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Theoretical research of dimensional optimization and choice of material strength in steel-concrete composite beams

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Abstract. The aim of this study is to find out how the change of individual parameters will affect the flexural strength of steel-concrete composite beams. The project was focused on the choice of strength of materials and the choice of dimension, specifically the height of the concrete slab and the size of the steel profile. The research aim is to reveal which parameters have dominant influence on the flexural strength and thus facilitate the optimization of the design in practice.

1. Introduction

Steel-concrete composite structures are becoming increasingly popular in the construction industry almost all over the world. Their use is mainly applied to the solution of multi-storey buildings. The composite structures use favourable properties of both materials - steel and concrete, which give us very good strength properties. Concrete has a high compressive strength, therefore it transmits the compressive load and conversely steel has a high tensile strength, thus it transmits the tensile load. Thanks to the combination of both materials an economical and effective cross-section is found. There are many of different combinations of material strengths and dimensions of the individual components. For this reason, our research is focused on the theoretical optimization and the choice of material according to its strength and dimensions of individual parts of composite beams.

The main aim of this research is to find out how the change of individual parameters will affect the flexural strength of steel-concrete composite beams. Specifically, we observe the changes in compressive strength of concrete, the height of concrete slab, yield strength of steel IPE profile and change of size of IPE profile (its area and height). From the relation for plastic calculation of flexural strength, a general mathematic relationship was formulated. This relationship shows the change of flexural strength with regards to the original value, when the values of any of the input parameters are changed. This relationship was further verified using a calculations processor and then a parametric study comparing the obtained flexural strength was performed. All calculations were performed with respect to Eurocodes [1], [2], [3].

2. Present state

Steel-concrete composite structures are designed according to the valid Eurocode 4. This standard considered the use only strength of concrete from C20/25 to C50/60 and steel up to strength class S420. Therefore, nowadays a large part of researchers focus on the use of higher strength materials and their use in practice, e. g. [4]. Another large part of research on composite steel-concrete beams is concentrated on the development and testing of new coupling elements, such as various types of perforated shear connectors or slip-released connectors.

V. Peetha, V. Senthikumar, K. Kalaviani and S. Navaneetha from the Department of Civil Engineering of the Bannari Amann Institute of Technology in Sathyamangalm in India performed a research comparing deformation and stress in composite beams [5]. They compared the stresses and deformations on a T-beam formed by a concrete slab of thickness 80, 100 and 120 mm and three different steel profiles ISMB 150, ISMB 200 and ISMB 250 (ISMB = Indian Standard Medium Beam). The beam was considered as simply supported with stable length of 1500 mm and a slab width 500 mm. The results were obtained using computation software, specifically modelling using the finite elements method in program ANSYS. Their research dealt only with the optimization of the dimensions of partial parts beam and did not include the influence of different strength of concrete or steel used.

The aim of this research is to extend the previously mentioned calculations by considering the changes in the strength of both used materials (steel and concrete), and to find out which parameter has a dominant effect on flexural strength of the composite beam.

3. Methods

The assumption of maintaining the flatness of the cross-section and the validity of the working diagrams apply when calculating the flexural strength of steel-concrete composite beams in the plastic area. The plastic neutral axis is located in most cases in concrete and the following calculations have been performed for this variant.

Consider a composite beam which is created by effective coupling of a concrete slab of width b_{eff}, height h_c and characteristic compressive strength f_{ck} and a steel profile of the IPE series of cross-section A_a, height h_a which is made of steel with a nominal yield strength f_y. A load that causes a simple bend will be considered on the upper surface of the concrete slab. Using the idealization of the stress course, we are able to draw a stress on beam for steel profile and concrete in compression (Figure 1). The force N_a acts on steel IPE profile in its center of gravity. An equally large oppositely oriented force N_c acts on concrete in the center of gravity of the pressed part of the concrete.

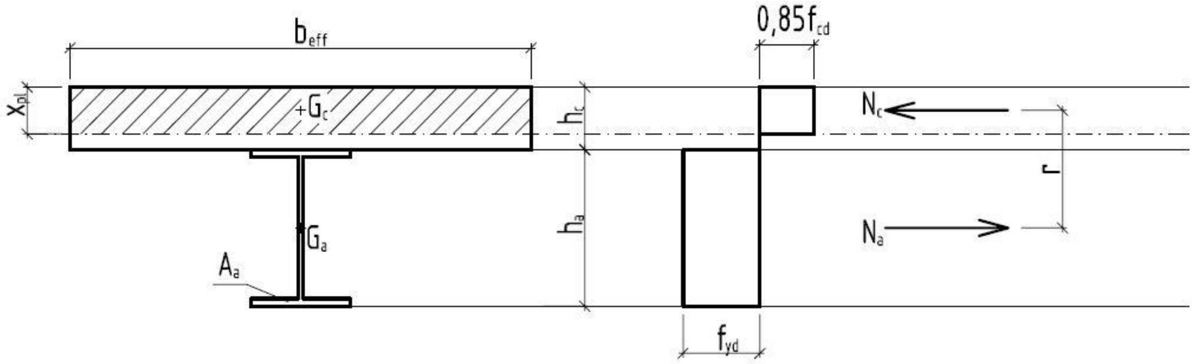

Figure 1. Stress acting on the composite beam as the plastic axis is located in the concrete.

The value of the force N_a acting on the IPE profile is calculated according to the relation:

$$N_a = f_{\mathrm{yd}} \cdot A_a \tag{1}$$

where A_a is the total area of the steel cross-section and f_{yd} is the yield strength of the steel used.

The value of the force N_c acting on the press part of the concrete slab is obtained from the relation:

$$N_c = 0.85 \cdot f_{\mathrm{cd}} \cdot x_{\mathrm{pl}} \cdot b_{\mathrm{eff}} \tag{2}$$

where f_{cd} is the design compressive strength of the concrete used, b_{eff} is the effective width of concrete slab and x_{pl} is the position of the neutral axis from the upper surface of concrete slab.

From the equality of the two forces N_a and N_c the position of the neutral axis can be calculated

$$x_{\mathrm{pl}} = \frac{f_{\mathrm{yd}} \cdot A_a}{0.85 \cdot f_{\mathrm{cd}} \cdot b_{\mathrm{eff}}} \tag{3}$$

The total load-bearing capacity of a steel-concrete composite beam can be calculated from the relation

$$M_{\mathrm{pl,Rd}} = N_a \cdot r \tag{4}$$

where N_a is the force acting on the steel profile and r denotes the arm between the force N_a and N_c, is the distance of the center of gravity of the IPE profile and the center of gravity of the pressed part of the concrete.

The size of the arm r can be calculated as

$$r = h_c + \frac{h_a}{2} - \frac{x_{\mathrm{pl}}}{2} \tag{5}$$

where h_c is the height of the concrete slab, h_a is the height of the IPE profile and x_{pl} is the distance of the neutral axis from the upper surface of the concrete slab.

If we substitute equation (3) into equation (5) and also equation (1) into equation (4) we obtain the relation for the calculation of the flexural strength of the composite beam

$$M_{\mathrm{pl,Rd}} = A_a \cdot f_{\mathrm{yd}} \cdot \left(h_c + \frac{h_a}{2} - \frac{A_a \cdot f_{\mathrm{yd}}}{2 \cdot 0.85 \cdot b_{\mathrm{eff}} \cdot f_{\mathrm{cd}}} \right) \tag{6}$$

Equation (6) served as the default for deriving relations for the new flexural strength $M_{pl,Rd,N}$, expressed as the sum of the original flexural strength and the increment caused by the percentage increase of one of the four examined parameters.

When the height of the concrete slab h_c changes, we get relation for the new flexural strength after the modification by the derivation

$$M_{\mathrm{pl,Rd},N} = M_{\mathrm{pl,Rd}} + (x-1) \cdot A_a \cdot f_{\mathrm{yd}} \cdot h_c \tag{7}$$

where parameter $x = h_{c,N} / h_c$, where $h_{c,N}$ is the new height of the concrete slab.

When the characteristic compressive strength of the concrete f_{ck} changes, we obtain a relationship for the new flexural strength after modifications

$$M_{\mathrm{pl,Rd},N} = M_{\mathrm{pl,Rd}} - \left(\frac{1}{x} - 1 \right) \cdot \frac{A_a^2 \cdot f_{\mathrm{yd}}^2}{2 \cdot 0.85 \cdot b_{\mathrm{eff}} \cdot f_{\mathrm{cd}}} \tag{8}$$

where the parameter $x = f_{ck,N} / f_{ck}$, where $f_{ck,N}$ is the characteristic compressive strength of the newly used concrete.

When the yield strength f_y of steel profile changes, we get the relationship for new flexural strength

$$M_{\mathrm{pl,Rd},N} = M_{\mathrm{pl,Rd}} + (x-1) \cdot A_a \cdot f_{\mathrm{yd}} \cdot h_c + (x-1) \cdot A_a \cdot f_{\mathrm{yd}} \cdot \frac{h_a}{2} - (x^2-1) \cdot \frac{A_a^2 \cdot f_{\mathrm{yd}}^2}{2 \cdot 0.85 \cdot b_{\mathrm{eff}} \cdot f_{\mathrm{cd}}} \tag{9}$$

where $x = f_{yd,N} / f_{y,d}$, where $f_{yd,N}$ is the yield strength of the newly used steel.

When the steel profile of the IPE type is changed, both the total cross-section area A_a and the height of the profile h_a will change. We derive the relationship for the new flexural strength

$$\begin{aligned} M_{\mathrm{pl,Rd},N} = {} & M_{\mathrm{pl,Rd}} + (x-1) \cdot A_a \cdot f_{\mathrm{yd}} \cdot h_c + (x-1) \cdot A_a \cdot f_{\mathrm{yd}} \cdot \frac{h_a}{2} - (x^2-1) \cdot \frac{A_a^2 \cdot f_{\mathrm{yd}}^2}{2 \cdot 0.85 \cdot b_{\mathrm{eff}} \cdot f_{\mathrm{cd}}} \\ & + (x-1) \cdot (y-1) \cdot A_a \cdot f_{\mathrm{yd}} \cdot \frac{h_a}{2} + (y-1) \cdot A_a \cdot f_{\mathrm{yd}} \cdot \frac{h_a}{2} \end{aligned} \tag{10}$$

where parameter $x = A_{a,N} / A_a$ and parameter $y = h_{a,N} / h_a$, where $A_{a,N}$ is cross-section area of new IPE profile and h_a is its height.

These derived equations were further verified using a spreadsheet program on specific cases.

4. Results

A simply supported steel-concrete composite beam with the length of 8 m was chosen as a basic pattern for the parametric study. The cross-section consisted of a concrete slab with an effective width b_{eff} = 2000 mm and height h_c = 80 mm made of concrete C20/25 and an IPE 200 made of steel S235.

Changing the IPE profile will cause a change of both the cross-section area of steel profile and its height and thus the position of center of gravity of the profile. Therefore, it was necessary to find the dependence between these two parameters *x* and *y*, so that the flexural strength can still be compared depending on only one parameter *x*, which expresses the proportional increase of one of the four monitored quantities. The dependence of the cross-section area on the section height was monitored on specific profiles of the IPE series from size 200 to size 360 mm. Their values were plotted on the graph shown in Figure 2 and approximated using the trend line so that we obtained the equation $y = - 1.106x^5 + 8.968x^4 -28.77x^3 + 45.26x^2 - 34.32x + 10.93$, which determines the approximate dependence between parameters *x* and *y*.

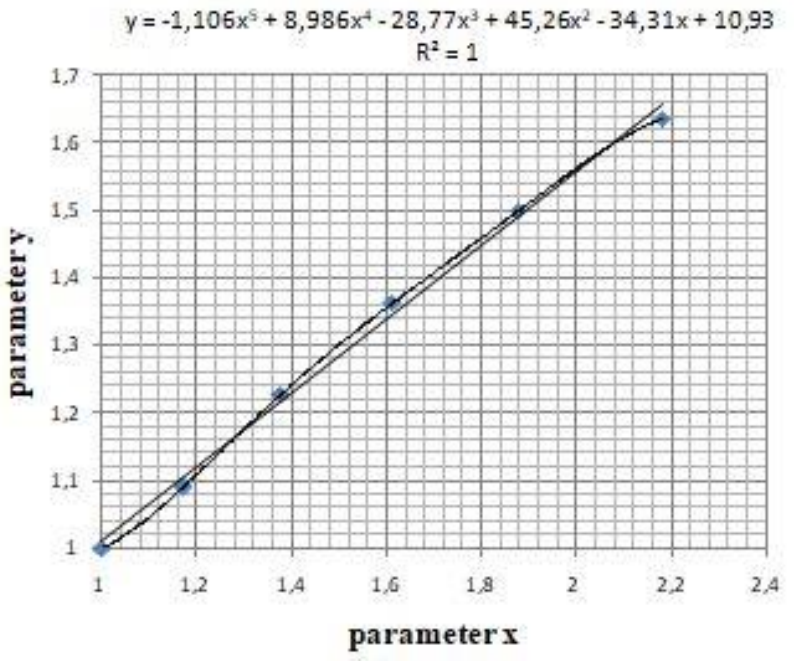

Figure 2. Interdependence of the change in the ration of cross-section area (parameter *x*) and height (parameter *y*) of the IPE profile.

Using a spreadsheet program, a parametric study was performed, in which the parameter *x* was inserted into the relationship (7), (8), (9) and (10), so that it monitored the development of the flexural strength with a growth of the monitored quantities by tens of percents from the value of the basic beam to doubling the parameter. The values of flexural strength were calculated in MPa and it was also determined by how many percent the flexural strength is higher compared with the basic steel-composite beam.

Table. 1 The value of flexural strength in MPa depending on the increase of the parameter *x* indicating the ration of new value of the monitored quantities to the original value.

x	$M_{pl,Rd,N}$ **for change** h_c	$M_{pl,Rd,N}$ **for change** f_{ck}	$M_{pl,Rd,N}$ **for change** f_y	$M_{pl,Rd,N}$ **for change IPE**
1.0	135.432	135.432	135.432	135.432
1.1	141.705	136.665	147.483	150.890
1.2	147.979	137.693	159.262	169.523
1.3	154.252	138.562	170.770	189.512
1.4	160.526	139.308	182.008	210.147
1.5	166.800	139.953	193.974	231.039
1.6	173.073	140.519	203.668	252.123
1.7	179.347	141.017	214.091	273.591

1.8	185.620	141.461	224.243	295.756
1.9	191.894	141.857	234.124	318.853
2.0	198.167	142.214	243.733	342.761

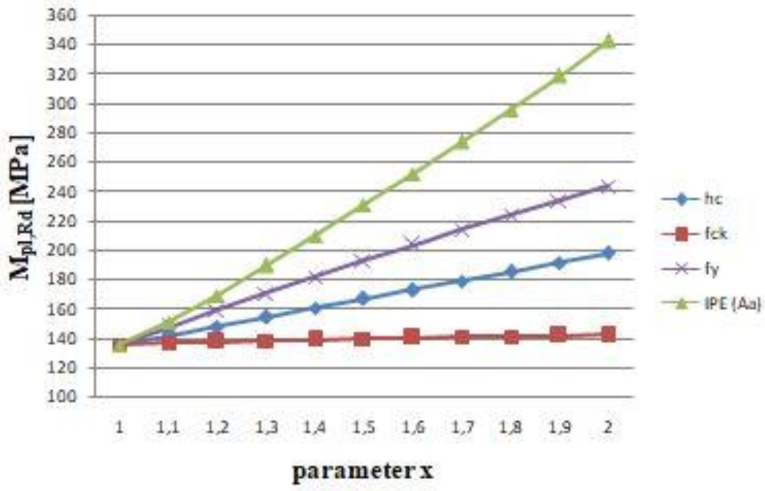

Figure 3. Graph of flexural strength depending on the parameter *x*.

Table. 2 Percentage increase of the flexural strength compared to the basic beam depending on the increase of parameter *x*, indicating the ratio of the new value of the monitored quantities to the original value.

x	$M_{pl,Rd,N}$ **for change** h_c	$M_{pl,Rd,N}$ **for change** f_{ck}	$M_{pl,Rd,N}$ **for change** f_y	$M_{pl,Rd,N}$ **for change IPE**
1.0	0.00	0.00	0.00	0.00
1.1	4.63	0.91	8.89	11.41
1.2	9.26	1.67	17.60	25.17
1.3	13.90	2.31	26.09	39.93
1.4	18.53	2.86	34.39	55.17
1.5	23.16	3.34	42.49	70.59
1.6	27.79	3.76	50.38	86.16
1.7	32.43	4.12	58.08	102.01
1.8	37.06	4.45	65.58	118.38
1.9	41.69	4.74	72.87	135.43
2.0	46.32	5.09	79.97	153.088

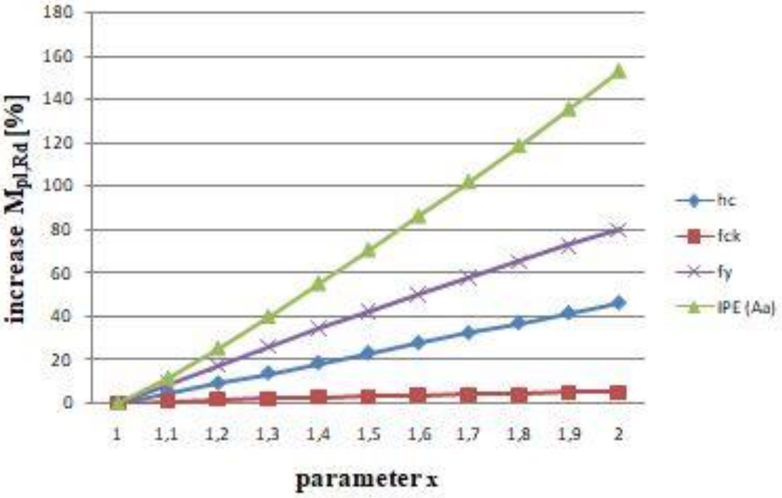

Figure 4. Graph showing how many percent the flexural strength increase depending on the parameter *x*.

5. Discussion

From equations (7), (8), (9) and (10) it is clear which members of the calculation affect the change of some of the observed quantities. E.g. by comparing relation (7) for changing the height of concrete slab and relation (9) for changing the strength of steel, it is clear that changing of the yield strength will increase the value of the original flexural strength more than changing the dimension of the slab. From the equations, we are able to find out that the dominant influence for the calculation has a change in the steel profile, where there is a change in the cross-section area and its height and thus the position of the center of gravity. On the contrary, the smallest effect is caused by the change of the compressive strength of concrete, where the parameter *x* appears in equation (8) in the denominator of the fraction and thus there is only a very gradual increase in flexural strength.

The values presented in table 1 and shown in the graph in Figure 3 show the effect of increasing the monitored variables by tens percent from the basic pattern. While a change in the compressive strength of concrete will cause only a negligible increase in flexural strength, by changing the height of the concrete slab we will achieve a significant improvement. The second best evaluated parameter was the change in steel strength and the largest increase is attained by changing the IPE steel profile.

From the values presented in table 2 and shown in the graph in figure 4, it can be seen by how many percent the flexural strength increases compared to the base pattern. When using higher strength concrete, we are talking about an increase in units of percent. When the thickness of concrete slab or the IPE profile material changes, the flexural strength increases by tens of percent. The change in steel causing almost double increase compared to the change in the dimension of the concrete slab and with increasing value of the parameter *x* this difference gradually decreases. And when changing the steel profile, we can achieve double flexural strength even with a 70% increase in cross-section area. The choice of a larger cross-section has the greatest influence on the flexural strength and increases with increasing parameter *x*.

6. Conclusion

The results of the study proofed that the dominant influence on the flexural strength has a steel profile, which forms the composite beam. The primary influence is the size of the selected profile and the secondary choice of the strength class of the steel. On the other hand, the height of the concrete slab has a significantly smallest effect on the flexural strength and compressive strength on concrete, almost negligible. This research focused only on flexural strength and was not considered in combination with other types of strain. Equally, the serviceability limit state was not taken into account, where a change in the dimension of either the concrete slab or the steel profile will cause an increase in the clear dimension of the beam, an increase in its weight and the rigidity of the beam.

7. References

[1] ČSN EN 1994-1-1 2006 Eurocode 4: Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings, Praha, Český normalizační institute

[2] ČSN EN 1992-1-1 2006 Eurocode 2: Design of concrete structures – Part 1-1: General rules and rules for buildings, Praha, Český normalizační institute,

[3] ČSN EN 1993-1-1 2006 Eurocode 3: Design of steel structures – Part 1-1: General rules and rules for buildings, Praha, Český normalizační institute

[4] Uy B 2018 Applications behaviour and construction of high performance steel in steel-concrete composite structures *12th Int. Conf. on Advances in Steel-Concrete Composite Strucrtures (Valencia)*

[5] Preetha V, Senthilkumar V, Kalaivani K and Navaneetha S 2019 Děformation Studies on Steel-Concrete Composite T Beam Section *Int. Conf. on Materials, Manufacturing and Machining (Tamilnadu)* vol 2128, ed A. Megalingam, M. Kumar and R. Shanmuga Prakash (College Park: AIP Conference Proceedings)

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