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DETERMINATION OF STIFFNESS OF THE CONNECTIONS OF COMPOSITE STEEL AND CONCRETE BRIDGE DECK BY THE LIMIT PERMISSIBLE DEFLECTIONS

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Abstract. The composite steel and concrete structures are used for constructing bridge floors and others buildings. The joint action of composite structures as well as their economic efficiency depends on the connection between the layers, i.e. stiffness of the steel beam and the concrete slab. Under the effect of external load in the connection of steel and concrete the shear deformations occur. The size of these deformations depends on the effective shear stiffness of the connection of layers. When designing the composite steel and concrete structures it is very important to accurately calculate their deflections. Deflection is largely dependent on the stiffness of the connection of steel and concrete. In isolated cases it is purposive to calculate the necessary stiffness of the connection of steel and concrete taking into consideration the permissible deflection of the composite steel and concrete structure. This paper gives the methodology which, based on the known permissible deflection of the structure, allows to calculate the necessary equivalent effective shear modulus of the steel-concrete connection. Experimental investigations of the composite steel and concrete beams were carried out. Deflections of the composite beams, also the shear deformations of steel and concrete connections and the effective shear stiffness of this connection were determined. Theoretical calculations of the effective shear stiffness of the connection of concrete slab and steel beam of the experimental composite steel and concrete beams were conducted. Investigations showed a rather good correspondence between the experimental and theoretical investigation results.

Keywords: composite structures, deflection, concrete and steel connection, effective shear stiffness, equivalent shear modulus.

1. Introduction

The composite steel and concrete structures are used for constructing various buildings. One of the more old types of buildings where such structures were used are bridges of various designation since the technology of construction process is not complicated, i.e. on steel beams in a rather simple way the shuttering is installed and the bearing concrete slab is concreted (Fig. 1).

Even today such composite structures are often calculated by identifying the resistance of beams and slabs separately, i. e. taking no account of their joint action. This is the way of calculation in case when there are no reliable methods to ensure the joint action of the elements (beam and slab) of composite steel and concrete structure (Fig. 1). The joint action of composite structures as well as their cost-efficiency depends on the stiffness of the connection between the steel beam and the concrete slab. Under the effect of external load, on the plane of their contact the shear deformations occur (Fig. 1b). If the shear deformations of connections are unrestricted the concrete slab may slip in respect of the beam's surface (Lam, El-Lobody 2005).

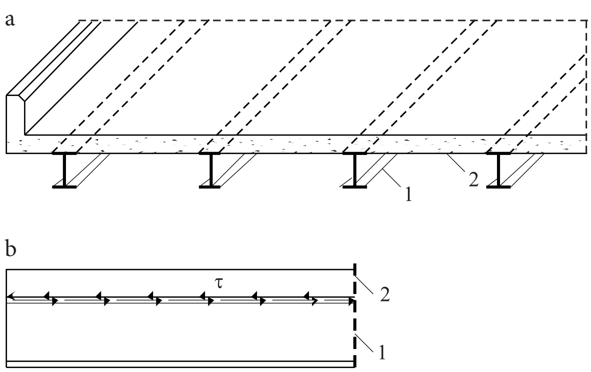

Fig. 1. The scheme of the composite steel-concrete floor: a – general view; b – longitudinal section of the beam; 1 – steel beam; 2 – concrete slab; τ – shear between the layers

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Due to that the total resistance of the composite steel-concrete structure decreases, deflections increase (Ellobody, Young 2006; Jurkiewiez *et al.* 2011; Oehlers *et al.* 1997; Tsalkatidis, Avdelas 2010) and vice versa, the more restricted shear the more increased resistance and decreased deflections (Fig. 2). This variation is characterized by the stiffness of connections between the concrete and the steel beam which in accordance with EC 4 is defined by the degree of shear connection η. Stiffness and the strength shear of the connection depend on multiple factors. Investigations show (Faggiano *et al.* 2009; Gurkšnys *et al.* 2005; Jurkiewiez *et al.* 2011; Jurkiewiez, Braymand 2007; Motak, Machacek 2004; Smith, Couchman 2010) that it is not always possible and necessary to reach the absolute shear connection or to avoid the slip between the layers. The same resistance is achieved by increasing the cross-sections of the layers and decreasing the connection stiffness. But in order to achieve it the slip between the layers must be restricted as it has a high influence on the deflection of structures. The graphs in Fig. 2 as well as the authors' calculations show that due to stiff connection the resistance can increase up to 3 times, and the deflection can decrease up to 9 times compared to the case where there is a sliding connection between the layers. On the other hand, it is necessary to keep a balance between the resistance of horizontal and vertical cross-sections. With the decreasing connection stiffness the slip is increasing, as well as the total deflection of the structure which has certain restrictions. In accordance with *Euronorms EC 1994-1 Eurocode 4 "Design of Composite Steel and Concrete Structures. Part 1-1: General Rules and Rules for Bridges"* and EC 1994-2 *Eurocode 4 "Design of Composite Steel and Concrete Structures. Part 2: Composite Bridges"*, the resistance of steel-concrete connection depends on the factors influencing the slip. These factors are: the form of connector, its stiffness degree, concrete strength, length of beam, level of stresses on the contact plane of slab and beam. All these factors must ensure that the deformations of structures do not exceed the permissible limits. Most of these factors are restricted by one coefficient η, which is calculated by different empirical formulas.

Accurate evaluation of all factors by determining the slip of layers in respect of each other and its effect on the structural behaviour under the acting load is a complicated task (Bullo, Di Marco 2004; Gurkšnys *et al.* 2005; Šliseris, Rocēns 2010). Commonly, it is suggested to use empirical formulas or experimental data like it was suggested in the design standards.

Therefore, the scientists seek for various analytical methods to determine the slip between the layers or the total stiffness of the steel-concrete connection (Bullo, Di Marco 2004; Hosain *et al.* 1992; Jurkiewiez, Hottier 2005; Loh *et al.* 2004; Marčiukaitis *et al.* 2006; Nie, Cai 2003; Oehlers, Sved 1995; Oehlers, Conghlan 1986; Ranzi *et al.* 2003; Salari *et al.* 1998; Wang 1998) that would help to identify the above-mentioned factors. However, in many cases those factors are identified by empirical coefficients recommended also by the official normative documents. Therefore, the aim of this article is to suggest methodology for the calculation of connection between the layers and to identify the validity limits of this calculation methodology following the requirements for the limit states of structures.

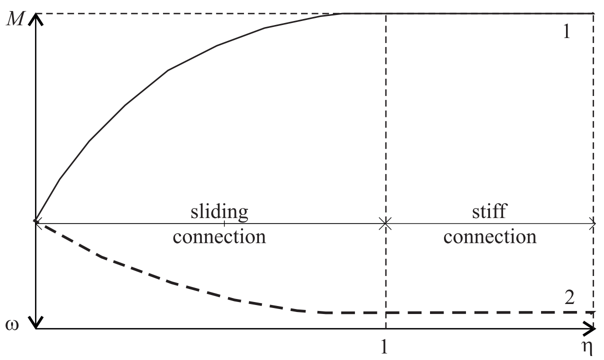

Fig. 2. The scheme of the effect of connections and their stiffness (D_{con}) on the resistance (1) and the deflections (2) of a layered structure

2. Calculation model of the stiffness of connection between the concrete slab and the steel beam

Behaviour of the flexural composite steel-concrete element is determined by two cross-sections: horizontal cross-section, i.e. the steel-concrete connection zone, and vertical cross-section. In the connection zone of the layers the shear efforts are acting, and in perpendicular section – bending moments.

Fig. 3 shows that under the active shear efforts and bending moments one layer (concrete slab) slips in respect of the steel beam on their contact plane.

Based on the theory of built-up bars (Rzanitsyn 1986), the actual slip of two layers in respect of each other at their contact surface is

$$u = u_{sc} - u_c, \tag{1}$$

where u_{sc} – the slip of lower layer (the steel beam); u_c – the slip of upper layer (the slab) in the connection zone of both layers.

Dependence between the slip and the relative deformations using (1) is:

$$\frac{du}{dx} = \varepsilon_{slip} = \varepsilon_{sc} - \varepsilon_c, \tag{2}$$

where ε_{slip} – deformations of the slip; ε_{sc} and ε_c – concrete and steel deformations in the contact surface of layers.

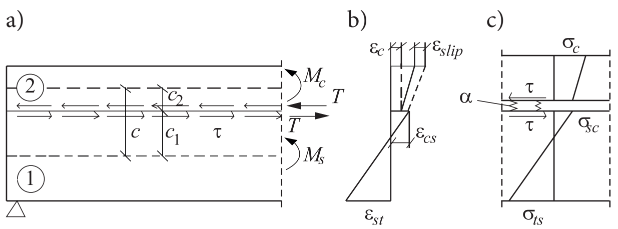

Fig. 3. Calculation schemes for the distribution of efforts (a), deformations (b) and stresses (c), and connection stiffness between concrete and metal (α)

Since the efforts are generated by bending moment, according to their distribution (Fig. 3a) the relative deformations of the slip of layers

$$\varepsilon_{sc} = \frac{T}{E_s A_s} - \frac{M_s}{E_s I_s} c_1; \tag{3}$$

$$\varepsilon_c = \frac{T}{E_c A_c} - \frac{M_c}{E_c I_c} c_2, \tag{4}$$

where T – shear force generating tangent stresses on the connection plane of layers; M_s and M_c – successive bending moments of the steel beam and concrete slab; E_s and E_c – modulus of elasticity of steel and concrete; A_s, A_c, I_s, I_c – total area of the cross sections and moments of inertia of the steel beam and the calculated concrete slab; c_1 and c_2 – distances from the centres of gravity of the beam and the slab up to their connection plane.

Having entered the values of relative deformations of the slip from the expressions (3) and (4) into the Eq (2) and having made appropriate calculations it was obtained that:

$$\frac{du}{dx} = \varepsilon_{slip} = T\left(\frac{1}{E_s A_s} + \frac{1}{E_c A_c}\right) -$$

$$\frac{M_{sum}\, c}{E_s A_s + E_c I_c} + \frac{T c^2}{E_s A_s + E_c I_c}, \tag{5}$$

where $M_{sum} = M_s + M_c$ total bending moment without respect to the connection between the layers; c – distance between the centre of gravity of the layers.

Analysis of the Eq (5) shows that the slip is generated by the shear and the difference of deformations on the contact plane generated by bending moments.

Using the theory of built-up bars for the calculation of deflections of two-layer structures, the total stiffness of the steel-concrete connection is required. Stiffness of the connection of layers has a larger influence on the deflections than on the resistance. Investigations showed that when using the theory of built-up bars, deflections of the composite structure are best described by the following equations:

$$\omega = \frac{5p\, l^4}{384 E_{eff} I_{eff}} + \frac{p}{\lambda^4 D}\left(\frac{1}{ch(0.5\lambda l)} + \frac{\lambda^2 l^2}{8} - 1\right), \tag{6}$$

where p – uniformly distributed load; l – span length.

$$\frac{1}{D} = \frac{1}{E_c I_c + E_s I_s} - \frac{1}{E_{eff} I_{eff}}. \tag{7}$$

Stiffness coefficient of the connection of the layers

$$\lambda = \sqrt{\alpha\,\gamma}\,, \tag{8}$$

$$E_{eff} I_{eff} = E_c I_c + E_s I_s + \frac{E_c A_c E_s A_s c^2}{E_c A_c + E_s A_s}; \tag{9}$$

$$\gamma = \frac{1}{E_c A_c} + \frac{1}{E_s A_s} + \frac{c^2}{E_c I_c + E_s I_s}, \tag{10}$$

where α – characteristics of the effective shear stiffness on the contact plane of the layers.

In the design of bridge floors, deflections are limited by certain standards. For example, the limit deflection for road bridges is $\frac{l}{400 \div 800}$. As the Eq (6) shows, in order to ensure deflection it is necessary to know what stiffness of the connection between the concrete slab and the steel beam must be.

3. Model for the determination of stiffness required to ensure the permissible deflection of the connection of steel-concrete beams

For the model development the statically determinate structure of the length l is studied, the limit deflection of which is $\omega_{\lim}$. The Eq (6) is transformed into

$$\omega_{\lim} = M\left(\frac{l^2}{8 E_{eff} I_{eff}} + \frac{1}{D}\frac{\mathrm{ch}(0.5\lambda l) - 1}{\lambda^2 \mathrm{ch}(0.5\lambda l)}\right). \tag{11}$$

In this equation the unknown is λ, which in the calculations is assumed together with l. Having denoted $z = 0.5\lambda l$ it is obtained

$$\omega_{\lim} = M l^2\left(\frac{1}{8 E_{eff} I_{eff}} + \frac{1}{4D}\frac{\mathrm{ch}z - 1}{z^2 \mathrm{ch}z}\right). \tag{12}$$

From (12) the members with the unknown z is expressed as:

$$\frac{\mathrm{ch}z - 1}{z^2 \mathrm{ch}z} = D\left(\frac{4\omega_{\lim}}{M l^2} - \frac{1}{2 E_{eff} I_{eff}}\right). \tag{13}$$

Having assumed appropriate denotations the Eq (11) is written in the following identical form:

$$f(z) \equiv \frac{\mathrm{ch}z - 1}{z^2 \mathrm{ch}z} = q, \tag{14}$$

$$q = D\left(\frac{4\omega_{\lim}}{M l^2} - \frac{1}{2 E_{eff} I_{eff}}\right). \tag{15}$$

Analysis shows (Fig. 4) that the left side $f(z)$ of the Eq (14) in the interval $(0;\infty)$ decreases from 0.5 to 0, since:

a) $$\lim_{z\to 0} f(z) = \lim_{z\to 0}\frac{z^2/2! + z^4/4! + \ldots}{z^2 \mathrm{ch}z} = 0.5, \tag{16}$$

b) $$\lim_{z\to\infty} f(z)=\lim_{z\to\infty}\left(\frac{1}{z^2}-\frac{1}{z^2\mathrm{ch}z}\right)=0, \tag{17}$$

besides, $\mathrm{th}z<z$, since $(\mathrm{th}z-z)'=-\mathrm{th}^2 z$, therefore

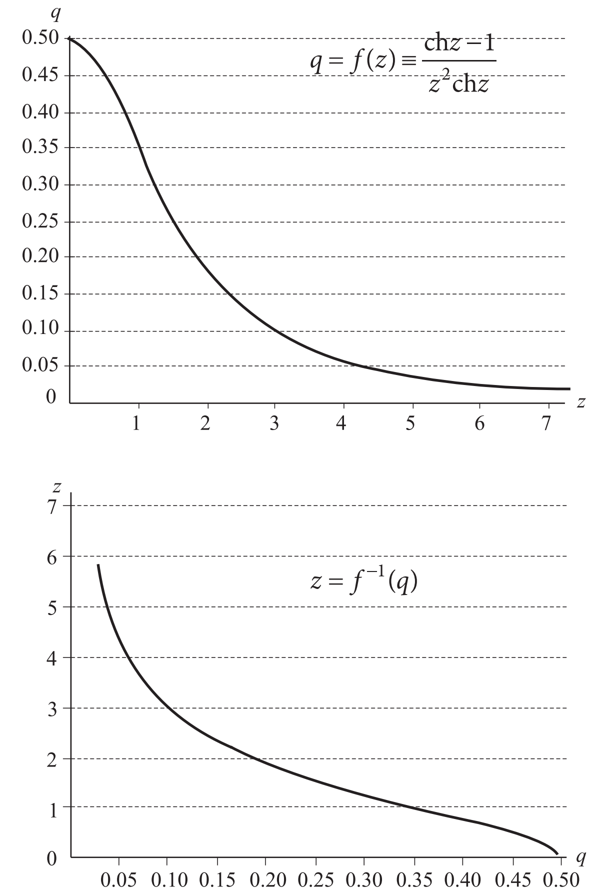

Fig. 4. The graphs of the function $f(z)$ and the inverse (solution) $f^{-1}(q)$

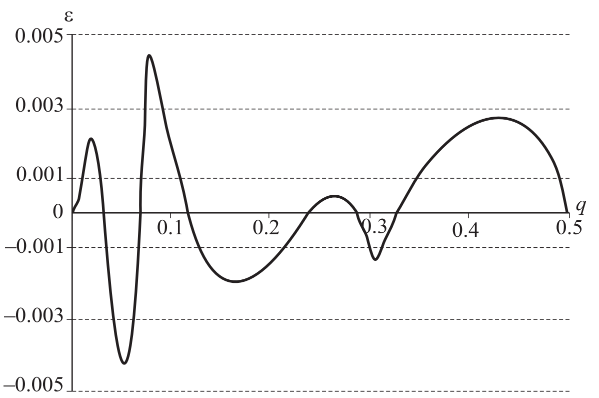

Fig. 5. Distribution of the difference ε (errors) of the exact and approximate solution (18–20) of the equation $\frac{\mathrm{ch}z-1}{z^2\mathrm{ch}z}=q$

c) $$f'(z)=\frac{z\mathrm{th}z-2(\mathrm{ch}z-1)}{z^3\mathrm{ch}z}<\frac{z^2-2(\mathrm{ch}z-1)}{z^3\mathrm{ch}z}=$$

$$\frac{-2\left(z^4/4!+z^6/6!+\ldots\right)}{z^3\mathrm{ch}z}<0. \tag{18}$$

It is easily notice that the function $f(z)$ is an even function, thus, the Eq (14) has only one solution if $0\le q\le 0.5$, and has no solutions if $q<0$ or $q<0.5$. Fig. 4 gives the graphs for $q=f(z)$ and the inverse $z=f^{-1}(q)$.

In the range $z\approx 0$ ($q\approx 0.5$), based on Eq (16) $f(z)=q\approx\frac{1}{2+c^2z^2}$, where $c=\mathrm{const}\approx 1$, therefore $z\approx c\sqrt{\frac{1}{q}-2}$ and using the method of least squares was obtained the approximate solution of the equation to be solved:

$$z=1.0889\sqrt{\frac{1}{q}-2}, \text{ when } 0\le q\le 0.074. \tag{19}$$

The absolute error of this solution in the above mentioned range does not exceed 0.005.

On the other hand, the analysis of graphs in Fig. 4 shows that by increasing the specific stiffness of the concrete slab and the steel beam of different layers it is possible to install the shear connection of less stiffness. And vice versa, in case of layers having lower stiffness, the connection stiffness has to be higher.

In a similar way in the range $z\approx\infty$ ($q\approx 0$), based on the condition of (17), it is obtained that $f(z)=q\approx\frac{1}{z^2}$, therefore $z\approx\sqrt{\frac{1}{q}}$ and seeking for the approximate solution in the form of $z\approx\sqrt{\frac{1}{q}}+c_0+c_1q+c_2q^2$ with the same absolute error of 0.005, it is obtained that

$$z=\frac{1}{\sqrt{q}}-20q^2, \text{ when } 0.074\le q\le 0.305; \tag{20}$$

$$z=\frac{1}{\sqrt{q}}-2.03q+0.041, \text{ when } 0.305<q\le 0.5. \tag{21}$$

The absolute error of the constructed approximate solution (19–21) of the Eq (15) in the whole variation range $0\le q\le 0.5$ of the parameter q (Eq(15)) does not exceed 0.005. A detail distribution of errors is shown in Fig. 5.

Finally, taking into consideration that $z=0.5\lambda l$, the following expression of the approximate solution $\lambda\in(0,\infty)$ of the Eq (11) is obtained:

$$\lambda = \begin{cases} \frac{2}{l}\left(\frac{1}{\sqrt{q}} - 20q^2\right), & q = 0...0.074, \\ \frac{2}{l}\left(\frac{1}{\sqrt{q}} - 2.03q + 0.041\right), & q = 0.074...0.305, \\ \frac{2}{l}\left(1.0889\sqrt{\frac{1}{q} - 2}\right), & q = 0.305...0.5. \end{cases} \quad (22)$$

The absolute error of this solution does not exceed the quantity $\varepsilon_l = \frac{0.005}{0.5l} = \frac{1}{100l}$.

4. Determination and experimental check of the shear stiffness

The main cause of shear is shear stresses in a contact zone. The shear deformations caused by shear stresses

$$\varepsilon_\tau = \varepsilon_{slip} = \frac{\tau}{G_w}, \quad (23)$$

where τ – shear stresses; G_w – the shear modulus which depends on a number of parameters and on which the total stiffness depends.

According to the suggested model (22), having calculated the required general connection stiffness coefficient λ, from the Eq (8) the characteristic of the shear stiffness of connection is calculated:

$$\alpha = \frac{\lambda^2}{\gamma}. \quad (24)$$

Analysis of Figs 4 and 5 shows that the total layers connection stiffness depends on the known parameters or those assumed in a design stage: acting load, the floor aperture of the structure, limit deflection, geometric characteristics of the cross-sections of different layers, modulus of elasticity of concrete and steel. There again, based on the theory of built-up bars, quantity describing the connection stiffness of the composite steel-concrete structures is:

$$\alpha = \frac{bG_w}{c}. \quad (25)$$

Therefore, the effective shear modulus of this connection

$$G_w = \frac{\alpha c}{b} = \frac{\lambda^2 c}{\gamma b}, \quad (26)$$

where b – width of layers connection.

Calculation methods for the composite steel-concrete structures indicate that in any case when calculating such structures it is essential to determine the shear stiffness of this connection. Therefore, when designing composite steel-concrete bridge floors in order to more accurately calculate the structure‘s deflection it is essential to determine stiffness of the partial shear connection of steel and concrete. When calculating deflections of the composite steel-concrete floors for the determination of stiffness of the partial shear connection between the layers, the shear stiffness of this connection must be known. Analysis showed that knowing the permissible deflection of the flexural composite steel-concrete structure and using calculation methodology suggested in this article one calculate the minimum permissible equivalent effective shear modulus of the connection between the layers $G_{w,eff,lim}$ which directly represents stiffness of the steel-concrete connection. Since there is as yet no methodology allowing to theoretically and reliably calculate the equivalent effective shear modulus ($G_{w,eff}$), describing the share stiffness of the projected steel-concrete connection, it is determined experimentally. This done by testing the fragments of the projected steel-concrete connection. Based on the results of experimental investigations the equivalent effective shear modulus of the steel-concrete connection $G_{w,eff}$ is determined. The experimental equivalent effective shear modulus ($G_{w,eff,exp}$) is compared to the limit permissible equivalent effective shear modulus ($G_{w,eff,lim}$) calculated by using methodology suggested by the authors. If the obtained experimental shear stiffness of the steel-concrete connection is higher than the limit permissible stiffness the connection is used for designing the projected floor.

In order to check the relation between the connection stiffness and deflection of the composite steel-concrete floors, calculated using methodology suggested by the authors of this article, the models of the composite steel-concrete beams were manufactured and tested. The cross-sections of the experimental composite beams is shown in Fig. 6. The specimens were made of 100 mm

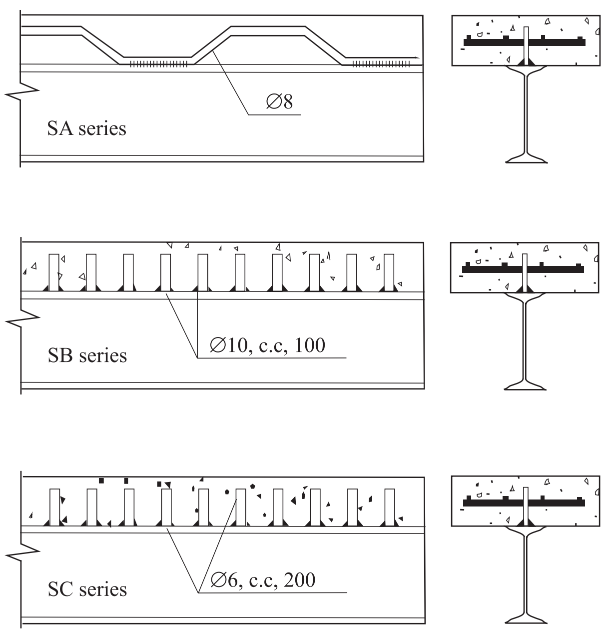

Fig. 6. General view of the beams

high structural steel section of I cross-section. The concrete layer was 50 mm in thickness and 200 mm in width. The cube strength of the concrete layer $f_{c,cube}$ = 23.1 MPa. The concrete layer in the middle of its cross-section was provided with reinforcing fabrics made of S240 class reinforcing steel Ø6 mm in diameter. Modulus of elasticity of the concrete E_{cm} = 24.9 × 10^3 MPa. The concrete layer and the structural steel section were joined by the shear connectors.

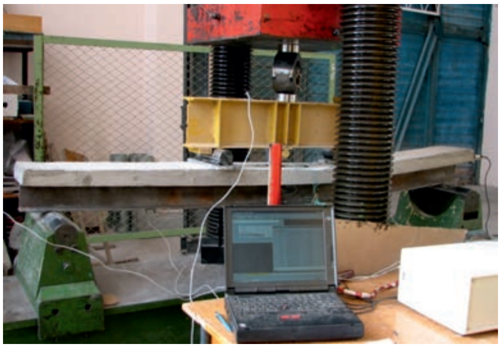

Fig. 7. General view of the set-up for the test of the beams

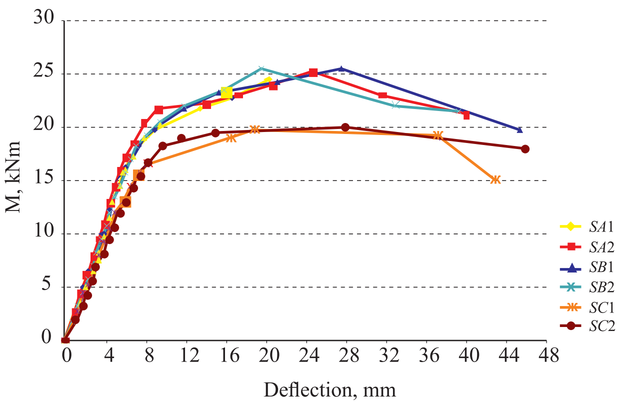

Fig. 8. Experimental deflections of the composite beams

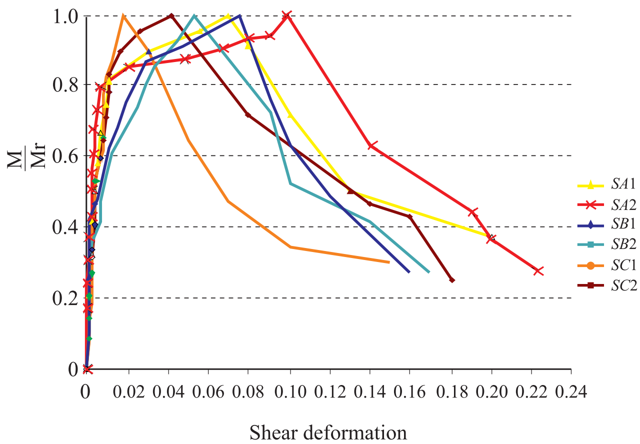

Fig. 9. Experimental shear deformation of the connections of composite beams

Six 2.0 m long composite beams were manufactured and tested (Fig. 6). The beams were grouped in three groups: *SA, SB, SC*. The type of the shear connectors between the concrete and the structural steel section varied in the individual groups. In the beams *SA* the shear connectors were made of a zigzag shape steel bar and situated at the middle of the top flange of the structural steel section along its full length. One side of the bar was welded to the structural steel section. The bar was Ø8 mm in diameter. The beams *SB* were provided with the vertical stud shear connector in diameter of Ø10 mm the end of which was welded to the structural steel section and spacing of connectors was 100 mm. The beams *SC* were provided with the vertical stud shear connector in diameter of Ø6 mm and with spacing of 200 mm. The stud shear connectors were manufactured of reinforcing steel of S240 class.

Manufactured specimens differ in the type and intensity of the shear connectors seeking to examine stiffness of the shear connection between the concrete and the structural steel section.

The beams were tested by two concentrated forces (Fig. 7). The load was increased in steps. Deflection of the beams was measured at the mid-span, also the slip of shear deformation was measured in the connection of the concrete layer and the steel section. The shear deformations were measured using electronic gauges of shear. Forces, deflections and shear deformations of the beam were recorded by the electronic gauges ALMEMO.

During the tests deflection and shear deformations of the beam was recorded at each load step. The graphs of deflections of the composite beams are shown in Fig. 8. Experimental investigations showed that deflections of the composite steel and concrete beams depend on the shear stiffness of the connection between the layers of concrete and steel. Stiffness of the connection is determined by the stiffness of the shear connectors provided between the layers.

Experimental investigation indicated that in behavior of the tested composite beams three stages in development of deflections is distinguished. The first stage is the stage of elastic behavior of the composite beam. Experimental investigations (Fig. 8) pointed out that the first stage reaches M ~ $0.60M_R$. The concrete layer in this stage acts jointly with the structural steel section. The slip in the contact between the concrete and the structural steel members was small and it is ignored.

It has no influence on the flexural stiffness of the composite steel and concrete beams. In this stage of behavior the growth of deflection was proportional with the load. It shows that composite beams are with full stiffness shear connection. The second stage of composite steel and concrete beam is stage of its elastic plastic behavior. It occurs when the bending moment exceeds $0.60M_R$ and continues up to $M \approx 0.85M_R$. During this stage of behavior the slip in the shear connection between the concrete and the steel of composite beams is demonstrated in Fig. 9. Experimental investigations showed that when the acting load exceeds $0.6M_R$ the shear deformations occur at the connection of the steel section and the concrete slab. It shows that the composite beams are with partial shear connection. Nevertheless, in this stage the shear connection of the composite beams is not destroyed, but in the concrete layer small cracks appear. The flexural stiffness of the composite beams decreases, deflections increase out of proportion (Fig. 8).

Comparison of Figs 8 and 9 shows that deflection of the flexural composite steel-concrete structures is influenced by the stiffness of steel and concrete connection.

The third stage begins when $M \approx (0.85–0.9)M_R$. It is the stage of failure of the composite steel and concrete beams (Fig. 8). At this stage of behavior of the composite beams the concrete layer and the structural steel section separate from each other. The concrete and the steel layers behave separately. Deflection of the beams increases continuously. Failure of the element commences. In the beams of *SA* group longitudinal crack in the reinforced concrete slab opened.

Analysis of results of experimental investigations showed that the beams of *SA* and *SB* groups were of the highest stiffness (their deflection was the smallest), while the shear stiffness of these beams was the highest. The shear connectors in the beams of *SA* group were made of a steel bar bent in the shape of a zigzag; the beams of *SB* group were provided with sufficiently closely spaced the stud shear connectors in diameter of Ø10mm. The lowest stiffness was of the beams which were provided with the shear connectors of the lowest stiffness (*SC*). This is noticed when analyzing the graphs of Fig. 9.

The experimental equivalent shear modulus ($G_{w,eff,exp}$), describing stiffness of the connection between the layers, was determined from the results of experimental investigations based on shear deformations of the connection and shear stresses acting at the connection. Experimental relationships between the shear deformations and the shear stresses of the experimental composite steel and concrete specimens are given in Figs 10–12.

The service load of the composite steel and concrete structures makes about 60% of the maximum load. This indicates that during the operation of structures at the connection of layers of the composite steel-concrete structures the shear deformations occur which influences the deflection of structures. Taking this into consideration and using the dependencies of shear deformations of the experimental composite steel and concrete beams presented in Figs 10–12 the experimental equivalent effective shear modulus of the steel and concrete connection $G_{w,eff,exp}$ was calculated. The equivalent effective shear modulus $G_{w,eff,exp}$ was determined under the acting load which made 0.6 and 0.7 of the maximum experimental load. Calculation results are given in Table 1.

In order to check suitability of methodology for the calculation of the equivalent effective shear modulus $G_{w,eff}$, suggested in this article, calculations of the experiment steel-concrete beams were carried out. Calculations were performed based on experimental deflections of steel-concrete beams under the certain load. Geometrical characteristics of the beams and mechanical characteristics of the materials were identified during the calculations.

The equivalent effective shear modulus $G_{w,eff}$ was calculated under the effect of external load equal to 0.6 and 0.7 from the maximum experimental load on beams.

Calculation results are given in Table 1.

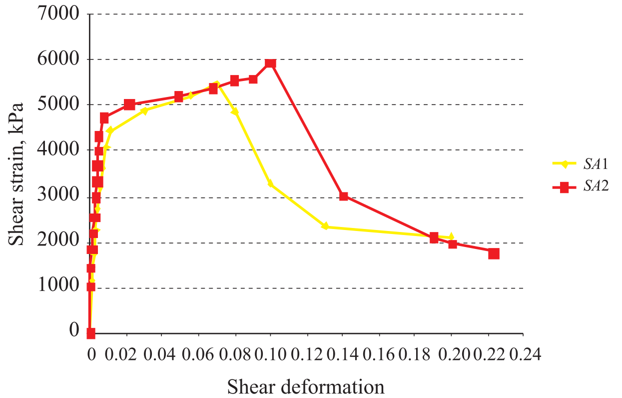

Fig. 10. Experimental results for *SA*1 and *SA*2 beams

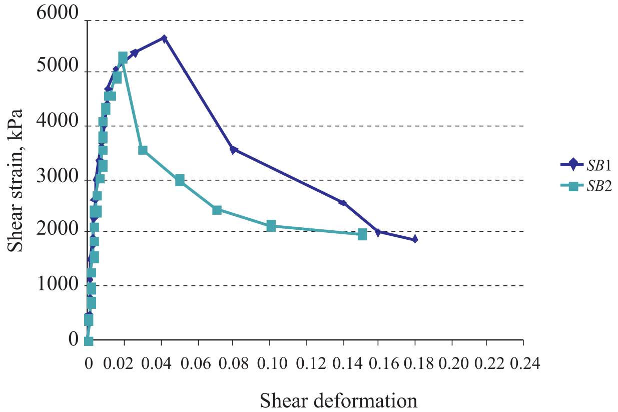

Fig. 11. Experimental results for *SB*1 and *SB*2 beams

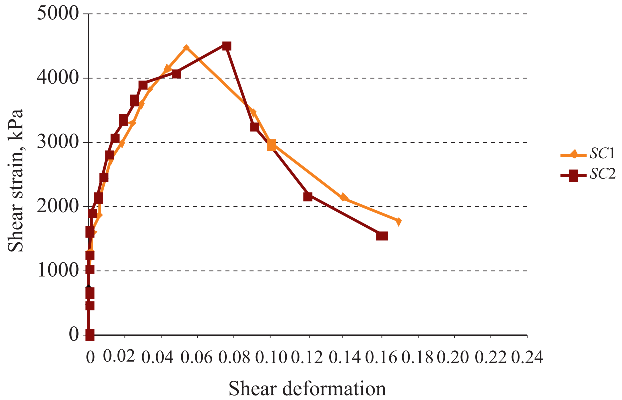

Fig. 12. Experimental results for *SC*1 end *SC*2 beams

Table 1. The experimental and the theoretical equivalent effective shear modulus of the steel and concrete connection

Beam No.	$\frac{M}{M_R}=0.6$					$\frac{M}{M_R}=0.7$				
	M, kNm	w, m	$G_{w,eff,\,exp}$, MN/m^2	$G_{w,eff,call}$, MN/m^2	$\frac{G_{w,\exp}}{G_{w,call}}$	M, kNm	w, m	$G_{w,eff,exp}$, MN/m^2	$G_{w,eff,call}$, MN/m^2	$\frac{G_{w,\exp}}{G_{w,call}}$
SA1	14.58	0.00535	587.9	603.8	0.974	17.01	0.00656	521.2	486.5	1.07
SA2	15.23	0.00482	1080.0	1080.0	1.00	17.77	0.00590	965.0	911.0	1.06
SB1	14.49	0.00524	672.6	621.0	1.08	16.90	0.00657	504.0	440.0	1.14
SB2	14.02	0.00526	501.8	542.0	0.924	16.36	0.00632	483.0	517.0	0.93
SC1	11.66	0.00519	216.7	201.0	1.07	13.61	0.00627	150.0	153.0	0.98
SC2	11.43	0.00483	276.0	270.0	1.02	13.33	0.00591	198.0	196.0	1.01

Comparison of the calculated equivalent effective shear modulus $G_{w,eff,cal}$ and the experimental equivalent effective shear modulus $G_{w,eff,exp}$ represented a rather good correspondence of results. The results of comparison given in Table 1 show that the calculated and the experimental equivalent effective shear modulus differs from 0 to 14%.

5. Conclusions and recommendations

The shear stiffness of the connection of steel and concrete layers in the composite steel and concrete bridge floors determines the total stiffness of the floor. Stiffness of the connection between the composite floor layers is suggested to be determined by the equivalent effective share modulus $G_{w,eff}$. The suggested theoretical model for the calculation of equivalent effective shear modulus $G_{w,eff}$ allows to rather accurately determine the shear stiffness of the steel-concrete connection. When using this model in a bridge design stage, taking into consideration the permissible deflection, it allows select the rational cross-section of the composite steel-concrete floor. Investigations show that the increase in the shear stiffness of the connection of layers enables to significantly reduce dimensions of the cross-section of the floor.

The implemented experimental and theoretical investigations as well as their comparison allows to state about the possibility of the suggested model to be applied for the design of the composite steel-concrete structures.

The suggested calculation methodology can be used to rather accurately determine the equivalent shear modulus of the steel-concrete connection showing the shear stiffness of this connection.

The suggested model for the determination of the equivalent effective shear modulus $G_{w,\,eff}$ assesses all the essential parameters and enables to calculate the slip between the layers. On the other hand, the model enables to guarantee the required stiffness value by changing various parameters and to select the desirable cost-effective alternative in order to increase stiffness of the connectors or of different layers.

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