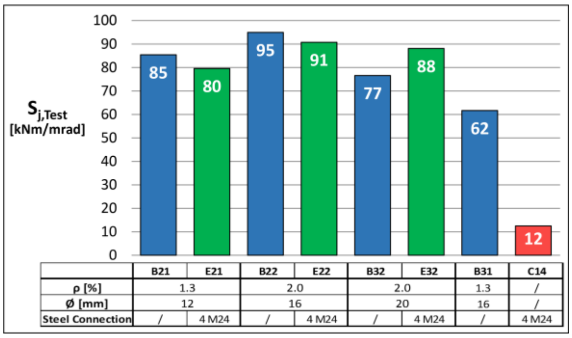

Fig. 4. Experimental joint stiffness comparison

Comparison of the joint stiffness presented in Fig. 4 leads to the following conclusions:

I. The stiffness increases with larger degree of reinforcement ρ

II. The stiffness decreases with bigger diameter of rebars Ø

III. Bolted flush endplate connections do not significantly influence the stiffness.

The experimental results are extensively described in [1].

3. Numerical simulations

3.1. Finite element model

To simulate the behaviour of the internal composite joints, an FE model was developed with the general purpose finite element package ABAQUS/Explicit [4]. 3D 8 nodes continuum elements of linear order and reduced integration (C3D8R elements) were used to model steel, concrete and bolt parts, see Fig. 5. All the reinforcement parts (stirrups, longitudinal reinforcement and CoSFB-dowel) were modelled with 3D beam element types with linear interpolation (B31 elements).

The mechanical interactions between steel, concrete and bolts were implemented using the general contact definition. In normal direction, hard contact allowing for separation after contact was defined whereas, in tangential direction, the penalty formulation with a friction coefficient of 0.4 was adopted. The interaction between reinforcement and the surrounding concrete was implemented using the predefined constraint for embedded reinforcement.

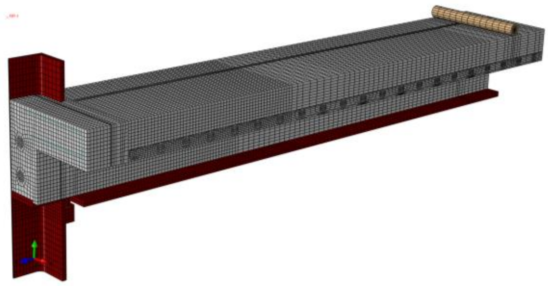

Fig. 5. Finite element model

Double symmetry boundary conditions were considered to reduce the numerical computation time. Hence, only a quarter of the model was reproduced. A reference point, coupled to the top nodes of the column section, was defined in order to apply a displacement controlled loading as that operated on the hydraulic jack during the experimental tests.

The dynamic explicit solver was used to analyse this FE model. In comparison to the implicit solver, this technique facilitates convergence issues for models involving a high degree of material degradation such as concrete cracking. Although Abaqus/Explicit provides a solution for true dynamic equilibrium, it can also be applied to quasi-static problems, provided that inertial effects are insignificant. On that basis, the adequate loading rate was identified to

0.30 mm/sec in an iterative process. This achieves good balance between external and internal work. The load has been applied using a smooth amplitude function as recommended in Abaqus [4].

Concrete material has been defined by dedicated concrete damaged plasticity model. In compression, the stress-strain definition of EN 1992 [5] has been implemented whereas in tension it was opted to introduce the stress-displacement curve from Model Code 2010 [6]. For the steel parts, elastic behaviour was assumed until material yielding, followed by a plastic material behaviour. Care was taken to convert the measured nominal material values into true stress-strain material values [4].

3.2. Validation of numerical results

In order to validate the FE model presented above, the experimental tests were reproduced numerically. The comparison between experimental and numerical moment-rotation curves for tests B21, E21 and C14, showing a very good resemblance, is presented in Fig. 6. Congruent results are also obtained for the other tests [1], validating hereby the FE model developed in this work. The failure of the simulated joint configurations represented very well the failure obtained experimentally for tests B21 and B22 (rupture of longitudinal rebar). Simulation of failure of bolts in tension was only obtained for tests C14, E22 and E32, at a very large rotation (above 110 mrad).

Moreover, very good similarity between experimental and numerical crack pattern was also obtained, see Fig. 7. This further proves the suitability of this numerical model to reproduce the behaviour of composite beam-to-column joints. Close agreement for the overall joint deformation as well as for the deformation shape of the endplate could also be observed. More detailed information can be found in [1].

3.3. Parametric study

The validated numerical model has been applied to perform a parametric study with the aim to investigate the influence of specific reinforcement properties on the ultimate rotation capacity of composite joints. In particular, the longitudinal reinforcement ratio and rebar diameter as well as the maximal elongation capacity of the bare reinforcement were varied in order to identify the effect of these parameters on the ductility of composite joints.

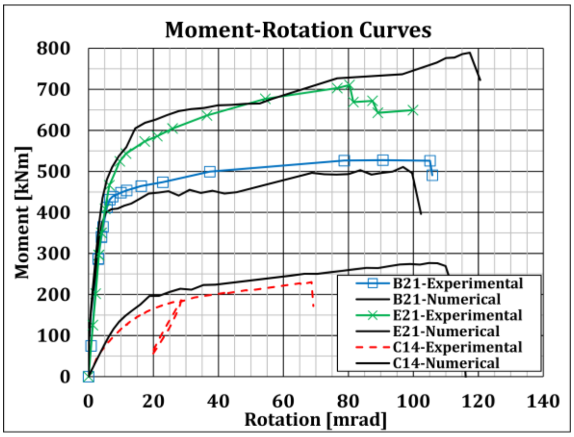

Fig. 6. Exp. vs. FEA moment-rotation curves

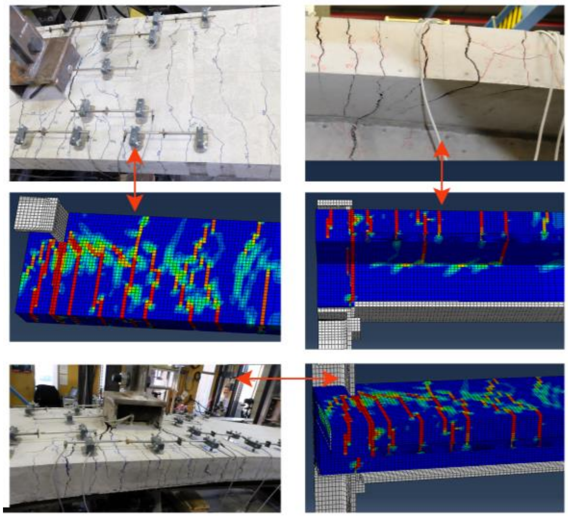

Fig. 7. Experimental vs. numerical crack pattern

The parametric study was divided into two groups. In the first group G1, reinforcement ratio and rebar diameter are varied within a practical range, see *Table 1*. Reinforcement ratios between 0.7 % and 2.5 % and rebar diameters between 12 mm and 20 mm were investigated in a total of 10 simulations. In the second group G2, 5 additional simulations were performed, in which the elongation capacity of the reinforcement was reduced to 50% of the initial value.

The ultimate rotation capacities achieved for these joint configurations are given in *Table 1*. For group G1 it can be observed that large ductility was obtained for all the simulations. The largest rotation capacity was reached for the joint with the largest reinforcement ratio and rebar diameter (P12-20). For group G2, it is noted that the rotation capacity is about half of the corresponding joint in group G1. This shows that in addition to the parameters (i) and (ii), the ultimate strain capacity of the bare reinforcement constitutes an important parameter, which should be taken into account in the analytical formulation for the rotation capacity.

Table 1. Numerical parametric study

	Test Ref.	No. rebar	Rebar Ø mm	ρ %	Φ_u mrad
Group G1	P10-12	10	12	0.7	80
	P10-14	10	14	1.0	90
	P12-12	12	12	0.8	80
	P12-14	12	14	1.2	93
	P12-16	12	16	1.5	101
	P12-20	12	20	2.4	138
	P14-12	14	12	1.0	80
	P14-14	14	14	1.3	95
	P16-12	16	12	1.1	80
	P18-16	18	16	2.3	130
Group G2	P10-14-b	10	14	1.2	48
	P12-16-b	12	16	1.5	59
	P12-20-b	12	20	2.4	70
	P14-12-b	14	12	1.0	39
	P18-16-b	18	16	2.3	70

4. Analytical method

The purpose of these experimental and numerical investigations was to develop a broad understanding on the behaviour of composite joints. On this basis, a mechanical model, taking into account the behaviour observed during the test conduction, was derived to formulate an analytical expression for the main structural properties of composite joints [1].

4.1. Joint stiffness

EN 1994 [2] suggests the following formula to determine the stiffness of composite joints:

$$S_j = \frac{E \cdot z_{eq}^2}{\sum_i \frac{1}{k_i}} \tag{1}$$

The factors k_i correspond to the stiffness coefficients of the basic joint components subjected to noteworthy deformations. For the steel components of joints, these factors are given in EN 1993-1-8 [7]. For internal joints with negligible deformation in the compression region (k_5=k_c=k_S=∞ in Fig. 8) and balanced bending moments, only the components in tension need to be considered. For boltless (e.g. Series B) and bolted (e.g. Series E) composite joints the stiffness is thus equal to:

$$S_{j,B} = E \cdot k_r \cdot h_r^2 \tag{2}$$

$$S_{j,E} = E \cdot k_r \cdot h_r^2 + E \cdot \textstyle\sum_j k_{eff,j} \cdot h_j^2 \tag{3}$$

For double sided joints with balanced hogging moments and insignificant slip, the stiffness coefficient of the reinforcement component is given in EN 1994, Table A.1 [2]:

$$k_r = \frac{A_s}{L_j} = \frac{A_s}{h_c/2} \tag{4}$$

A_s is the reinforcement area and L_j is the **effective joint length**. In EN 1994 [2], this length is roughly estimated to half the column depth h_c. For simplification, EN 1994 [2] allows to treat the reinforcement component as a bolt-row, see Fig. 8. This assumes a linear deformation shape of the joint. Although the numerical results presented in [1] contradict this assumption, this approximation has little influence on the stiffness value of flushed endplate connections. This is mainly due to the small internal lever arm of the bolt-rows in relation to the reinforcement leading to an insignificant stiffness of the bare steelwork connection. Neglecting the lower bolt-rows in the assessment of the overall rigidity of composite joint has consequently little influence on the results.

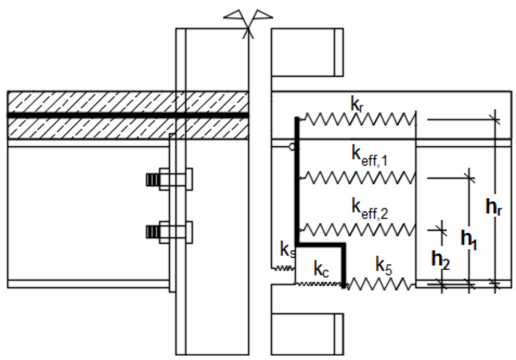

Fig. 8. Component model for composite joints

In [1], it was found that the rough estimation provided by EN 1994 [2] for the effective joint length L_j is not representative for the true joint behaviour. As a matter of fact, the analysis of the experimental crack pattern permitted to discover that this length L_j is correlated to the cracking phenomenon and more specifically to the parameters (i) and (ii). The numerical investigations confirmed this outcome. As a consequence, it could be deduced that the effective joint region increases for:

- larger reinforcement ratios ρ and
- bigger diameter Ø of longitudinal rebar.

It must be stated that this outcome is in line with the conclusion deduced from the measured joint stiffness. According to these observations, a new analytical formula for L_j has been derived:

$$L_j = \frac{h_c}{2} + n \cdot 2 \cdot L_t \tag{5}$$

where L_t is the transmission length:

$$L_t = \frac{f_{ctm} \cdot \varnothing}{4 \cdot \tau_{bm} \cdot \rho_{eff}} = \frac{\varnothing}{6.4 \cdot \rho_{eff}} \tag{6}$$

In Eq. (6), ρ_{eff} is the effective reinforcement ratio, calculated on the basis of the effective concrete area $A_{c,eff}$ according to EN 1992 [5]. More information about the background of this quantity is given in [8]. The factor n considers the correlation discovered between reinforcement ratio and effective joint length:

$$n = \begin{cases} 1.5 & 1.0\,\% \leq \rho_{eff} \leq 1.6\,\% \\ 2.5 & 1.6\,\% < \rho_{eff} \leq 1.9\,\% \\ 3.5 & 1.9\,\% < \rho_{eff} \leq 2.2\,\% \\ 4.5 & 2.2\,\% < \rho_{eff} \leq 2.9\,\% \\ 5.5 & 2.9\,\% < \rho_{eff} \leq 3.5\,\% \end{cases} \tag{7}$$

In order to verify the reliability of this new method, the stiffness of composite joints, tested in the present and earlier research, are assessed analytically. Fig. 9 shows, that this new formula is able to predict with a sufficient degree of exactness the stiffness measured from experimental tests.

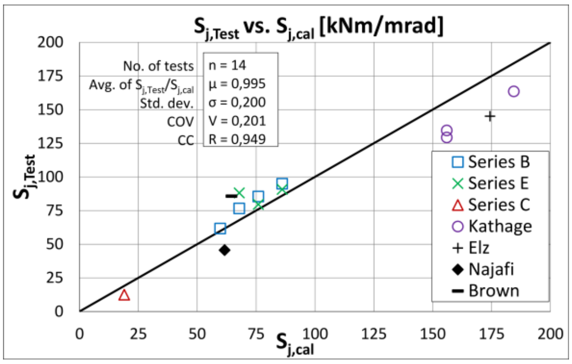

Fig. 9. Exp. vs. Calc. stiffness acc. to new method

EN 1994 [2] significantly overestimates the measured stiffnesses, see Fig. 10. In comparison to EN 1994 [2], the new proposal, presented in this paper ensures a substantial improvement in the capacity of predicting the stiffness of composite joints. This issue of EN 1994 [2] was already reported by other researchers, confirming the necessity of a normative review for this specific joint property [9, 10].

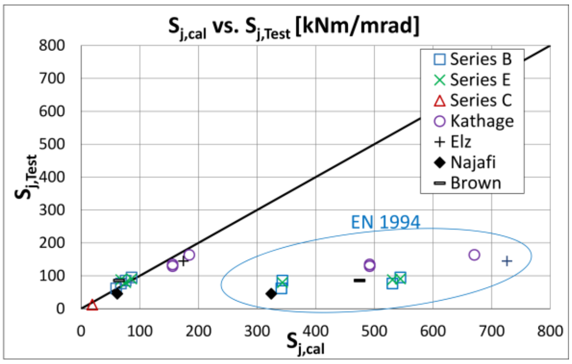

Fig. 10. EC-method vs. new proposal for S_j

4.2. Rotation capacity

The need for large rotation capacities in the plastic analysis of composite beams obliges the structural engineer to a conscious design of composite joints. In this context, steelwork connections shall present a ductile behaviour by providing thin end-/finplates so as to avoid the brittle tension or shear failure of bolts. This recommendation is not only valid for composite joints. It should also be adopted for steel joints, whenever ductility constitutes a structural need. By following this recommendation and ensuring that local instabilities in the members are avoided, the ultimate rotation capacity of composite joins is solely defined by the deformation capacity of the embedded reinforcement in longitudinal direction. The latter is not only related to the maximum strain capacity of the bare reinforcement but also depends on the participation of concrete between the cracks, the **tension stiffening effect**.

This effect was extensively described by Kreller [11] and implemented in Model Code 1990 [12]. It induces a reduction of the ductility of the embedded rebars. The result is a smaller ultimate elongation capacity of this component ε_{smu} in comparison to that of the bare steel reinforcing bars ε_{su}. The full description of this phenomenon as well as formulas to determine ε_{smu} are presented in [1]. In Fig. 11, design aids in form of charts are provided to facilitate the determination of ε_{smu} and ε_{smy}. These charts assume an ultimate strain capacity ε_{su}=5% for the bare rebars. It corresponds to the 5%-fractile of B500B reinforcement according to EN 1992 [5]. Additional design aids covering different values for ε_{su} can be retrieved from [1].

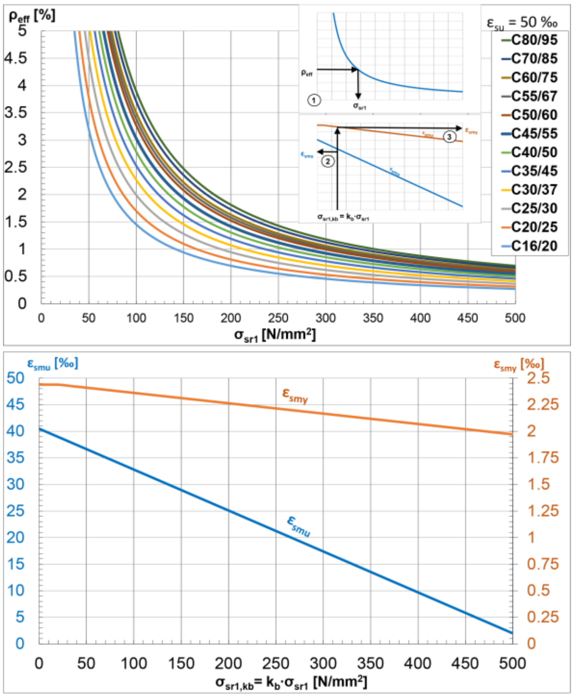

Fig. 11. Design aids for $\varepsilon_{su} = 5\%$

Once the elongation capacity of the reinforcement component in composite joints is determined, the ultimate rotation capacity Φ_u can be calculated on behalf of the mechanical model presented in Fig. 12.

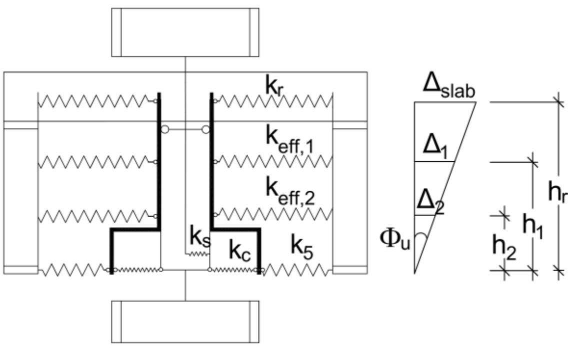

Fig. 12. Mechanical model for the ult. rot. capacity

The following expression is deduced:

$$\Phi_u = \frac{\Delta_{slab}}{h_r} \tag{8}$$

The magnitude of the slab elongation Δ_{slab} can be derived from the strain distribution $\varepsilon_{sm}(x)$ in the reinforcement along the effective joint length L_j. Assuming a linear strain distribution, see Fig. 13, the slab elongation can be given as:

$$\Delta_{slab} = \int_0^{L_j} \varepsilon_{sm}(x) \cdot dx$$

$$= \varepsilon_{smu} \cdot \frac{h_c}{2} + \frac{\varepsilon_{smu}+\varepsilon_{smy}}{2} \cdot \left(L_j - \frac{h_c}{2}\right) \tag{9}$$

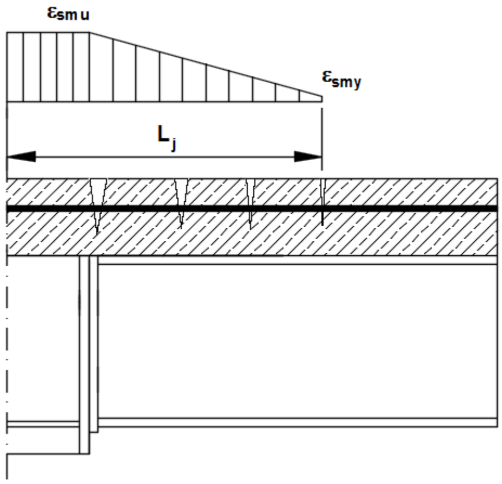

Fig. 13. ULS: strain distribution in reinforcement

The ultimate rotation capacity follows to:

$$\Phi_u = \left[\varepsilon_{smu} \cdot \frac{h_c}{2} + \frac{\varepsilon_{smu}+\varepsilon_{smy}}{2} \cdot \left(L_j - \frac{h_c}{2}\right)\right] \cdot \frac{1}{h_r} \tag{10}$$

The ultimate strain capacity ε_{smu} and the yield strain ε_{smy} of the reinforcement component are derived according to the procedure proposed by Kreller [11]. In order to consider the fact that, prior to the first crack occurrence, the stress distribution is not constant over the thickness of the slab, the reinforcement stress at first crack $\sigma_{sr1,kb}$ is re-evaluated using the factor k_b:

$$\sigma_{sr1,kb} = k_b \cdot \frac{f_{ctk;0.05}}{\rho_{eff}} \cdot \left(1+(\alpha_e - 1) \cdot \rho_{eff}\right) \tag{11}$$

with:

k_b	factor considering non-constant tensile stresses in the slab = $\frac{1}{1+\frac{d}{2 \cdot z_{i,0}}}$
d	concrete slab thickness
$z_{i,0}$	vertical distance between the centroids of uncracked unreinforced concrete flange and uncracked unreinforced composite section
$f_{ctk;0.05}$	5%-fractile concrete tensile strength
α_e	ratio between steel and concrete Young's moduli = $\frac{E_s}{E_c}$

The accuracy of this new proposal is evaluated by comparing the analytical results with the rotation capacities obtained experimentally and numerically. Fig. 14 confirms the suitability of the analytical approach suggested in this paper by showing the good concordance with the results.

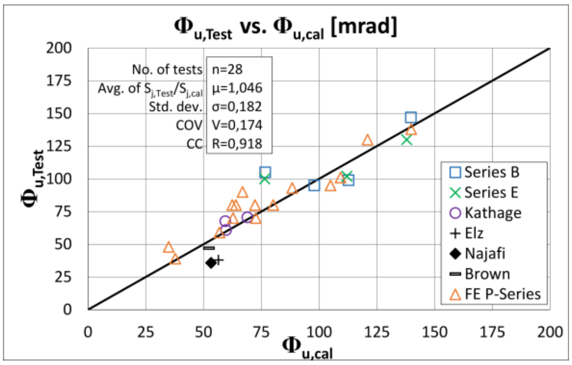

Fig. 14. Experimental/numerical vs. predicted ultimate rotation capacities

4.3. Range of validity

The application of these new analytical methods is subjected to the following conditions:

- Reinforcement ratio $\rho_{eff} \geq 1.0\%$
- Rebar diameter $12\ mm \leq \emptyset \leq 20\ mm$
- Minimal ductility class for rebars: B
- Ductile failure of steelwork connection
- No local buckling of column web and
- No local buckling of beam flange
- Compressive load bearing capacity of beam bottom flange is larger than the sum of the resistances of the tension components
- Double sided symmetric joints
- Non-cyclic loading
- Joints under hogging bending moments

5. Conclusions

A new method to calculate the stiffness S_j and the ultimate rotation capacity Φ_u of composite joints was developed and presented in this paper. The reliability of this method was verified based on experimental and numerical investigations carried out in the present and former research projects. Close agreement was achieved between analytical and measured values. This method allows to design semi-continuous composite beams according to a plastic global analysis. More information about the rotation verification at the joint as well as a simplified procedure enabling the more efficient design of composite structure involving composite joints is given in [1].

Acknowledgment

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