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A FINITE ELEMENT ANALYSIS OF STEEL PLATE–CONCRETE COMPOSITE BEAMS INCLUDING THE INFLUENCE OF STIFFNESS OF THE CONNECTORS ON DELEFCTION

ANALIZA NUMERYCZNA BELKI ZESPOLONEJ TYPU STALOWA BLACHA–BETON Z UWZGLĘDNIENIEM WPŁYWU PODATNOŚCI ŁĄCZNIKÓW NA UGIĘCIA

A b s t r a c t

The aim of this paper is to present an assessment of slip influence on the deflection of steel plate–concrete composite beams, which are a new type of design concept. The article discusses the non-linear analysis of simply supported beams using Ansys. Willam-Warnke model was used for concrete – this allows the analysis of a complex stress state. For steel elements, bilinear models were used and it was assumed that they work in the uniaxial stress state. Spring elements were used in order to include the slip in the numerical model. The analysis was verified by experimental studies.

Keywords: composite beam, interface slip, steel plate-concrete composite beam, deflection, finite element analysis

S t r e s z c z e n i e

W artykule przedstawiono ocenę wpływu poślizgu na ugięcie belek zespolonych typu stalowa blacha–beton, które stanowią nowe rozwiązanie konstrukcyjne. Zaprezentowano analizę numeryczną belek wolnopodpartych obciążonych. W przypadku elementów betonowych zastosowano model betonu zgodnie z teorią Willama-Warnkea, który pozwala na analizę złożonych stanów naprężeń. Dla elementów stalowych zastosowano model biliniowy oraz założono jednoosiowy stan naprężeń. W celu uwzględnienia wpływu podatności łączników wykorzystano elementy sprężynowe. Wyniki analizy zostały zweryfikowane rezultatami badań doświadczalnych.

Słowa kluczowe: konstrukcja zespolona, poślizg w płaszczyźnie zespolenia, belka zespolona typu stalowa płyta-beton, ugięcia, metoda elementów skończonych

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1. Introduction

Composite structures are designed to optimise the desired properties of two basic materials used in construction, steel and concrete. Many years of experience has led to the creation of a new design concept defined as steel plate-concrete composite structures (SPCC) [4]; their characteristic feature is the connection of traditional reinforced concrete beams with steel plates resulting in a kind of external reinforcement. Both parts are connected together by shear connectors that provide a good bond between two elements. It can also be seen that this type of structure design is an evolution of the composite structures inspired by classical methods of strengthening reinforced concrete beams with steel plates glued onto parts of the reinforced concrete beams exposed to the heaviest loads.

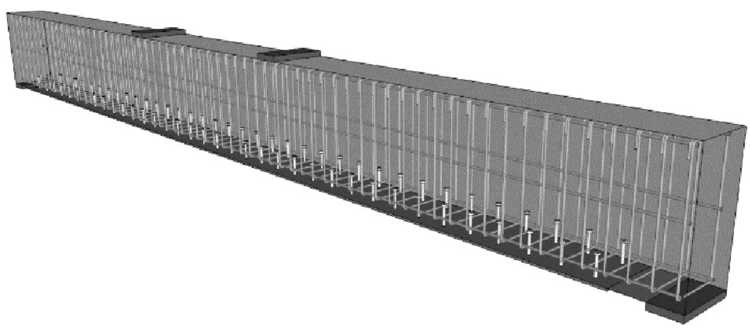

Fig. 1. Construction scheme of the steel plate-concrete composite beam

This paper presents a method of modelling structures which includes the deformability of shear connectors using the finite element method implemented in the Ansys software program. The results of numerical analysis were verified by experimental studies [4] and theoretical analysis.

2. Problem

Steel plate-concrete composite beams are an innovation in civil engineering and many aspects of their behaviour require further research. Experimental studies which serve as validation of the presented methods and models were carried out by Nie & Zhao [4]. They examined five simply supported beams of different load arrangement, depth and length of steel plate, spacing and material properties of the connectors and the compressive strength of concrete.

Experimental studies on steel plate-concrete beams have shown that the application of the procedures proposed in the standard codes does not provide accurate deflection results [4].

Table 1

Description of tested beams [4]

Beam No.	SCCB-2	SCCB-3	SCCB-5	SCCB-7	SCCB-8
Depth of concrete beam [mm]	500	500	500	500	500
Width [mm]	250	250	250	250	250
Span [mm]	5000	5000	5000	5000	5000
Depth of steel plate [mm]	8	10	8	8	8
Length of steel plate [mm]	5200	5200	4700	4700	4700
Shear span [mm]	1500	1500	2500	2500	2000
Studs spacing [mm]	130	130	130	170	85
Characteristic value of concrete compressive strength [MPa]	40.7	46.3	45.1	46.4	37.4
Characteristic value of yield strength of steel plate [MPa]	327.0	291.0	327.0	327.0	327.0

Table 2

Experimental and theoretical deflection results [4] at half the ultimate load

Deflection [mm]					
Beam No.	SCCB-2	SCCB-3	SCCB-5	SCCB-7	SCCB-8
Experimental results	9.42	8.66	8.97	7.85	8.53
ACI	7.24	6.68	6.50	7.06	6.55
EC 2	7.12	6.57	6.35	6.96	6.45
Chinese Code	8.33	7.81	7.58	8.30	7.61

It is related to the behaviour of this type of structures which can not be classified neither as composite nor reinforced concrete structures. The underestimation of the deflection is mainly due to not considering the stiffness of studs – this causes the slip effect at the interface and, consequently, deflection to be neglected. In addition, an important issue which affects deflections is reinforced concrete beam cracking [1]; however, cracking in these beams differs from cracking in conventional reinforced concrete beams. Experiments have shown that these structures are characterized by a different arrangement of cracks. This difference results from different interaction between rebars and steel plates with concrete. The use of a well-known theory of reinforced concrete elements is possible, but it is flawed.

3. Theoretical analysis

The proposed method of calculating the deflection of steel plate-concrete composite beams is based on the procedure included in [2], which has been modified to take into consideration the influence of stiffness. The first step requires calculating the deflections of the reinforced concrete structure taking into account its cracking and tension stiffening. The second step involves additional deflection resulting from interface slip, which affects beam stiffness, and consequently, deflection.

If the steel plate is assumed to act as longitudinal reinforcement and the impact of concrete shrinkage is omitted, deflection of the reinforced concrete element can be calculated as [2]:

$$f_r = (1-\zeta) f_{\mathrm{I}} + \zeta f_{\mathrm{II}} \tag{1}$$

where:

- f_{I} – deflection of uncracked conditions,
- f_{II} – deflection of fully cracked conditions,
- ζ – the distribution coefficient allowing for tensioning stiffening.

The additional deflection for a simply-supported beam loaded symmetrically with two concentrated forces (Fig. 2) can be calculated as [5]:

$$\Delta f = \Delta f(b) = \beta P \left(\frac{L-2b}{4h} + \frac{e^{\alpha b} - e^{\alpha L - \alpha b}}{2\alpha h (1+e^{\alpha L})} \right) \tag{2}$$

which can be written in this form after introducing the following formulas:

$$n = \frac{E_s}{E_c} \tag{3}$$

where:

- E_s – elasticity modulus of steel,
- E_c – elasticity modulus of concrete.

$$I_0 = I_s + \frac{I_c}{n} \tag{4}$$

where:

- I_s – moment inertia of steel section,
- I_c – moment inertia of concrete section.

$$d_c = \frac{1}{2}(h_c + h_s) \tag{5}$$

where:

- h_s – depth of the steel plate,
- h_c – depth of the concrete beam.

$$A_0 = \frac{A_s A_c}{nA_s + A_c} \tag{6}$$

where:

- A_s – area of steel,
- A_c – area of concrete.

$$\frac{1}{A'} = \left(d_c^2 + \frac{I_0}{A_0} \right) \tag{7}$$

$$\alpha^2 = \frac{k}{pE_s I_0 A'} \tag{8}$$

$$\beta = \frac{A' p d_c}{k} \tag{9}$$

where:

k – shear-slip stiffness of the stud,
p – pitch between the studs,
b – distance from the centre to concentrated force,
P – applied load,
L – length,
h – depth of entire section.

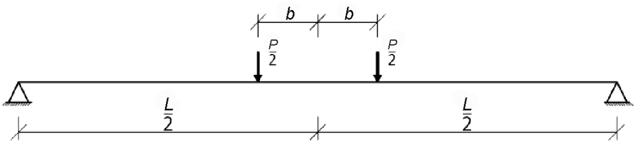

Fig. 2. Static diagram of analysed steel plate-concrete composite beam

Using the relationships derived for reinforced concrete (1) and taking into account additional deflection due to slip (2), the total deflection of steel plate-concrete composite structures can be expressed by the formula:

$$f_{\text{tot}} = f_r + \Delta f \tag{10}$$

In paper [4], the authors assume that half of the ultimate load was used as the value for which the deflection was calculated. This assumption is based on the fact that in the actual design, deflection is calculated for load levels, which are mainly around 50–60% of the bearing capacity of the beam. The plot in Fig. 3 confirms that the analysis using the proposed theory is justified; therefore, further theoretical and numerical analyses have been performed using this assumption.

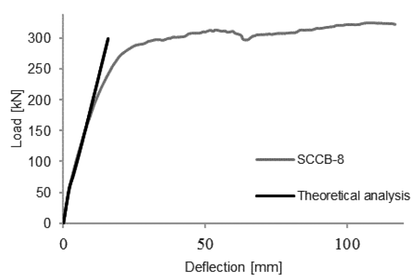

Fig. 3. Load-deflection curve for SCCB-8 beam

4. Numerical analysis

In order to compare the experimental results with the numerical analysis, a calibration model based on an SCCB-8 beam was developed. A strong agreement of the results confirmed the usefulness of the presented method and the same approach was used in other specimens. As a starting point, the tests of Jianguo Nie & Zhao Jie were adopted [4], these examined five beams of different parameters – the main parameters are shown in Table 1.

4.1. Geometric and materials parameters

The simply supported beams used in tests had a rectangular cross-section of 250×500 mm and was 5200 mm in length. Because of the support conditions, the effective span was 5000 mm. At the bottom, the steel plate of dimensions 250×8 mm was connected by headed studs to the reinforced concrete beam – this was shorter than the concrete part of the beam and was 4700 mm in length. The rebars were arranged in three levels:

– at the top two rebars having a diameter of 12 mm with 28 mm of cover,
– at the bottom and in the middle two rebars having a diameter of 10 mm.

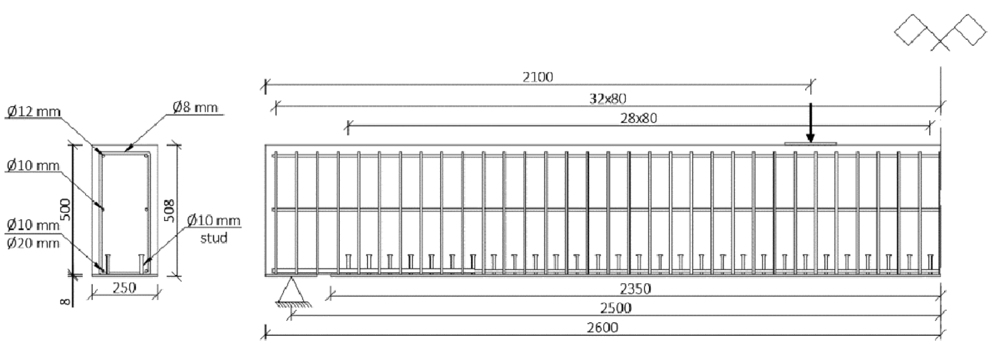

Fig. 4. Geometry of steel plate-concrete composite beam SCCB-8

The material parameters were selected after the experimental studies [4]. If the property needed to prepare a numerical model was not included in the study, it was selected for the material based on the literature recommendations.

Failure criteria for concrete in a complex state of stress were adopted according to the model proposed by Willam & Warnkea. The linear-elastic model of concrete requires the elastic modulus of concrete and the tensile strength which were not specified in [4]. Their values were determined according to the formula given in [3].

For steel elements, a bilinear model was used. Where there were no experimental results available, it was assumed that the basic parameters such as the modulus of elasticity and Poisson's ratio had the same values for each of the modelled components.

Table 3

Willam-Warnke model parameters for beam SCCB-8

Parameter	
Modulus of elasticity of concrete	29.0 GPa
Poisson ratio	0.2
Shear transfer coefficients for an open crack	0.3
Shear transfer coefficients for a closed crack	1.0
Uniaxial tensile cracking stress	3.8 MPa
Uniaxial crushing stress	37.4 MPa
Biaxial crushing stress	44.9 MPa
Biaxial crushing stress under the ambient hydrostatic stress state	54.2 MPa
Uniaxial crushing stress under the ambient hydrostatic stress state	64.5 MPa
Stiffness multiplier for the cracked tensile condition	0.6 10–6

4.2. Finite element model

In the numerical analysis, a variety of finite elements were used depending on the type and characteristics of the modelled element [7]. Table 6 shows all element types used.

Table 4

Finite element types

Concrete beam	Steel plate	Support pads	Interface
SOLID65	SHELL181	SOLID45	TARGE170 CONTA174
Longitudinal reinforcement		Stirrups	Headed studs
LINK180		LINK180	LINK180 COMBIN39

Connectors were modelled using two different finite elements – LINK180 and COMBIN39. The first finite element transfers the loads from the concrete to the steel plate – this was modelled between existing nodes of the finite element mesh of the concrete beam. In order to take into account the stiffness of headed studs, a COMBIN39 finite element was used – this acts as a spring with a non-linear, force-displacement characteristic. There are many studies of connector stiffness; however, for the purposes of this analysis, the relationship derived in [6] was used:

$$F_d = F_{du}\left(1 - \frac{1}{e^{\Delta u_s}}\right)^{0.558} \tag{11}$$

where:

- d – stud diameter,
- f_c – compressive strength of concrete,
- f_y – steel yield strength,
- Δu_s – connector displacement.

$$F_{du} = 1.3d^2\sqrt{1.2 f_c f_y} \tag{12}$$

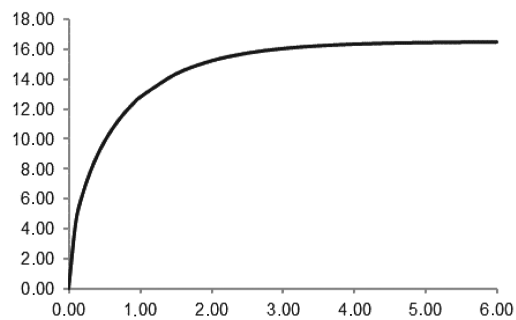

Fig. 5. Force-displacement curve for the COMBIN39 element

To include the contact between the reinforced concrete beam and the steel plate, CONTA174 and TARGE170 finite elements of friction coefficient of 0.45 were used – this provided the interaction of these two materials for the model.

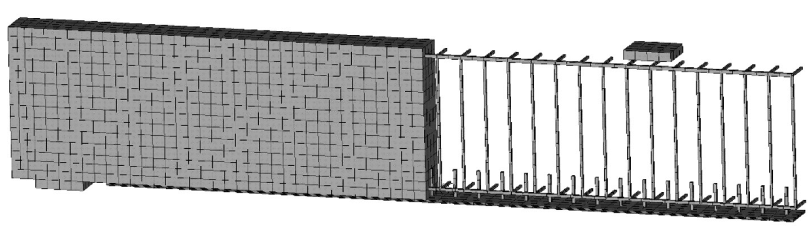

Fig. 6. Finite element mesh

Due to their symmetry, only quarter of each beam was modelled. At the centre of each span, the X and Z directions were fixed. At the end of each beam, a movable support was used in the X direction. The load was applied as in laboratory tested beams. The analysis was divided into load steps in order to achieve convergence. The analysis was performed until a load equalling half of the ultimate load was reached, which according to the assumptions in [4], corresponds to half of the ultimate load and is identified with reaching the maximum deflection in the serviceability limit state.

4.3. Results

The results of the analysis and experimental studies [4] for calibration beam SCCB-8 are shown in Table 5. The comparison of these results shows strong agreement.

Table 5

Experimental, theoretical and numerical results

Parameter	Experimental Study (d)	EC 2	Theoretical Analysis (t)	Difference $\left(\frac{d-t}{d}\right)$	Numerical analysis (n)	Difference $\left(\frac{d-n}{d}\right)$
Deflection at the centre of the span at load of 162.5 kN [mm]	8.53	6.45	8.41	1.4%	8.10	5.0%
First crack load [kN]	51.00	52.85	52.85	3.6%	52.90	3.7%

The proposed model which takes into account the stiffness of the studs properly models steel plate-concrete composite beam response in the serviceability limit state. In the laboratory tested beam, it was 8.53 mm and in numerical analysis, 8.10 mm.

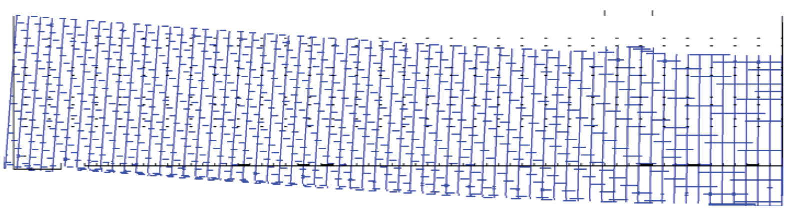

Fig. 7. Deformation of the SCCB-8 beam at half the ultimate load

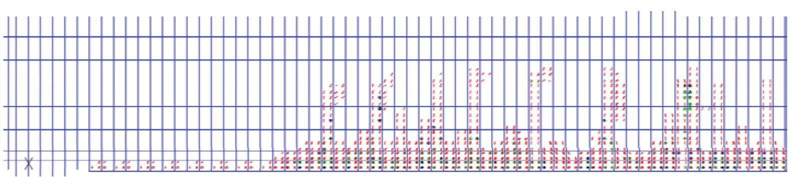

Fig. 8. Cracking pattern of the SCCB-8 beam at half of the ultimate load

The analysis of load-deflection curves shows the characteristic behaviour of the element, which in the first phase behaves linearly. Once cracking occurs, the stresses in the steel part of the composite beam increase significantly – this can be observed on the plot as a sudden change in the slope of the curve. In the nonlinear region, subsequent cracking occurs, this causes a further increase of the stress level in the steel.

Other steel plate-concrete composite beams were made using appropriate materials and geometric parameters in a manner analogous to that presented for beam SCCB-8. The results of the theoretical and numerical analysis and their comparison with the experimental studies of five beams described in [4] and the results obtained from the calculations based on EC2 procedures are presented in Figures 8–12. A satisfactory correlation of results in each phase of the response of the beams is obtained. Both the comparison of the results in accordance with the standard code procedures and taking into account the slip at the interface shows the influence of the stud stiffness and the need to accommodate this phenomenon. The application of non-linear relationships involving deflection under *the* applied load enables correct description of the structural behaviour.

The results are questionable only in the case of the SCCB-7 beam; however, the abnormality may be due to the experimental conditions or it may be connected with material parameters other than those adopted.

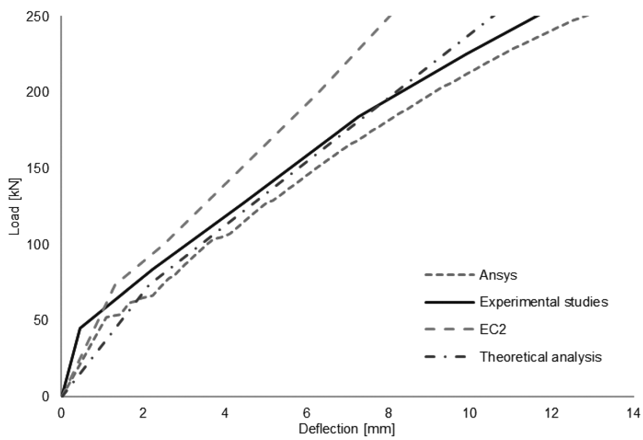

Fig. 9. Load-deflection curves for SCCB-2 beam

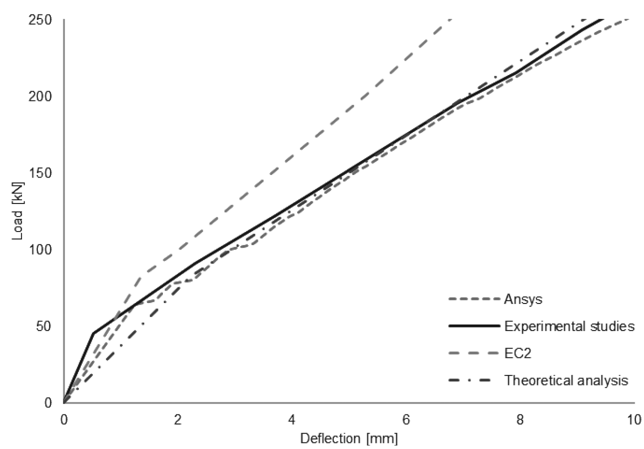

Fig. 10. Load-deflection curves for SCCB-3 beam

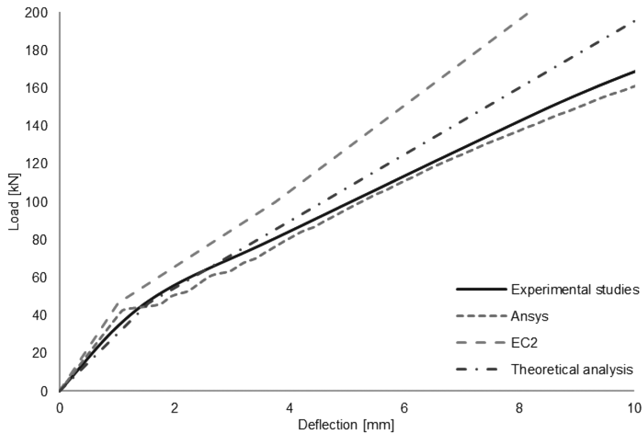

Fig. 11. Load-deflection curves for SCCB-5 beam

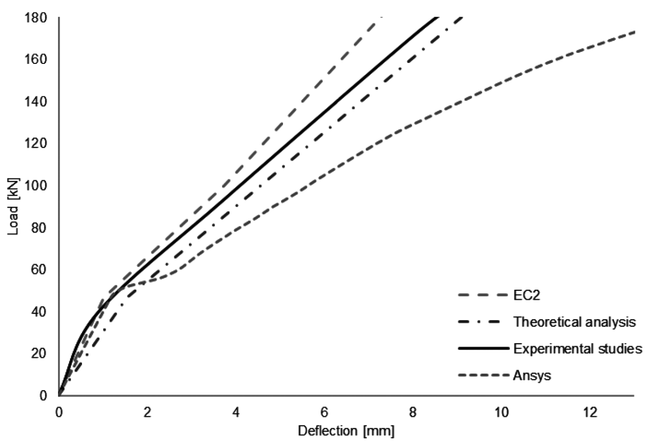

Fig. 12. Load-deflection curves for SCCB-7 beam

5. Conclusions

The presented method of calculating deflections and modelling of the steel plate-concrete composite beam can be successfully used. The model takes into account such aspects as the composite action of concrete and steel, the discrete model of reinforcing steel embedded in the concrete beam, the cracking of the reinforced concrete, the tension stiffening effect, the contact between the reinforced concrete beam, and the steel plate and shear connectors influence on the beam response. This allowed an in-depth analysis of the interesting phenomena that occur in there types of elements, mainly the influence of the interface slip on the behaviour of the beam due to the deformability of the shear connectors.

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