ANALYSIS OF COMPOSITE STEEL – REINFORCED CONCRETE (SRC) COLUMNS

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Abstract

A composite SRC column is defined as a composite member with components of concrete and structural steel. Composite SRC columns are a very important application and widespread use of them is found, particularly in high-rise buildings. The paper presents some results of theoretical and experimental analyses of steel-reinforced concrete composite columns. There is a wide variety of types of columns with various types of cross-sections. We are concerned with composite SRC columns, which are completely or partially concrete-encased steel columns. The main topic is a theoretical analysis of the design method according to EN 1994-1-1 and experimental investigations.

A partially encased steel-reinforced concrete cross-section was selected for short-term laboratory tests of composite steel-reinforced concrete columns. A total of 12 columns were tested in two series. In the first series 6 columns with a length of 3 m and with eccentricities of normal compression forces of 30 and 80 mm were tested. The second series contained 6 columns with lengths of 4 m and with eccentricities of 40 and 60 mm. The evaluation of the test results is also shown in comparison with the design method according to EN 1994-1-1.

Streszczenie

Kompozytowy słup SRC jest elementem zespolonym, wykonanym z betonu i stali konstrukcyjnej. Słupy kompozytowe SRC mają bardzo ważne i szerokie zastosowanie, szczególnie w przypadku budynków wysokich. Artykuł prezentuje prace teoretyczne i eksperymentalne przeprowadzone na żelbetowych słupach kompozytowych. Istnieje szeroka gama słupów o różnych typach przekrojów. W artykule przeanalizowano słupy kompozytowe SRC będące słupami stalowymi całkowicie lub częściowo pokrytymi betonem. Głównym tematem jest teoretyczna analiza metody projektowej zawartej w normie EN 1994-1-1 oraz badania doświadczalne.

W celu przeprowadzenia krótkotrwałych badań laboratoryjnych żelbetowych słupów kompozytowych wybrano częściowo zamknięty żelbetowy przekrój. Łącznie w dwóch seriach zbadano 12 słupów. W pierwszej serii zbadano 6 słupów o wysokości 3 m i sile ściskającej przyłożonej na mimośrodzie równym 30 i 80 mm. Druga seria obejmowała 6 słupów o wysokości 4 m i mimośrodach równych 40 i 60 mm. Ocena wyników badań została przedstawiona w odniesieniu do metody projektowej zawartej w normie EN 1994-1-1.

Keywords: **Column; Steel; concrete; Reinforced concrete; Composite.**

1. INTRODUCTION

Composite steel-reinforced concrete (SRC) columns are a very important application of composite structures, and widespread use of them is found, particularly in high-rise buildings. A composite SRC column is defined as a composite member with components of concrete (better reinforced concrete) and structural steel. These two components act together to resist external forces. A composite column is a composite member, which is mainly subjected to compression or to compression and bending.

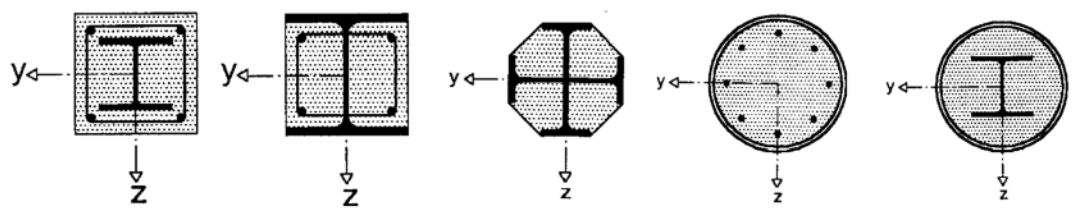


Figure 1.
Types of cross-sections of SRC columns

There is a wide variety of types of columns with various types of cross-sections. The most commonly used and studied are the two main types of typical cross-sections of composite columns:

- completely or partially concrete-encased steel sections,
- concrete-filled rectangular and circular steel tubes.

Problems in the design of composite steel-reinforced concrete constructions are quite actual today. The research work was therefore directed at an analysis of the design of composite steel-reinforced concrete columns. It was based on contemporary European codes, which use the latest knowledge gained from science and investigations.

The problems in the design of composite steel-reinforced concrete columns were divided into two main sections:

- analyses of simplified and general methods and their differences,
- the resistance of composite steel-reinforced concrete columns loaded by a normal compressive force and bending moment.

2. ANALYSIS OF SIMPLIFIED AND GENERAL METHODS AND THEIR DIFFERENCES

Now we are concerned with the resistance of composite SRC columns to combined compression and bending. There are a number of design proposals that can be used to establish the load-moment strength interaction relationship. Among these are the proposals of Wakabayashi, the SSLC method, the Roik-Bergmann method, the EC4 method and others.

The Wakabayashi method:

This method [15] provides the simplest equations for the ultimate strength of the failure envelope. For this, the strengths of the concrete and steel elements are found independently and are then superimposed.

The American Structural Specifications Liaison Committee method (SSLC):

A simplified force-moment strength interaction function has been recommended [16].

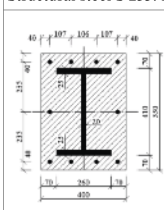
The Roik and Bergmann method:

The solution [5] can only be applied to a cross-section that is doubly symmetrical, which is often the case in practice. The interaction curve is replaced by the A(E)CDB polygon.

The Eurocode method:

Here, the preference was given to the method developed by Roik, Bergmann and others at the University of Bochum, Germany. It has a wider scope, is based on a clearer conceptual model and is slightly simpler [4] . Two design methods are provided:

Concrete C20/25: f_{ck} = 20MPa, E_{cm} = 30MPa, γ_c = 1.5
Reinforcement 10 425(R): f_{sk} = 410 MPa, E_s = 210000 MPa, γ_s = 1.15
Structural steel S 235: f_{yk} =235 MPa, E_y = 210000 MPa, γ_y = 1.15



Method of calculation		Plastic interaction curve	Roik-Bergmann (EN 1994-1-1)	SSLC	Wakabayashi's method
Point	N [kN]	M [kNm]			
B	0	972.6	972.6	824.8	854.4
C	1115	1004	1004	806,5	1007
D	2229	972.6	972.6	751.5	854.4
A	7477	0	0	0	0

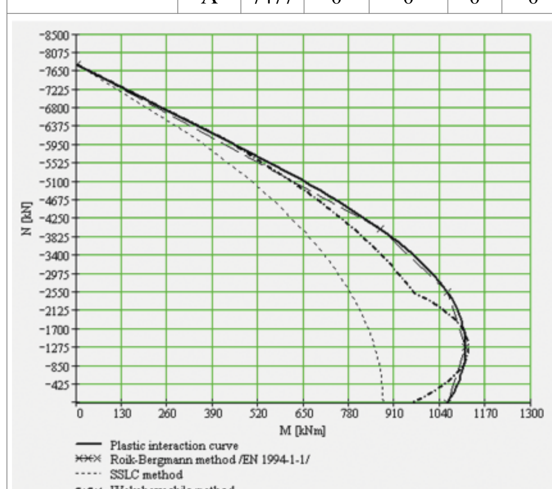
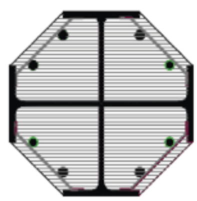


Figure 2.
Differences in the simplified method

Table 1.
The properties of an example of a partially concrete-encased section in the shape of an octagon

		**Group**	1	2	3	4
		Concrete	C50/60	C40/50	C30/37	C20/25
		Steel	S450	S355	S275	S235
		Reinforcement	10 505	10 505	10 505	10 505
		b/h [mm]	500/300	300/500	400/400	600/600
		μ_{st} [%]	0.42	1.16	2.49	3.21
Example in group	**1**	**$\delta=(A_a \cdot f_{yd})/N_{plRd}$**	0.25	0.23	0.26	0.25
	2		0.34	0.32	0.37	0.46
	3		0.51	0.49	0.54	0.61
	4		0.72	0.70	0.71	0.73
	5		0.86	0.84	0.85	0.82

a general method, whose scope includes members with non-symmetrical or non-uniform cross-sections over the column's length and

a simplified method for members of a doubly symmetrical and uniform cross-section over the member's length.

Through analysis in accordance with the simplified methods, we particularly focused on finding a simplified solution for determining point B in a polygonal interaction curve according to code EN 1994-1-1. This problem was solved by substituting the polygonal interaction curve with a sinusoid. The two basic points A $[0;N_{pl,Rd}]$ and D $[M_{max,Rd};0,5N_{pm,Rd}]$ were used for determination of the formula of the sinusoid (Fig. 3). Fig. 2 includes the interaction functions determined for the cross-section of a SRC column with a completely concrete-encased I steel section for the calculation methods presented.

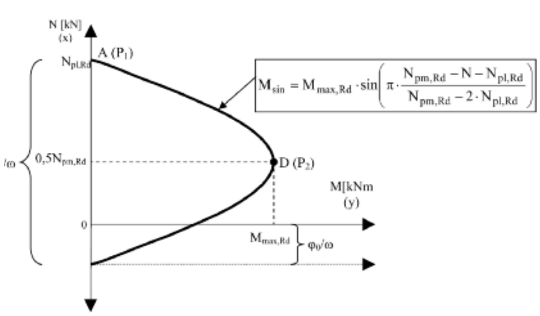


Figure 3.
The sinusoidal interaction diagram

The effect of the necessity and suitability of using point E in the polygonal interaction curve for the basic types of cross-sections, which are described in code EN 1994-1-1, was also analyzed. Then we derived the approximate relations for determining the position of point E by using a linear regression (Fig. 4).

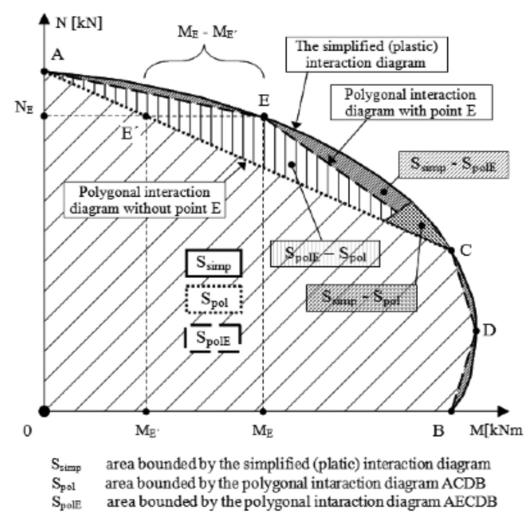


Figure 4.
The interaction diagrams and their parameters for the analysis of point E

Through analysis of the simplified methods and general method of Eurocode 4, a program in MathCAD, which permits checking a composite SRC column with an arbitrary cross-section which is symmetrical according to the vertical axis, was created. The program allows the use of an interaction curve (plastic, elastic-plastic, polygonal, sinusoidal) with or without a second-order effect. The program was used to calculate and compare 150 examples of the basic types of composite SRC cross-sections, which are defined in code EN 1994-1-1.

Table 1 presents the properties of an example of partially concrete-encased sections of SRC columns for which the sinusoidal and polygonal interaction diagram is shown in Fig. 5. Conclusions and conditions were deducted for these cross-sections, for which it is possible to substitute a polygonal interaction curve with a sinusoid and for which cross-sections it is necessary to use point E in the polygonal interaction curve.

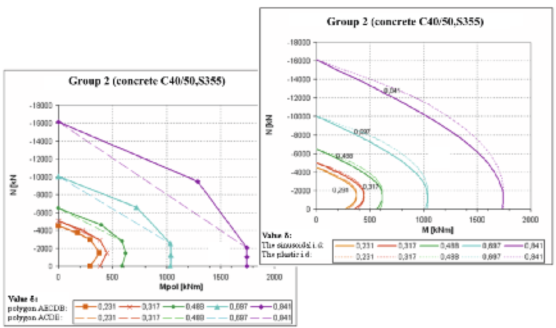


Figure 5.
Sinusoidal and polygonal interaction diagram

3. RESISTANCE OF COMPOSITE STEEL-REINFORCED CONCRETE COLUMNS LOADED BY NORMAL COMPRESSIVE FORCE AND BENDING MOMENT

In order to verify the methodology of determining the resistance of the cross-section and take into account a second order theory, the experimental investigation was created. The objective of this investigation was:

- to verify the theoretical background of the design and check the composite steel-reinforced concrete columns according to EN 1994-1-1
- to analyze the effect of the second-order theory and to generate an interaction curve with the effect of slenderness
- to compare the simplified and general methods according to EN 1994-1-1 and verify the program in MathCAD.

In the EN 1994-1-1 code the second-order effects may be allowed for by using the factor k. We used the following relations for this experimental verification.

$$\left.\begin{aligned} M &= M^{I} + M^{II} \\ M &= k \cdot M^{I} \end{aligned}\right\} \quad k = M/(M - M^{II}), \qquad (1)$$

where

M is the failure bending moment ,

M^{I} is the primary bending moment,

M^{II} is the increment of the bending moment through the effect of the second-order theory.

The value M^{II}, which presents increments of the bending moment according to the effect of the second order theory, may be calculated for constituent steps of the load according to the following relation:

$$M_n^{II} = N_n \cdot \sum_{i=1}^{n} \Delta w_i = \left(N_1 + \sum_{i=1}^{n-1} \Delta N_i \right) \cdot \sum_{i=1}^{n} \Delta w_i , \quad (2)$$

where

n is the step of the load,

N_n is the normal compressive load at the n –th step of the load,

Δw_i is the increment of deflection for the i-th step of the load,

ΔN_i is theincrement of the normal compressive load for the i-th step of the load.

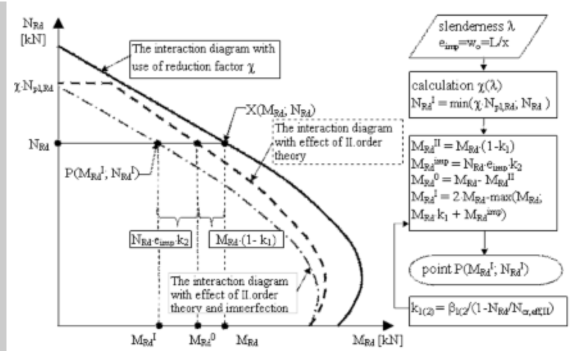


Figure 6.
The procedure of generating an interaction diagram with the effect of the second- order theory

For short-term laboratory tests of composite steel-reinforced concrete columns, a partially encased steel-reinforced concrete cross-section with a steel HEA 280 profile (structural steel S 235), an encased web (concrete C30/37), and reinforced by longitudinal reinforcement 4ϕR16 (10 505(R)) and stirrups ϕR8/250 mm (10 505(R)) was selected.

A total of 12 columns in two series were tested. In the first series 6 columns with lengths of 3 m and with eccentricities of normal compression forces of 30 and 80 mm were tested. The second series contained 6

Figure 7.
Preparation of columns for experimental research

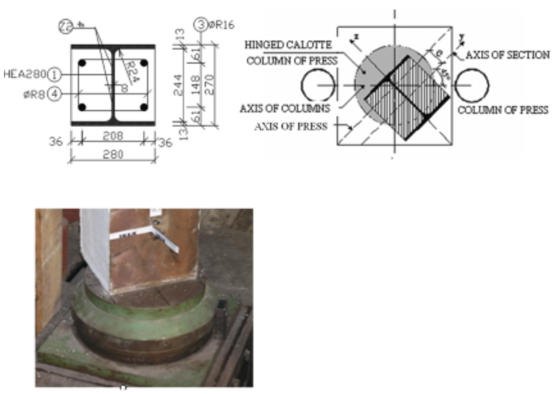


Figure 8.
Cross-section of the column and the test set-up

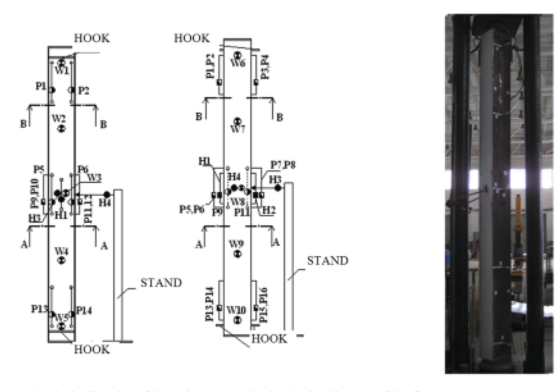
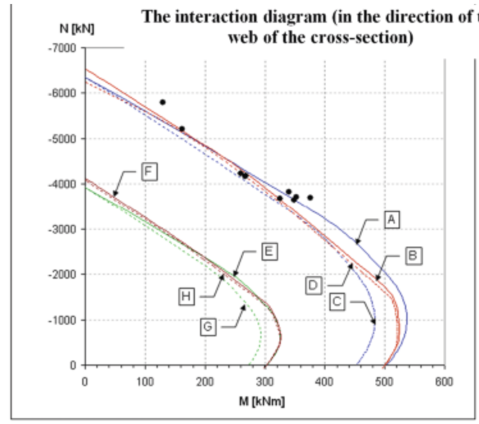


Figure 9.
Arrangment of the measured apparatus

columns with lengths of 4 m and with eccentricities of 40 and 60 mm.

The columns were put under press by using hinged semicircular calottes, and the normal compression force was brought to the column with the eccentricity of the location of the column on semicircular calottes



A Plastic interaction diagram (i.d.) with measured material properties $\alpha_M = 1.0$
B Elastic-plastic i.d. (parabola-rectangle) with measured material properties
C Plastic i.d. with measured material properties $\alpha_M = 0.9$
D Elastic-plastic i.d. (bilinear) with measured material properties
E Plastic i.d. with material properties determined according to code $\alpha_M = 1.0$
F Elastic-plastic i.d. (parabola-rectangle) with material properties according to code
G Plastic i.d. with material properties determined according to code $\alpha_M = 0.9$
H Elastic-plastic i.d. (bilinear) with material properties according to code
• The measured failure resistance values of the columns

Figure 10.
Comparison of the simplified and general methods for the buckling y-y axis

in the direction of the web of the cross-section. The relative strains and horizontal deflection up to the failure were measured for each column using:

- deformeters (P1-P16) with 400 mm bases,
- H1 and H2 fixed deformeters with 300 mm bases.
- H3 and H4 deflection meters accurate to 0.01 mm, which were located on fixed stands in the middle of the column in the direction of the webs (H3) and in the direction of the flange (H4) of the HEA section,
- theodolites, in the direction of the webs and in the direction of the flange of the HEA section, where the value of the horizontal deflection of the columns were measured at geodetic points W1 to W10.

The measured data were processed statistically, and the conclusions and recommendations were derived from the data. A comparison of the results of all the tests and interaction curves according to EC4 (simplified method and general method) is given in Figure 10.

The measured values and values determined according to code EN 1994-1-1 for the simplified k method, which represents the factor of the second-order theory, were compared.

The relation for the calculation of factor k, which was derived from the measured values, confirmed the

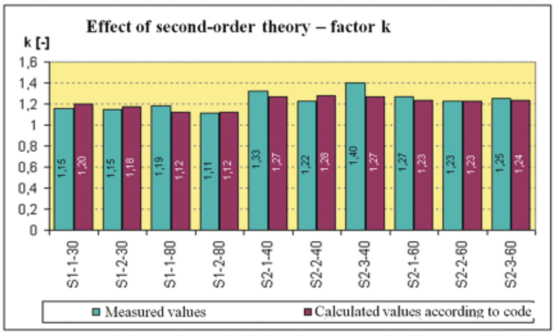


Figure 11.
Comparison of the measured and calculated values of factor k

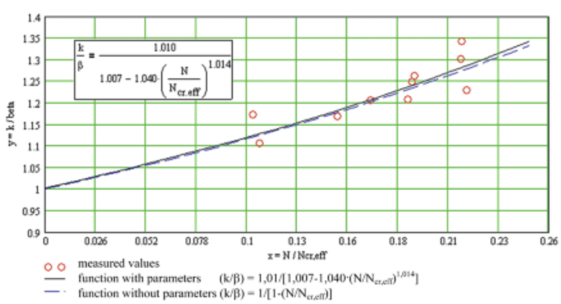


Figure 12.
Function for calculation of the value k determined from the measured values

correctness of the relation given by code EN 1994-1-1 (Figure 11).

4. CONCLUSIONS

Analysis of the simplified and general methods and their differences:

- A program for calculating and analyzing the resistance of a composite column was created according to code EN 1994-1-1, and 150 examples using this program for analysis of the simplified method were calculated.
- An equation for substituting a plastic or polygonal interaction diagram with sunisoid interaction diagram was derived.
- The suitability of using a sunisoid interaction diagram for the basic types of cross-sections which were given in code EN 1994-1-1, was analysed.
- The suitability or necessity of point E in the polygonal interaction diagram for the basic types of cross-sections, which is given in code EN 1994-1-1, was analysed.
- The approximate equations for determining the position of point E using linear and polynomial regressions were derived (Table 2).

Resistance of composite steel-reinforced concrete columns loaded with the normal compressive force and the bending moment.

- The measured initial imperfections were much less than the values given in code EN 1994-1-1.
- The lack of conformity upon the check of the steel section not concrete-encased according to code EN 1993-1-1 and the steel section with concrete encased according to code EN 1994-1-1 was determined, where for the steel section not concrete-encased, we determined the higher values of the resistance bending moment.
- The general method provides a lesser value of resistance than the simplified method for the measured material properties in centric compression, particularly for the parabole-rectangle stress and strain diagram, because the structural steel and reinforcing steel is not fully exploited (the strain of the concrete in compression is limited).
- The M_{Rd} method of checking, which is recommended by code EN 1994-1-1 for the simplified method, provides much lesser values of resistance in comparison with the $M_{Rd}N_{Rd}$ method.

Table 2.
Approximate equations for calculating the position of point E

Cross-section	$N_E/N_{pl,Rd}$	R^2	x_{ue}/h	R^2
partially concrete-encased steel I sections (direction of the web)	$-0.5\delta+0.9$	0.69	-	
partially concrete-encased steel I sections (direction of the flange)	$-0.2\delta+0.8$	0.32	-	
completely concrete-encased steel I sections (direction of the web)	$-0.3\delta+0.8$	0.27	$-0.2\partial+0.95$	0.8
completely concrete-encased steel I sections (direction of the flange)	$-0.3\delta+0.85$	0.70	-	
partially concrete-encased section in the shape of an octagon	$-0.4\delta+0.9$	0.80	$-0.2\partial+0.95$	0.7
concrete-filled rectangular steel tubes	$-0.45\delta+0.80$	0.67	-	
concrete-filled circular steel tubes	$-0.40\delta+0.90$*	0.64	-	

*the equation may only be used for a column with a relative slenderness of $\lambda < 0.25$

Figure 13.
Failure of the SRC columns

- The experiment confirmed the correctness of the equation for calculating factor k, which represents the effect of the second-order theory.

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