Comparative study of an optimal utilization in case of composite columns of HSS and HPC

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***Abstract*—** Several important parameters in the procedure of an optimal design of load-bearing structures exist in a field of civil engineering. As an example of those parameters the using of an efficient and suitable material can be mentioned. In general, the composite steel-concrete columns are usually designed by using of a steel grade S235 or S355 and with a concrete class up to C40/50. The use of high-strength steel seems to be unsuitable, especially in case of buckling, because the utilization of steel is lower (the extreme fiber stress does not reach a yield limit and a modulus of elasticity stays unchanged).

However, the high strength materials can be still advantageously used for an increasing of a load-carrying capacity together with a reduction of a self-weight (in comparison to the columns made of an ordinary class of concrete or steel grade).

This paper presents some information about a comparative study in the event of using high-strength steel (HSS) and high-performance concrete (HPC) in case of the design of compressed composite columns. The study is partially based on a previous research on the authors' workplace (Faculty of Civil Engineering at Brno University of Technology) and it deals with the problems of the design especially in case of the composite columns of a circular and partially encased H cross-section under centric compressive loading according to all the rules given by Eurocode.

***Keywords*—**Comparative study, composite column, efficient design, high-performance concrete, high-strength steel.

I. Introduction

GENERALLY, there is more often a tendency in these days of the usage of the materials with qualitatively higher properties, like high-strength steel (HSS) or high-performance concrete (HPC). This tendency is mainly possible especially due to ongoing and continuous development as well as thanks to an advanced research in case of both aforesaid materials – steel and concrete.

They can be used in case of civil engineering buildings and structures either separately (as all the different supporting members like columns, struts, beams, girders, purlins, etc.), or they can be as well combined together as the composite structure members (composite columns and beams, etc.).

The use of HSS and HPC can help to reach more effective design, but it also supposed to be very important and efficient in case of composite steel-concrete structures to find and to determine more specifically some convenient relations of both used material parameters by reason of their better and more comparable utilization as well as because of their own improvement.

In the event of members under compression loading the use of high-strength materials goes mostly to higher load-carrying capacity of these members. But this effect doesn't occur generally, primarily because of stability problems connected with a buckling (Fig. 1).

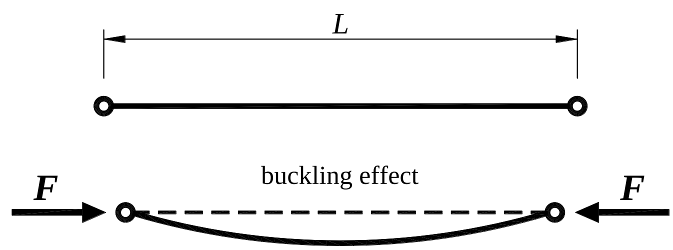

Fig. 1 the illustration of the buckling effect

That's why it is necessary to find effective relations of both materials parameters, which can affect the load-carrying capacity the most. Because this capacity depends in case of the mentioned buckling effect also on a different important parameter of the compression cross-section, which is the slenderness (it means it depends not only on the strength itself).

Next, this paper is focused on the problems of composite steel-concrete columns of circular hollow section compared with the partially encased H cross-section under the centric compression load.

II. Composite columns under compression load

A. Basic information about composite columns

In the event of the compression loading force, the steel-concrete composite columns are mostly used – either made of hot-rolled steel cross-sections (by using of steel cross-sections of I, IPE, HEA, HEB, etc.) fully or partially encased by concrete, or made of rectangular respectively circular

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hollow sections (for example RHS, CHS, etc.) completely filled by concrete. It is also possible to combine different types of steel cross sections or their parts. In some cases also the steel reinforcement can be added, too, if necessary.

For some typical examples of composite steel-concrete column cross-sections see Fig. 2.

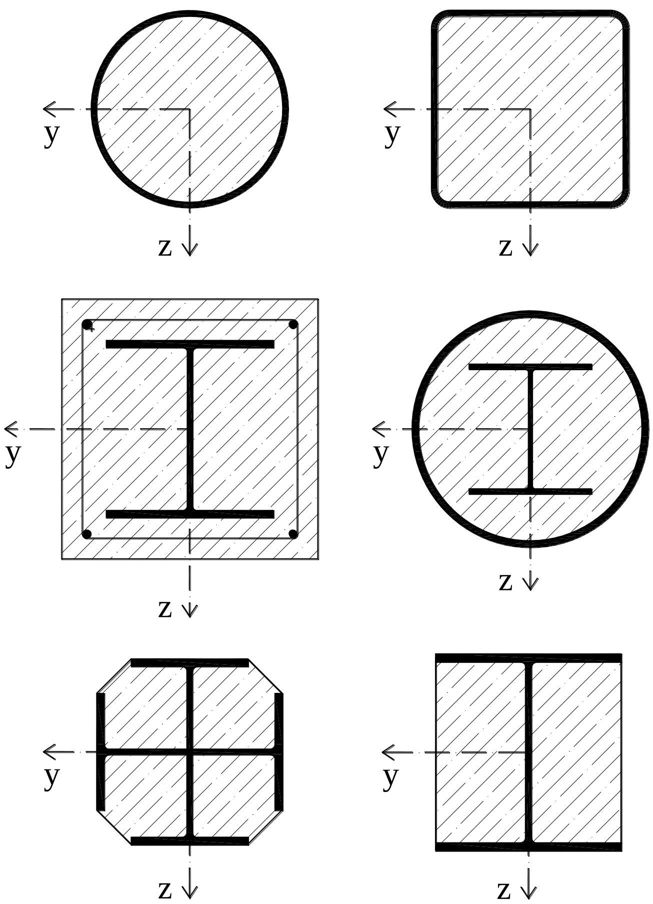

Fig. 2 some typical examples of steel-concrete composite columns

The comparative study, described below, is focused only on next two specific types of generally used composite cross-sections.

The first one is the partially encased H cross-section and the second one is the concrete filled circular tube. Both of them have been taken for the study without any steel reinforcement. The basic schemes of them together with their dimensions are shown in Fig. 3.

B. Load-carrying capacity determination

According to the standard EN 1994-1-1 [1] the simplified method can be used for the determination and obtaining of the buckling resistance as well as for the design in case of composite columns and composite compression members with concrete encased and concrete filled rectangular or circular hollow sections doubly symmetrical and with the uniform cross-section over the member length.

In this method even the positive effect caused by the confinement can be taken into account in case of concrete filled circular tubes. However, some conditions have to be satisfied, if this simplified method is used.

First, the relative slenderness $\bar{\lambda}$ according (1) should fulfill the following limit given in the inequality (2)

$$\bar{\lambda} = \sqrt{\frac{N_{pl,Rk}}{N_{cr}}}\,, \tag{1}$$

$$\bar{\lambda} \leq 2.0\,, \tag{2}$$

where $N_{pl,Rk}$ is the characteristic value of the plastic resistance of the composite section and N_{cr} value is the elastic critical normal force.

Next, the steel contribution ratio δ given by the form in (3) should fulfil the condition in (4)

$$\delta = \frac{A_a\, f_{yd}}{N_{pl,Rd}}\,, \tag{3}$$

$$0.2 \leq \delta \leq 0.9\,, \tag{4}$$

where A_a is the cross-sectional area of the structural steel section, f_{yd} is the design value of a yield strength of structural steel and $N_{pl,Rd}$ is the design value of the plastic resistance of the composite section.

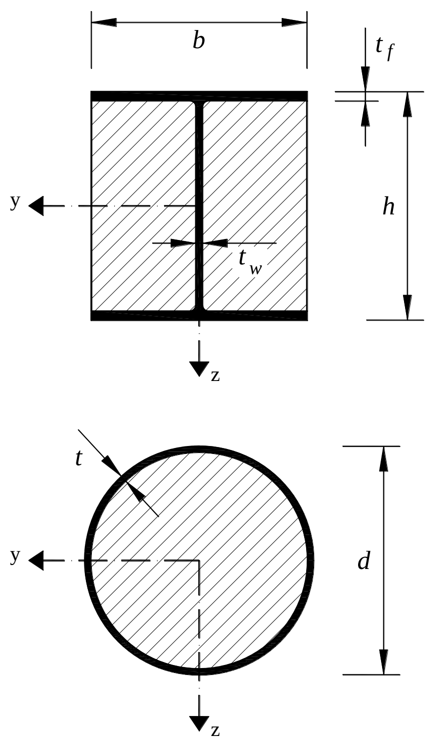

Fig. 3 the types of cross-section selected for the comparative study (on the top: the partially encased H cross-section, on the bottom: the filled circular hollow section)

The last conditions set the limits of the maximum dimension ratios (with the relevant geometric values according to Fig. 3) as follows:

$$\max(d/t) \leq 90 \frac{235}{f_y}, \tag{5}$$

$$\max(b/t_f) \leq 44 \sqrt{\frac{235}{f_y}}. \tag{6}$$

The characteristic and design value of the plastic resistance to compressive normal force $N_{pl,Rk}$ and $N_{pl,Rd}$ used in (1) and (3) can be obtained by the next two formulas

$$N_{pl,Rk} = A_a f_{yk} + 0.85 A_c f_{ck} + A_s f_{sk}, \tag{7}$$

$$N_{pl,Rd} = A_a f_{yd} + 0.85 A_c f_{cd} + A_s f_{sd}, \tag{8}$$

where A_c is the cross-sectional area of concrete, A_s is the cross-sectional area of reinforcement (if considered), f_{yk} is the characteristic (nominal) value of the yield strength of structural steel, f_{ck} is the characteristic value of the cylinder compressive strength of concrete and f_{sk} is the characteristic value of the yield strength of reinforcing steel (if considered).

Then, in general, if the reinforcement is used, then the longitudinal reinforcement that may be used in calculation should not exceed 6 % of the concrete area.

For the obtaining of the design value of the plastic resistance to compressive normal force $N_{pl,Rd}$ according to the formula (8) the design values of strengths (f_{yd} - design value of the yield strength of structural steel, f_{cd} - design value of the cylinder compressive strength of concrete and f_{sd} - design value of the yield strength of reinforcing steel) should be used instead of characteristic values used in the formula (7). Also, in case of concrete filled sections the coefficient 0.85 may be replaced by the value 1.0.

Next, the elastic critical force N_{cr} used in the formula (1) for the relative slenderness is determined in (9) for the relevant buckling mode of a section, with using of the effective flexural stiffness taken as $(EI)_{eff}$ given by the form (10)

$$N_{cr} = \frac{\pi^2 (EI)_{eff}}{L_{cr}^2}, \tag{9}$$

$$(EI)_{eff} = E_a I_a + K_e E_{cm} I_c + E_s I_s, \tag{10}$$

where L_{cr} is the buckling length in the buckling plane, E_a is the modulus of elasticity of structural steel, E_{cm} is the secant modulus of elasticity of concrete, E_s is the design value of modulus of elasticity of reinforcing steel (if considered), I_a is the second moment area of the structural steel section, I_c is the second moment of area of the un-cracked concrete section, I_s is the second moment area of the steel reinforcement (if considered) and K_e is the correction factor, which should be taken as 0.6.

Finally, the design value of the buckling load-carrying capacity of the steel-concrete compression member is written as a product of two values in the form $\chi\ N_{pl,Rd}$, where $N_{pl,Rd}$ is defined in (7) and the value χ represents the reduction factor for the relevant buckling mode according [2].

It has to be mentioned, that the standard for the composite steel and concrete compression structures [1] considers the steel grades S235 to S460 and concrete strength classes C20/25 to C50/60.

The upper limit in case of the concrete class can be taken as slightly conservative, wherefore the strength classes up to C90/105 were taken in described comparative study, as they are defined in the separate standard for concrete structures [3].

C. 2.3 The description of previously realized comparative study with partially encased H cross-sections

When some of the high-strength materials are applied in case of composite steel and concrete columns, the influence of the starting values of their various geometric and material parameters has to be evaluated to get an economic and efficient design.

For this reason a comparative study was made in case of one of the most commonly used types of composite steel-concrete columns. This study was created mainly based on a previously performed research [4], which was realized on the authors' workplace (Institute of Metal and Timber Structures, Faculty of Civil Engineering, Brno University of Technology) as well as on the numerical analysis. Some its results have been already published, see [5], [6].

In mentioned study the hinged column with the partially encased hot-rolled HEA cross-section was used as the main profile (see Fig. 3 on the top), whereas the critical length was taken as $L_{cr} = L = 3.0$ m thanks to hinged connections at the both sides. Next, the most common dimensions of this type of the profile HEA (see Table I) together with combinations of steel grades from S235 to S690 defined in [7] and concrete classes from C16/20 to C90/105 [3] were used.

Table I HEA cross-sections for the comparative study

HEA Cross-section		A 10^3 [mm^2]	I_y 10^6 [mm^4]	I_z 10^6 [mm^4]
1	HEA 120	2530	6,06	2,31
2	HEA 140	3140	10,33	3,89
3	HEA 160	3880	16,73	6,16
4	HEA 180	3530	25,10	9,25
5	HEA 200	5380	36,90	13,40
6	HEA 220	6430	54,10	19,60
7	HEA 240	7680	77,60	27,70

As the most important parameter the ratio between the elastic critical force and the characteristic plastic resistance $N_{cr} / N_{pl,Rk}$ was taken within the limits ±10 % around the full or total (i.e. 100 %) utilization of the cross-section.

Then, the economic analysis was made for the selected geometric and material specifications to get the best price of column to buckling load-carrying capacity ratio, whereas only a weight of both materials (steel and concrete) was considered in case of the total price determination [8]. See Fig. 4, where the price in dependence of the weight for the selected HEA profiles is shown and Fig. 5, where the similar price comparison is described in case of the class of concrete and its cubic volume.

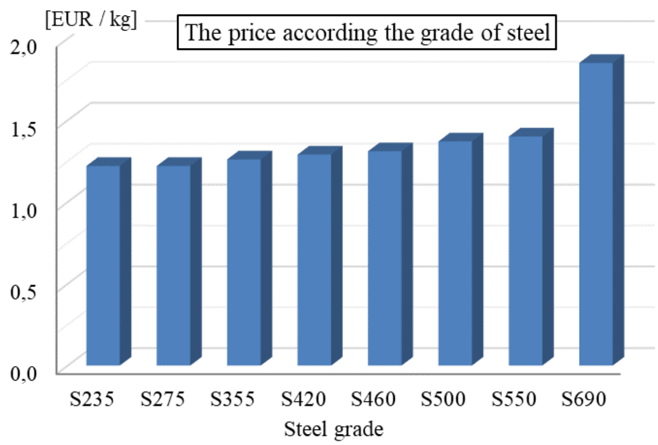

Fig. 4 the relationship between price and grade of steel depending on the weight of steel member (hot-rolled HEA)

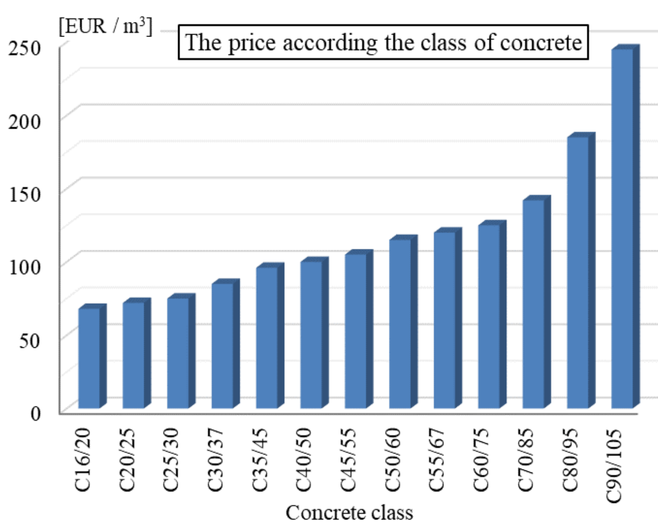

Fig. 5 the relationship between price and class of concrete depending on the cubic volume of concrete

For an example of an evaluation of this study see next Fig. 6, where are displayed some of the best relationships in case of the price-to-buckling load-bearing capacity ratios together with the appropriate combination of material parameters of selected composite steel-concrete columns.

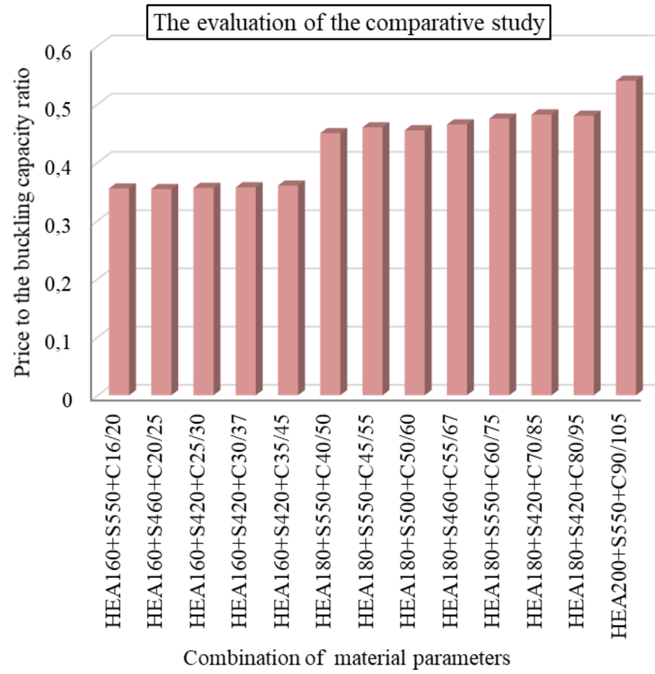

Fig. 6 the relationship between price and class of concrete depending on the cubic volume of concrete

In the end of this study the final resultant profile (with the best $N_{cr} / N_{pl,Rk}$ ratio) was chosen. It consisted of the HEA 180 cross-section with the steel grade S420 and with the concrete class C70/85 (values: $N_{pl,Rk}$ = 3799 kN; $\chi\, N_{pl,Rd}$ = 1782 kN).

From now on, this combination of material parameters together with the profile (i.e. HEA 180 + S420 + C70/85) is, within the simplification, marked as “#1#” in the whole text and in all tables below in case of a new comparative study.

III. Comparative Study in Case of Concrete Filled Circular Sections

A. *Initial phase and a selection of the study criteria*

On the basis of the previous results the selected cross-section #1# mentioned above has been taken as the starting value for the comparison with the concrete filled circular hollow sections (CHS) in a new comparative study. Although, the study was at the beginning elaborated for whole spectrum of steel circular hollow section assortment, only the cases with similar parameters to the profile #1# were chosen to get the possibility to compare both these types of composite cross-section.

From this point of view only the values of the plastic resistances to compression, elastic critical normal forces and geometric parameters can be compared. On the other hand, the final values of the buckling load-carrying capacities are not properly comparable, because of different buckling curves of both used steel profiles.

First, only the cases with the ratio $N_{cr} / N_{pl,Rk}$ around a value 1.0 (i.e. about 100 % utilization) were selected from all the possible combinations of circular hollow sections together with all steel grades and concrete classes.

More specifically, only the values with the ratio N_{cr} / $N_{pl,Rk}$ from the interval 0.95 to 1.05 were taken for the next step (see below in the next chapter). Together they were 118 results, i.e. combinations of steel and concrete material parameters and steel circular tubes (CHS) dimensions.

B. Results of the comparative study

Next, from all the 118 results, the ones with the values of the characteristic plastic resistance $N_{pl,Rk}$ nearly equal to the one in case of section #1# were taken. Nine cases satisfied this criterion and they are written in the first nine rows of Table II. Besides, two cases also satisfied the criterion (with the N_{cr} / $N_{pl,Rk}$ ratio) and in addition their cross-sectional area A_a was very similar to the one in case of section #1# (with 1.5 % difference). These two cases are written in rows 10 and 11 of Table II. Values of the profile #1# are in the last row.

Table II selected composite cross-sections with the concrete filled circular hollow sections in comparison to the cross-section #1#

Steel CHS profile		Steel grade	Concrete class	$N_{pl,Rk}$	A_a
				kN	mm^2
1	CHS 140×25	S355	C90/105	3779	9032
2	CHS 152×16	S420	C80/95	3776	6836
3	CHS 152×16	S420	C90/105	3889	6836
4	CHS 152×16	S460	C50/60	3710	6836
5	CHS 152×16	S460	C55/67	3767	6836
6	CHS 152×16	S460	C60/75	3823	6836
7	CHS 152×14	S460	C80/95	3758	6070
8	CHS159×12,5	S460	C80/95	3775	5753
9	CHS 152×14	S460	C90/105	3879	6070
10	CHS 140×11	S420	C45/55	2364	4458
11	CHS 152×10	S460	C70/85	3010	4461
#1#	HEA 180	S420	C70/85	3799	4530

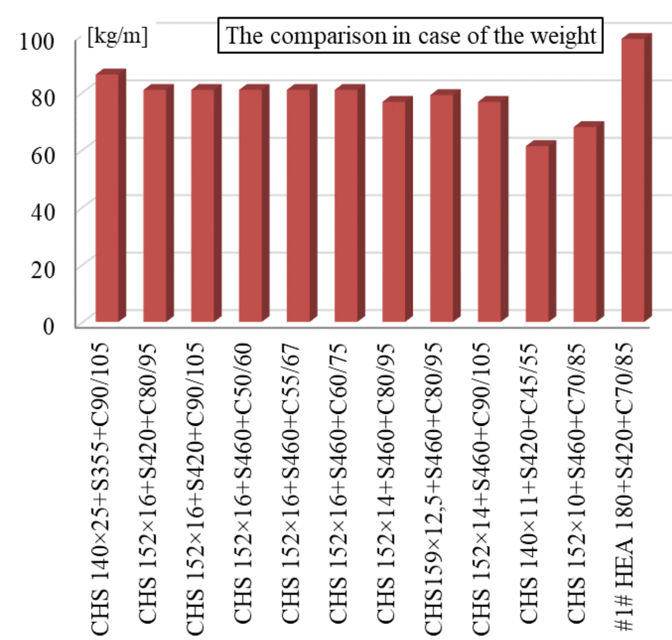

Fig. 7 the comparison in case of the weight of the column

For all selected composite column cross-sections according to Table II the comparison in case of the weight of a column and in case of the cross-section area is shown in the graphs on the Fig. 7 and Fig. 8.

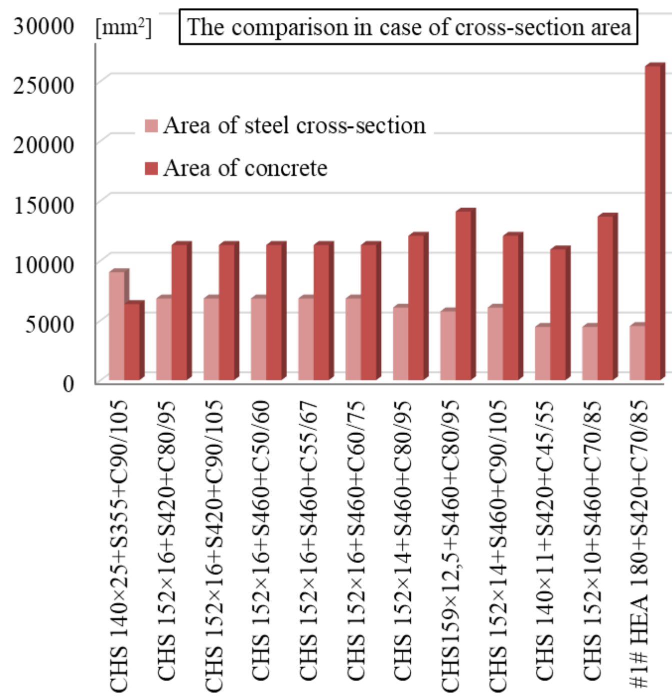

Fig. 8 the comparison in case of the cross-section area

Similarly, the comparison of these selected columns in case of all the important force values (i.e. $N_{pl,Rd}$, N_{cr} and the buckling resistance $\chi\, N_{pl,Rd}$) are described through the graph in the next Fig. 9.

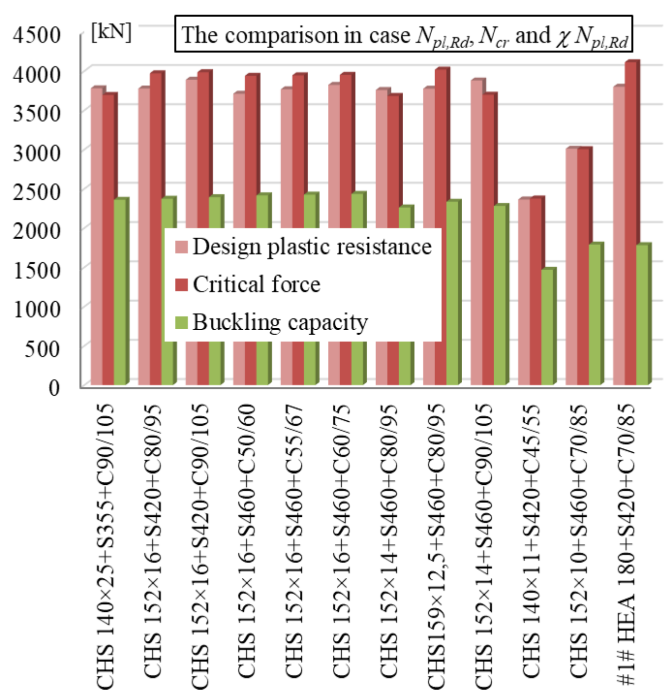

Fig. 9 the comparison in case of the force values

Next, for better illustration, the Table III shows altogether information about all geometric characteristics and material parameters in case of all selected variants. This table is divided into two parts underneath (according row numbers).

Table III results of the comparative study in case of selected variants of concrete filled circular sections

Nr.	Steel				Concrete		
	Section	f_{yd}	A_a	I_a	Class	A_c	I_c
		-	-	10^4		-	10^4
		MPa	mm^2	mm^4		mm^2	mm^4
1	CHS 140×25	355	9032	1564	C90/105	6362	322
2	CHS 152×16	420	6836	1602	C80/95	11310	1018
3	CHS 152×16	420	6836	1602	C90/105	11310	1018
4	CHS 152×16	460	6836	1602	C50/60	11310	1018
5	CHS 152×16	460	6836	1602	C55/67	11310	1018
6	CHS 152×16	460	6836	1602	C60/75	11310	1018
7	CHS 152×14	460	6070	1460	C80/95	12076	1161
8	CHS159×12,5	460	5753	1555	C80/95	14103	1583
9	CHS 152×14	460	6070	1460	C90/105	12076	1161
10	CHS 140×11	420	4458	934	C45/55	10936	952
11	CHS 152×10	460	4461	1130	C70/85	13685	1490

Nr.	Composite section (L_{cr} = 3,0 m; buckling curve "a")						
	$(EI)_{eff}$	$N_{pl,Rk}$	N_{cr}	$\bar{\lambda}$	χ	$\chi N_{pl,Rd}$	N_{cr}/N_{pl}
	10^{10} mm^6	kN	kN	-	-	kN	%
1	336,9	3779	3694	1,01	0,658	2360	97,8
2	362,2	3776	3971	0,98	0,683	2373	105,2
3	363,4	3889	3985	0,99	0,674	2393	102,5
4	359,1	3710	3938	0,97	0,686	2416	106,1
5	359,7	3767	3945	0,98	0,682	2426	105
6	360,3	3823	3951	0,98	0,677	2435	103,4
7	335,8	3758	3682	1,01	0,658	2262	98
8	366,4	3775	4018	0,97	0,687	2335	106,4
9	337,2	3879	3698	1,02	0,649	2281	95,3
10	216,7	2364	2376	1,00	0,667	1468	100,5
11	274,0	3010	3004	1,00	0,665	1789	99,8

In the end, from all these eleven variants two cases with the smallest variation of the relevant characteristics from the starting section #1# were selected for the final comparison. They are written in Table IV together with the section #1#, where also the weight of each of these combinations is added in the last column.

Table IV comparison of selected circular section and section #1#

Steel			Concrete		Composite section			
section	grade	A_a	class	A_c	$N_{pl,Rk}$	N_{cr}	$\chi N_{pl,Rd}$	m
	-	mm^2		mm^2	kN	kN	kN	kg/m
HEA180 (#1#)	S420	4530	C70/85	26250	3799	4111	1782	98,6
CHS159×12,5	S460	5753	C80/95	14103	3775	4018	2335	79
CHS 152×10	S460	4461	C70/85	13685	3010	3004	1789	67,9

Then, for better illustration, these three composite profiles are compared also in the graph in Fig. 10.

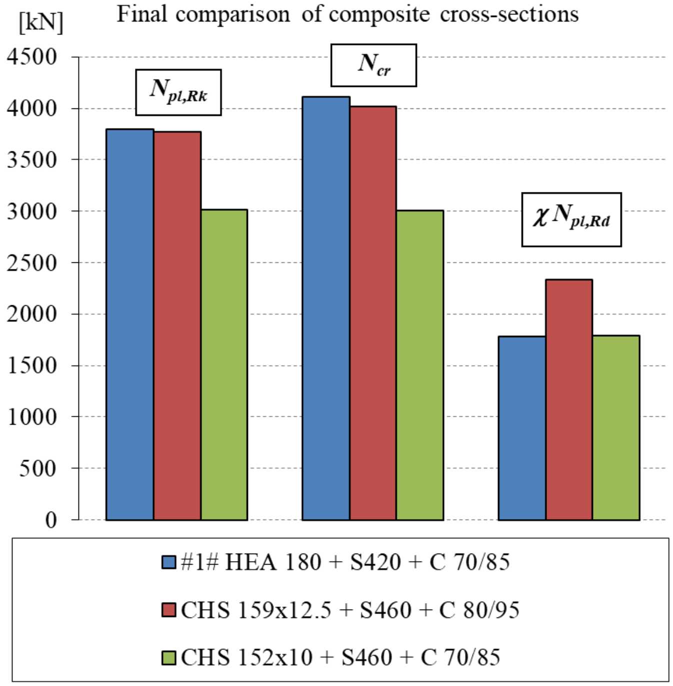

Fig. 10 the final comparison of selected composite cross-section in case of $N_{pl,Rk}$, N_{cr} and $\chi N_{pl,Rd}$

The first filled circular section (CHS 159×12,5, S460, C80/95) has almost the same value of $N_{pl,Rk}$ and it needs higher class of concrete and steel grade then #1#, but the weight is lower because of smaller cross-section area and also the buckling load-carrying capacity is more efficient.

In case of the second circular composite section (CHS 152×10, S460, C70/85) the cross-sectional area of steel is very similar as in #1#, the concrete class is the same as well as the buckling capacity, but it needs a higher grade of steel and its plastic resistance and the critical force are lower.

IV. Conclusion

Some particular conclusions have been mentioned above as the results of the comparative study of composite compression columns of concrete filled steel circular hollow sections in comparison to partially encased sections, both with using the HSS and HPC.

The described method can be used in case of any type of cross-section for the obtaining of the most efficient combination of design parameters.

Generally, the usage of high-strength steel and high-performance concrete in case of composite compression members can be suitable for the reduction of their self-weight and for an economic design. However, the columns should also satisfy the basic condition of ULS and SLS and although the load-carrying capacity in the event of circular hollow sections filled by concrete can be usually higher then partially encased sections with comparable geometric characteristics, the final decision can depend on the technology, which is usually more expensive in case of circular sections production.

The results of described study can be applied and verified in numerical models as well as they can be also used for the selection of the test specimens in case of planned loading tests of the compression composite columns. For some another previous authors' experiences with high-strength materials in case of composite columns see [9], [10].

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References

[1] EN 1994-1-1 *Eurocode 4: Design of composite steel and concrete structures – Part 1-1: General rules and rules for buildings*, CEN Brussels, 2011.
[2] EN 1993-1-1 Eurocode 3: *Design of steel structures – Part 1-1: General rules and rules for buildings*, CEN Brussels, 2016.
[3] EN 1992-1-1 Eurocode 2: *Design of concrete structures – Part 1-1: General rules and rules for buildings*, CEN Brussels, 2011.
[4] J. Melcher and M. Karmazínová, "Loading tests of compression composite steel-concrete members filled by high-performance concrete", Research report, Brno University of Technology, Brno, 2002, unpublished.
[5] V. Röder, "Optimized design of composite steel-concrete columns with the use of high strength materials", *Konstrukce*, Konstrukce media, vol. 03, 2009, pp. 21-26, ISSN 1213-8762.
[6] M. Karmazínová, J. Melcher and V. Röder, "Load-carrying capacity of steel-concrete compression members composed of high-strength materials", in *Proceedings of 9th International Conference on Steel Concrete Composite and Hybrid Structures (ASCCS 2009)*, Research Publishing Services, Singapore, pp. 239-244, 2009, ISBN 978-981-08-3068-7.
[7] EN 1993-1-12 Eurocode 3: *Design of steel structures – Part 1-12: Additional rules for the extension of EN 1993 up to steel grades S700*, CEN Brussels, 2007.
[8] M. Štrba, V. Röder, "The comparison of HSS and HPC composite columns of circular and H cross-section", in *Proceedings of 10th International Scientific Conference VSU' 2010*, Higher School of Civil Engineering „L. Karavelov", Sofia, Bulgaria, 2010, pp. 131-136, ISSN 1314-071X.
[9] M. Štrba, M Karmazínová and J. Melcher, "Reliable and effective design of composite members - Steel-concrete composite members using high-strength materials", in *Proceedings of the 6th European Conference on Steel and Composite Structures Eurosteel 2011*, Budapest, pp. 1839-1844, 2011, ISBN 978-92-9147-103-4.
[10] P. Bukovská, M. Karmazínová and M. Štrba, "High-performance concrete-filled steel tubes buckling resistance", in *Proceedings of the 6th European Conference on Steel and Composite Structures Eurosteel 2011*, Budapest, pp. 1749-1754, 2011, ISBN 978-92-9147-103-4.

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