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Modelling of Composite Steel and Concrete Beam with the Lightweight Concrete Slab

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***Abstract*—**Well-designed composite steel and concrete structures highlight the good material properties and lower the deficiencies of steel and concrete, in particular they make use of high tensile strength of steel and high stiffness of concrete. The most common composite steel and concrete structure is a simply supported beam, which concrete slab transferring the slab load to a beam is connected to the steel cross-section. The aim of this paper is to find the most adequate numerical model of a simply supported composite beam with the cross-sectional and material parameters based on the results of a processed parametric study and numerical analysis. The paper also evaluates the suitability of using compact concrete with the lightweight aggregates for composite steel and concrete beams. The most adequate numerical model will be used in the resent future to compare the results of laboratory tests.

***Keywords*—**Composite beams, high-performance concrete, high-strength steel, lightweight concrete slab, modeling.

I. Introduction

WITH the increasing requirements for the complex buildings construction, from the project design to the final solution of the building, the demands for applied materials are growing. In the recent years the materials development has been tending to the use of high-performance concrete and high-strength steel. In the field of structural concrete the emerging application of the light-weight concrete with light natural or artificial aggregates is appearing [8]. The behaviour of the composite steel and concrete structures is significantly affected by the choice of steel and concrete strength grade. Both of the materials have quite different material properties. The strength of steel varies between 200 and 800 MPa, the density is 7850kg/m^3. The compressive strength of normal concrete ranges between 20 and 100 MPa, whereas the tensile strength is almost zero. The density of normal concrete is about 2500kg/m^3. The compact concrete with light-weight aggregates can reach up to 80 MPa, whereas the density compared to the normal concrete may be up to half, which can be of considerable benefit mostly for multi-storey buildings or for reconstructions, where the further weight increase is undesirable [8]. It is obvious that using the materials of higher strength leads to increasing resistance of composite steel and concrete beams; on the other hand, it is necessary to consider the price of those materials.

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II. The Processed Parametric Study

A. The Aim of the Parametric Study

The paper is based on a processed parametric study (further PS) which summarizes the results of the numerical analyses of the composite steel and concrete beams with the slab composed of normal concrete (further composite beams with C) and the composite steel and concrete beams with the light-weight concrete slab (further composite beams with LC).

The aim of PS is to find a suitable cross-section for which the use of high-strength materials is effective and for which the resistance of the beams with LC is close to the resistance of the beams with C.

B. The Assumptions and Arrangements of the Parametric Study

In PS the plastic resistance $M_{pl,Rd}$ of the composite steel and concrete beams combined from steel of strength grades S235 - S500 and concrete of strength grades C25/30 - C90/105 and LC20/22 - LC80/88 is calculated according to [1].The light-weight concrete density class is D 1,6 according to [4]. The density of the light-weight concrete from this class is 1750kg/m^3.

To simplify and clarify PS the concrete deck of a constant depth d=100mm is chosen according to Fig. 1. The effective width is also of the constant value 2,0m, which is permitted for building constructions according to [1]. The variables therefore remain the height h of the steel cross-section IPE, strength of concrete and strength of steel. The full shear connection is considered to limit the longitudinal slip and to avoid the separation of the steel and concrete parts [1].

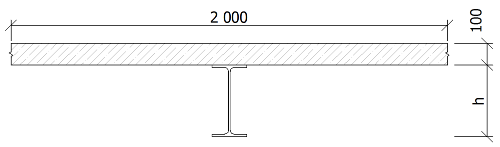

Fig. 1 Cross-section of a composite beam chosen for PS

C. The Results of the Parametric Study

The PS proves that the resistance of composite beams with C is increasing as expected with the increasing strength of concrete and steel as it can be seen in Figs. 2-7 and also with the increasing height of the IPE cross-section. Approximately from the beams with the cross-section IPE 360 it is possible to pursue cases, when the resistance is lower with the use of steel of higher strength grade than with the use of lower strength grade. In those cases the use of high-strength steel is not effective. For using high-strength materials the most suitable are the beams with cross-section IPE 300 and concrete up to the grade C50/60.

The characteristic compressive cylinder strength of concrete with light-weight aggregates f_{lck} is according to [4] of the same value as the characteristic compressive cylinder strength of normal concrete f_{ck}. The difference is in calculation of the design strength, where the coefficient α_{lcc}=0,85 is used for light-weight concrete and α_{cc}=1,0 for normal concrete. The lower design strength of light-weight concrete causes the displacement of the plastic neutral axis lower in the cross-section of composite beam, in some cases in the steel cross-section. On the one hand, this causes the apparent increasing of $M_{pl,\ Rd}$, due to higher influence of steel on the resistance of composite cross-section; on the other hand, the displacement into the steel part brings out more cases, when it is necessary reduce the resistance with the factor β as it can be seen in Figs. 5-7. The reducing can reach units or tens of percent [9].

The results of PS show that it is effective to use materials with higher strength for beams with IPE cross-sections up to 360 mm. However, it is appropriate to choose the combination of higher strength grade of steel and higher strength grade of concrete. Otherwise, when using lower strength grade of concrete, it is necessary to reduce the resistance of composite beams with the factor β. It is efficient to use the strength grades of concrete approximately up to LC50/55.

When it is not necessary to reduce the resistance of composite beams with LC by multiplying by the factor β, the difference between the resistances of composite beams with C and LC varies from 0,5% for cross-sections with lower IPE profiles to 8% for cross-sections with higher IPE profiles. When the reducing is necessary, the difference can reach up to 15%. The difference is increasing with using the higher strength grade of steel and with using higher IPE cross section. With the increasing strength of concrete, the difference is decreasing.

The resistance of composite beams with LC is in many cases almost identical to the resistance of beams with C. The cases when the reduction of the resistance with the factor β is necessary should be avoided, or better examine, if the reduction is necessary. Based on these results, the composite beam with steel cross-section IPE 300 and the span of 8,0m was chosen for the further analysis. The materials´ properties according to [2], [3] are in the Table I.

TABLE I
THE MATERIALS OF CROSS-SECTION

C40/50						
f_{ck} [MPa]	α_{cc}	γ_c	f_{cd} [MPa]	ρ [kN/m^3]	E_{cm} [GPa]	$E_{c,eff}$ [GPa]
40,0	1,0	1,5	26,67	25,0	35,0	17,5
LC40/44						
f_{lck} [MPa]	α_{lcc}	γ_c	f_{lcd} [MPa]	ρ_l [kN/m^3]	E_{lcm} [GPa]	$E_{lc,eff}$ [GPa]
40,0	0,85	1,5	22,67	17,5	22,0	11,0
S355						
f_y [MPa]	-	γ_a	f_{yd} [MPa]	ρ [kN/m^3]	E [GPa]	-
355,0	-	1,0	355,0	78,5	210,0	-

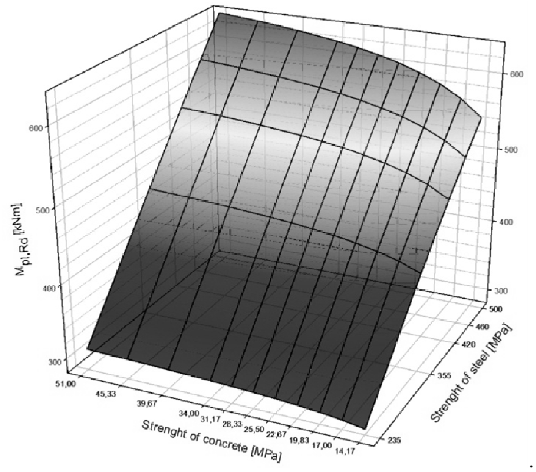

Fig. 2 The spatial relation between plastic resistance and strength of concrete and strength of steel for composite beams with C

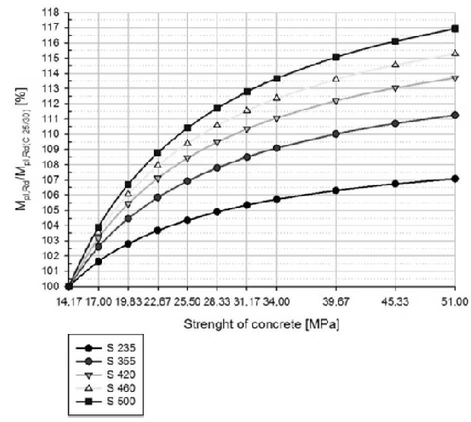

Fig. 3 The relation between the ratio of $M_{pl,Rd}/M_{pl,Rd(S235)}$ and strength of concrete for composite beams with C

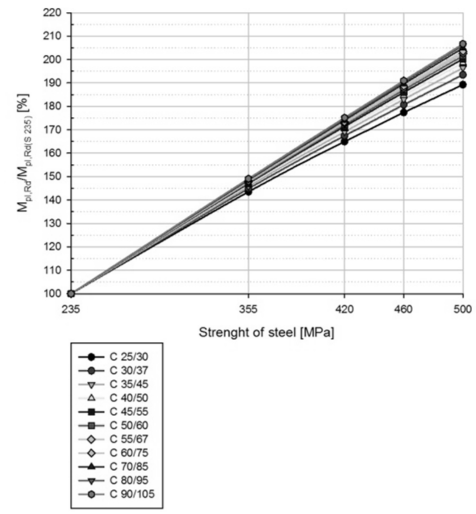

Fig. 4 The relation between the ratio of $M_{pl,Rd}/M_{pl,Rd(C25/30)}$ and strength of concrete for composite beams with C

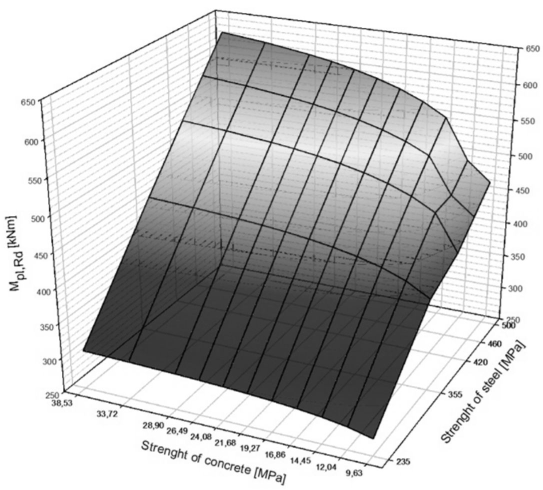

Fig. 5 The spatial relation between plastic resistance and strength of concrete and strength of steel for composite beams with LC

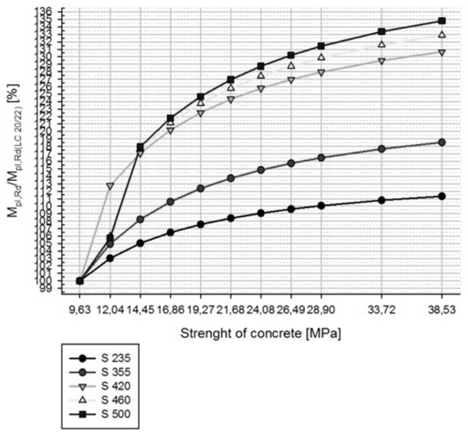

Fig. 6 The relation between the ratio of $M_{pl,Rd}/M_{pl,Rd(S235)}$ and strength of concrete for composite beams with LC

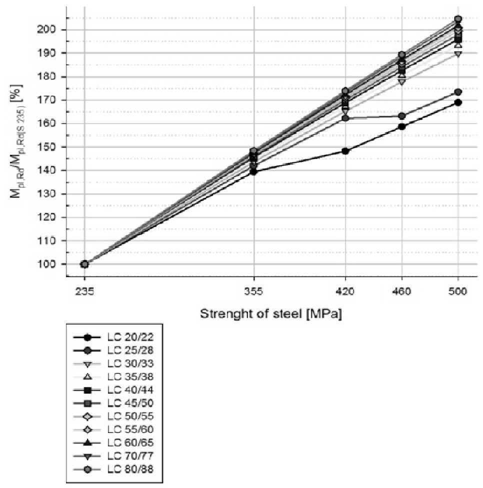

Fig. 7 The relation between the ratio of $M_{pl,Rd}/M_{pl,Rd(C25/30)}$ and strength of concrete for composite beams with LC

The light-weight concrete shows lower values of static elasticity modulus than common concrete, because the elasticity modulus of aggregate is one of the most important factors of elasticity modulus of concrete. In a view of the fact, that [4] does not give any requirements of the static elasticity modulus, the producers do not have an obligation to monitor and declare this property [7]. The mean value estimation of the secant modulus of elasticity of light-weight concrete E_{lcm} can be obtained from [3] by multiplying the value E_{cm} for normal concrete by coefficient η_E.

$$\eta = (\rho / 2000)^2 \qquad (1)$$

The influence of shear lag may be taken into account by using the effective width b_{eff} of the concrete deck. For simplification in structures for buildings, the effects of creep in composite beams may be taken into account by replacing concrete areas A_c by effective equivalent steel areas A_c/n for both short-term and long-term loading, where n is the nominal modular ratio corresponding to an effective modulus of elasticity for concrete $E_{c,eff}$ taken as $E_{cm}/2$ [6]. The influence of shrinkage of concrete is negligible for all beams with the ratio of the span to the overall height of the beam (steel cross-section + concrete deck) higher than 200 [5].

III. The Manual Calculation

For the calculation of cross-section characteristics it is necessary to replace the composite cross-section by using one material, in the case of this PS it would be steel, so the effective equivalent cross-section arises according to Fig. 8. The replacing is performed by using the coefficient n, which indicates the ratio corresponding to a modulus of elasticity for steel and effective modulus of elasticity for concrete.

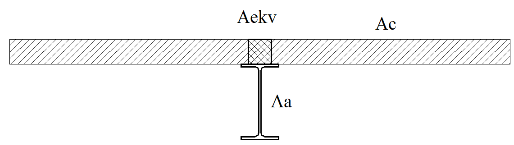

Fig. 8 The effective equivalent cross-section

When considering the imposed load of $5kN/m^2$ the values of stress and deformations on the beams with C and LC are as it can be seen in Table II.

TABLE II
THE VALUES OF STRESS AND DEFORMATIONS

Composite beam with C			Composite beam with LC		
σa [MPa]	σc [MPa]	δ [mm]	σa [MPa]	σc [MPa]	δ [mm]
142,85	-3,90	15,10	134,01	-2,93	15,12

IV. The Results of RFEM Calculation

The main aim of this paper is to find the most suitable numerical model corresponding to the real behaviour of composite steel and concrete beams. The most adequate model will be used to compare the results of future experiments.

The paper presents four numerical models made in FEM software RFEM of the Dlubal Software Ltd. Company. The

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supports are considered in the level of lower flange of IPE cross section. The imposed load $5kN/m^2$ is considered as deck load on the concrete slab.

A. Full Shear Connection Model with 3D Elements

The first numerical model is a simply supported steel beam with rigidly connected concrete slab. Both, beam and the slab, are modelled as spatial elements. The values of stress and deformation should correspond to those of manual calculation.

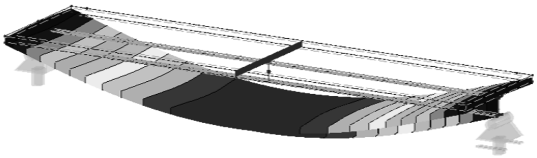

Fig. 9 The deformation of numerical model

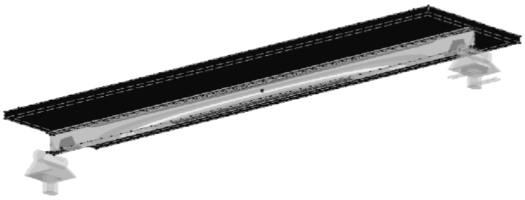

Fig. 10 The values of stress

B. Additional Module COMPOSITE-BEAM8

The Dlubal Software Ltd. Company provides additional module for designing composite steel and concrete structures. The module enables to model partial shear connection and also to calculate the influence of shrinkage of the concrete slab. However, there is no possibility to use the lightweight concrete yet and also to change the material properties.

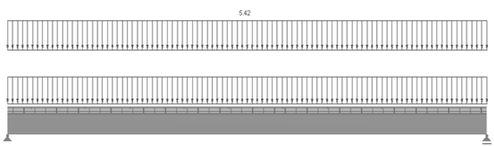

Fig. 11 Composite steel and concrete beam with C, permanent and imposed load

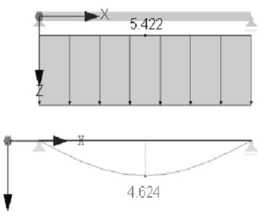

Fig. 12 The deformation caused by self-weight

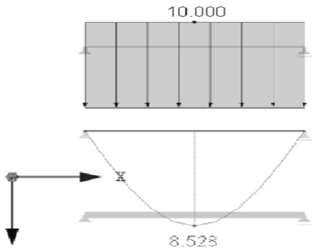

Fig. 13 The deformation caused by imposed load

In the following models, the main aim is to enable consideration of the partial shear connection.

C. The Contact Surfaces Enabling the Consideration of Partial Shear Connection

The third model consists of elements called as contact surfaces. These are surfaces of required thickness. There is a possibility to specify the type of shear connection between steel and concrete part. However, the steel beam modelled by using the contact surfaces does not consider the influence of the curved part of IPE cross-section, so the values of deformation are larger than those calculated manually.

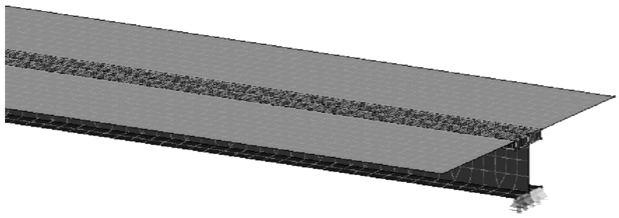

Fig. 14 Numerical model using contact surfaces

D. Steel 3D Element and Concrete Contact Surface Enabling the Consideration of Partial Shear Connection

The last model has the advantages of all the previous numerical models. It is supposed to be the most realistic model describing the behaviour of composite beams.

The steel beam is modelled as 3D element with the dimensions of IPE300 cross-section. The concrete slab is modelled as a contact surface, so there is a possibility to specify the shear connection between the steel and concrete part.

V. Conclusion

TABLE III
THE VALUES OF DEFORMATIONS CALCULATED MANUALLY AND USING NUMERICAL MODELS A-D

	Ec [GPa]	$\delta_{selfweight}$ [mm]	$\delta_{imposed}$ [mm]	δ_{total} [mm]
Manual calculation	35,0	4,65	8,58	13,23
	17,5	**5,31**	**9,79**	**15,10**
	22,0	3,67	9,35	13,02
	11,0	**4,26**	**10,86**	**15,12**
Model A	35,0	4,67	8,60	13,26
	17,5	5,27	9,71	14,98
	22,0	3,73	9,49	13,22
	11,0	4,24	10,79	15,03
Model B	35,0	4,62	8,53	13,15
	17,5	-	-	-
	22,0	-	-	-
	11,0	-	-	-
Model C	35,0	4,19	10,73	14,91
	17,5	4,51	11,39	15,90
	22,0	4,82	12,35	17,17
	11,0	5,09	12,86	17,96
Model D	35,0	4,81	8,88	13,69
	17,5	**5,38**	**9,91**	**15,29**
	22,0	3,81	9,72	13,52
	11,0	**4,31**	**10,98**	**15,30**

In the Table III there are the values of deformations calculated manually and using numerical models A-D. The results obtained by using model A and D are almost identical (the difference between manual calculation and model A is less than 1% and between manual calculation and model D is about 1,01%). the difference between the two models is whether it is necessary to consider the partial shear connection or longitudinal slip or not.

For the future research, it is recommended to test the shear connectors in the standard push test according to [1]. The results from push test can be implemented in the numerical model D and this may be compared with the result of bending test.

In the Table IV there are the values of stresses calculated manually and by relevant numerical models.

TABLE IV
THE VALUES OF STRESSES CALCULATED MANUALLY AND USING NUMERICAL MODELS A AND D

	C			LC		
	σa [MPa]	σc [MPa]	δ [mm]	σa [MPa]	σc [MPa]	δ [mm]
Manual calc.	206,75	-5,65	15,10	195,35	-4,27	15,12
Model A	205,48	-5,365	14,98	195,96	-4,237	15,03
Model D	209,74	-6,049	15,29	198,75	-4,767	15,3

Acknowledgment

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