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RESEARCH ON LOAD CAPACITY OF CONCRETE FILLED COLUMNS WITH BATTENED STEEL SECTIONS

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Abstract. The paper presents experimental and numerical results for selected built-up steel columns filled with concrete. The laboratory tests were accompanied by numerical analysis carried out using general purpose, finite element program ABAQUS. Based on heretofore research presented in this paper, one may assumes that the application of concrete filled columns with battened steel sections is economically very profitable. For columns filled with concrete strength class C20/25 the increase of load bearing capacity was 42% and for elements filled with concrete strength class C50/60 – above 100%. The application of the shorter distance between battens allowed to obtain additional increase of ultimate load (for concrete C20/25 – about 8%). The numerical analysis also confirmed the increase of the load capacity for the columns. The best correlation between numerical and experimental results was obtained for the assumed eccentricity of 1 mm. Moreover the higher rigidity of those members in relation to steel columns is not connected with significant increase of the cost. The study was conducted as a part of the research project nr 4TO7E01528, founded by the Polish Ministry of Science and Higher Education.

Keywords: ABAQUS, columns filled with concrete, composite columns, loading carrying capacity, built-up columns.

1. Introduction

As it comes from the literature review, the first research on the two-branch steel columns filled with concrete was conducted in 1934–35 in Germany (Klöppel 1935).

The columns built of two battened channels filled with concrete were tested. The changed parameters were: distance between branches and battens, length of the columns, position of the channels in the cross section.

According to Klöppel (1935), the concrete fill increased the magnitude of the ultimate loading, by 33%.

Based on the experimental results, the author proposed the method of calculating load capacity of such types of columns.

Other researches performed on the battened steel sections filled with concrete concerned the bond between steel and concrete. For example, Hunaiti conducted push-out tests to determine the strength of bond between these two materials and to examine the factors likely to affect the bond strength in the columns built of two battened channels (Hunaiti 1991).

The influence of reinforcement arrangement on the stress – strain dependence for confined concrete is presented in (Mander *et al*. 1988). The tests were conducted on the elements made of reinforced concrete.

Steel-concrete composite columns with two battened chords could have the wide application in the industrial buildings. However the computation and design of this kind of columns is not included in the existing standard's rules.

As it was mentioned before, the researches covered only columns built of two C channels connected through batten plates. The authors of this paper didn't find any information about strength and behavior of columns, consisted of double I-sections filled with concrete. In authors' opinion there is possibility to apply a composite action of this type of columns in underground substructures, in buildings erected by "up& down" method or for strengthening steel columns in existing structures.

In this paper the analysis of the results of laboratory tests on the new solution of steel columns filled with concrete are presented. The steel cross section of the tested columns consists of two battened I-shapes HE160A. Previously the authors tested the composite columns built of encased single I-shape HE 160A (Zoltowski *et al*. 2004; Szmigiera 2007). The objective of the research is to determine how the concrete filling influences the behavior of the built-up steel columns and to estimate their load capacity. While considering that type of columns, a question may be raised: do the battened steel sections filled with concrete may be considered as composite and on what conditions.

2. Description of the research

2.1. Tested units

So far, twenty units in natural scale were tested, including two steel columns and eighteen columns with concrete fill with different strength. The results for fourteen of those have been presented in this paper.

The cross-section of the tested elements was composed of two steel I-shape HE 160A made of the S235JRG2 steel grade (Fig. 1). The elements were 2500 mm high, the spacing of the section of the chords was adopted as 240 mm.

In order to obtain more information on the performance of that type of columns, the variable parameters had to be introduced. The battens were placed with two distances: 780 mm and 240 mm.

Six columns were filled with C20/25 concrete strength class, another six with C50/60 class (Fig. 2), following the standard recommendation concerning the weakest and the strongest concrete in composite structures. For each type of columns, the above cited different distances of battens were applied.

The two remaining elements were not filled with concrete and were used for comparative tests.

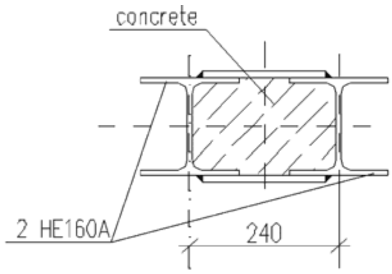


Fig. 1. Cross section of the tested elements

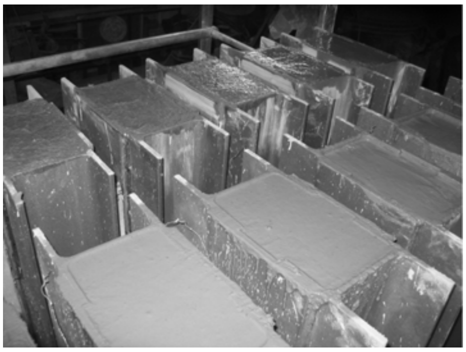


Fig. 2. Columns after filling with concrete

2.2. Test procedures and equipment

All the tests were carried out in a hydraulic testing machine with capacity of 6000 kN. The stub specimen were centered in the testing machine to ensure that the compressive axial load was applied without any eccentricity to the entire transversal cross-section. The load was applied in increments of 200 kN up to the maximum value, and then decreased. After each increment of the load, the force value was kept constant during about 3 minutes. The behaviour of the tested columns under the increasing load was observed. All specimens were loaded up to failure. In some cases the maximum value of the load was reached during the last increment. This value was recorded as the failure load after which the immediate drop of the load was observed, due to buckling and crushing the concrete.

After the maximum recorded compressive force had been reached, the loading in the hydraulic press was kept constant, in order to observe the failure mode.

Apart from the value of the failure load, the strains of steel and concrete, as well as the shortening and deflection of the tested units, were recorded during the tests for each increment of loading. The measurements of the longitudinal and transversal strains of steel and concrete were made with electrical resistance strain gauges. On the three testing levels (upper, middle and bottom) the strain gauges with 20 mm base were placed on the flanges and on the web of the sections, while the strain gauges with the 75 mm were stuck to the concrete (Zoltowski *et al*. 2006a, b). The deflections of the columns in two planes and their shortening were recorded with LVDT's in four points of the column cross section. The test setup for both types of the tested columns are presented in Figs. 3 and 4.

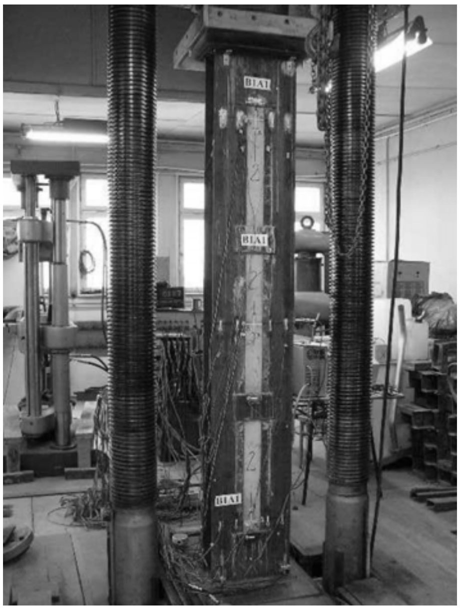


Fig. 3. Columns with 780 mm distance between battens

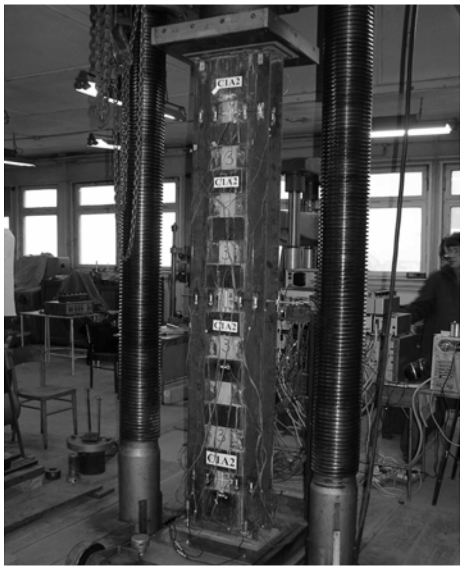


Fig. 4. Columns with 240 mm distance between battens

3. Results of the research

3.1. Laboratory tests

The characteristics of the tested columns and the results of laboratory tests are presented in Table 1. Based on the values of the failure load presented in Table 1, it is clearly visible that filling the column with concrete significantly influences on the increase of its bearing capacity. By applying the C20/25 concrete strength class, the failure load grown by 42% for the I series, and 56% for the II series. In the case of applying the C50/60 concrete strength class, the doubled increase of bearing capacity compared to the steel columns was obtained.

While analyzing the results presented in Table 1, another important conclusion concerning the influence of the distance between battens on the load capacity of the tested members may be drawn. The obtained values of the destructive forces for the columns of the I and II series indicated that the distance between battens in the steel columns filled with the C20/25 concrete strength class had a noticeable influence on the bearing capacity of those columns. The concentration of battens on the series II sections caused the increase of the failure force by about 10% related to the columns of the I series.

Interestingly, the above relation was not observed in the case of columns filled with the C50/60 concrete strength class of the III and IV series. During the tests, almost identical values of the failure load were recorded for both distances of battens.

Table 1. Characteristics of columns and the results of research

Test series	Denotation of columns	Strength class of the filling concrete	Distance between battens [mm]	Failure force [kN]		Increase of force*
					Mean	
1	2	3	4	5	6	7
0	A1	–	780	2160	–	–
	A2		240	2140		
I	B1A1-1	C20/25**	780	3200	3060	1.42
	B1A1-2			3000		
	B1A1-3			2980		
II	C1A2-1		240	3440	3333	1.56
	C1A2-2			3200		
	C1A2-3			3360		
III	B2A1-1	C50/60***	780	4400	4333	2.01
	B2A1-2			4200		
	B2A1-3			4400		
IV	C2A2-1		240	4200	4377	2.05
	C2A2-2			4530		
	C2A2-3			4400		

* the relation of the failure force of concrete-steel columns to that of steel columns, with the same spacing of battens,
** all elements types B1A1 and C1A2 were filled with the same concrete mix,
*** all elements types B2A1 and C2A2 were filled with the same concrete mix.

The bearing capacity of the applied concrete had also a significant influence on the behavior of the tested elements. During the tests of columns filled with a weaker concrete, already after crossing the force value of 2200 kN vertical cracks on the contact of concrete and the section flanges, in the area between the battens occurred. Whilst increasing the loading force on columns filled with C50/60 concrete strength class caused no noticeable changes on the surface of the tested elements, until the failure load was obtained. As late as at the moment of failure, a cracking of concrete, sometimes accompanied by an explosive fall off of elements occurred. It was also accompanied by local buckling of flanges of the sections.

While testing the described elements, the determination of whether a sufficient bond between concrete and steel existed, so columns of that type may be considered as composite structures. Such a trial was undertaken by analyzing the curves of concrete and steel strains in the three sections on the height of the elements.

In Figs. 5 and 6, diagrams of strains of steel and concrete in columns with bigger distance between battens are presented. Each curve shows the readings of the strain gauges situated on the perimeter of the upper section of the column: four on the steel sections and two on the concrete surface.

As it follows from the analysis of the results, the increase of deformation is slower in columns filled with stronger concrete. Deformations of the steel and concrete columns made of C 50/60 concrete are slightly smaller

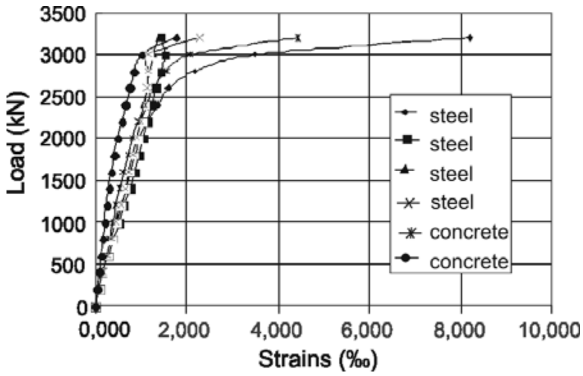


Fig. 5. Strains of steel and concrete in B1A1 type columns (C20/25)

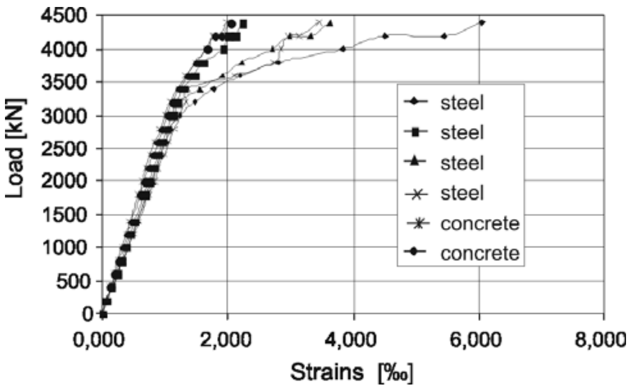


Fig. 6. Strains of steel and concrete in B2A1 type columns (C50/60)

with the same level of load. One can also observe that the deformations in each of the columns are similar. At the same time this convergence is greater in the case of columns filled with stronger concrete.

Comparison the diagrams for columns with smaller distance between battens, presented in Figs. 7 and 8, leads to another conclusion. Regardless of the strength class of concrete filling the columns, the increase of steel deformations are comparable. At the same time, the concrete deformations are clearly smaller than those of steel. This is especially visible in the column made of the C20/25 concrete strength class.

Comparing the diagrams in Figs. 7 and 8 with diagrams in Figs. 5 and 6 one may also note that, regardless of the strength class of the filling concrete, in columns with smaller distance between battens, the greater values of deformation in the steel sections occur than those in the columns of bigger distance of them.

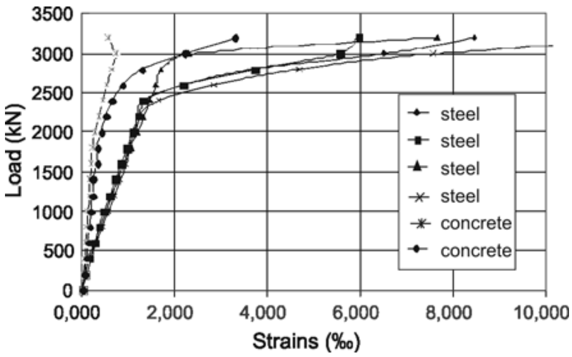


Fig. 7. Strains of steel and concrete in C1A2 type columns (C20/25)

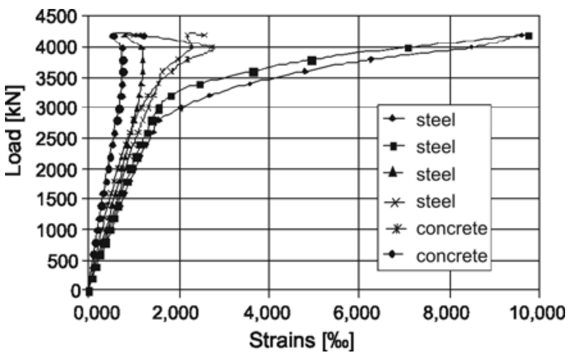


Fig. 8. Strains of steel and concrete in C2A2 type columns (C50/60)

3.2. Estimation of load capacity of tested columns

Based on the received results an estimation of the load carrying capacity of the tested columns was developed. In the present codes there are no rules for design such types of columns. Having the values of the ultimate loading for the tested columns, the authors tried to check if it is possible to estimate the load capacity of these columns using the formulas for typical composite columns included in the existing codes. For that reason the calculations were made according to EC 4.

The load bearing capacity of axially compressed members was calculated using the following expression from the simplified method:

$$\frac{N_{Ed}}{\chi N_{pl,Rd}} \leq 1, \quad (1)$$

where: N_{Ed} – design value of the applied axial force; χ – reduction factor given in Eurocode 4, for the relevant buckling mode observed in the tests; N_{plRd} – the plastic resistance of the composite section calculated from:

$$N_{pl,Rd} = A_a f_{yd} + 0{,}85 A_c f_{cd}, \quad (2)$$

where: A_a – cross-sectional area of the structural steel section; A_c – cross-sectional area of concrete; f_{yd} – mean value of the yield strenght of structural steel, tested in the laboratory; f_{cd} – mean value of the cube compressive strenght of concrete, tested in the laboratory.

Expression (2) applies to the concrete encased and partially concrete encased steel sections. For concrete filled sections the coefficient 0,85 may be replaced by 1,0.

Results of calculations and comparison with the values of ultimate loading are presented in Table 2.

The theoretical values of load calculated according to expressions (1) and (2) are presented in columns number 6 and 7.

Conclusions from the comparison of values of theoretical and research value of the ultimate load for tested columns are the following:

- in all cases, the theoretical values are less then the ultimate load from the tests;
- the results calculated according to the expression for concrete filled sections are more close- to the ultimate load from the tests (column 10) than for partially encased sections (column 9);
- for columns of type B1A1 and C1A2 (concrete strength class C20/25) the results of calculations are close to the ultimate load from the tests than for the columns type B2A1 and C2A2 (concrete C50/60).

Table 2. Comparison of value of ultimate loading from tests and calculations (according to Eurocode 4)

Specimens	Concrete		Steel		Ultimate load from calculations [kN]		Ultimate load N_n from tests [kN]	Relation of load	
	f_c [MPa]	E_{cm} [GPa]	f_a [MPa]	E_a [GPa]	For partially encased sections N_o	For concrete filled sections N_z		N_n/N_o	N_n/N_z
1	2	3	4	5	6	7	8	9	10
B1A1	33.3	27.4	304	205	2871	2997	3060	1.07	1.02
C1A2							3333	1.16	1.11
B2A1	79.5	41.4	272.1		3652	3937	4333	1.19	1.10
C2A2							4377	1.20	1.11

3.3. Numerical analysis

The preliminary numerical analysis was conducted for the selected tested elements with the help of the Abaqus/Standard Version 6.6-1 program (ABAQUS, 2006).

The FE model development was divided into two stages. In the first stage, a 3D model for column A1 was created and then a parametric study was conducted. The goal was to determine optimal model parameters for boundary condition representation, loading and imperfections, mesh density, element type, and analysis type and controls. The verification was done through comparison with experimental data in terms of ultimate loading and post buckling deformation. In the second stage, a concrete core was added and a limited calibration process was conducted focusing on material properties of concrete and concrete – steel interaction. The properties of materials are presented in the Table 3.

The stress-strain relationship for steel used in the FEA is shown in the Fig. 9.

The first curve in Fig. 9 named "ABAQUS input" depicts relation between true stress σ_T and true plastic strain ε_T^{PL}

$$\varepsilon_T^{PL} = \varepsilon_T - \frac{\sigma_T}{E_s}, \quad (3)$$

Table 3. Basic material properties for steel and concrete

Steel S235JRG2		Concrete C20/25	
Elastic modulus E_s	205 GPa	Elastic modulus E_{c0}	27,4 GPa
Poisson ratio ν_s	0.3	Poisson ratio ν_c	0,18
Yield stress σ_{sY}	267 MPa	Yield stress σ_{cY}*	17,29 MPa
Ultimata stress σ_{sU}	401 MPa	Crushing failure stress σ_{cU}*	31,7 MPa
		Plastic strain At failure ε_{cF}*	0,0015
		Cracking failure stress σ_{cT}	2,8 MPa

* approximated values (based on ABAQUS, 2006)

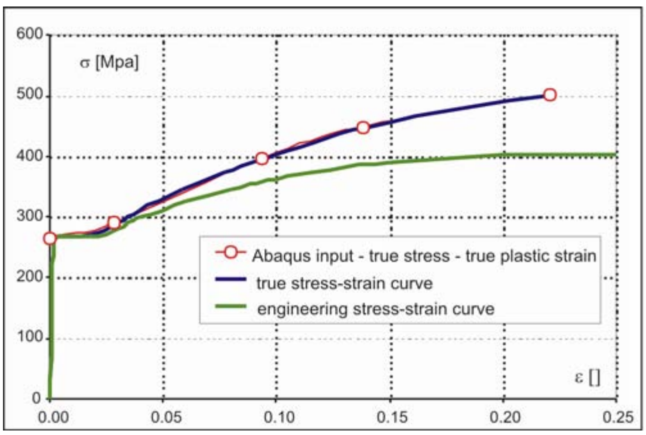


Fig. 9. Stress – strain curves for steel S235JRG2

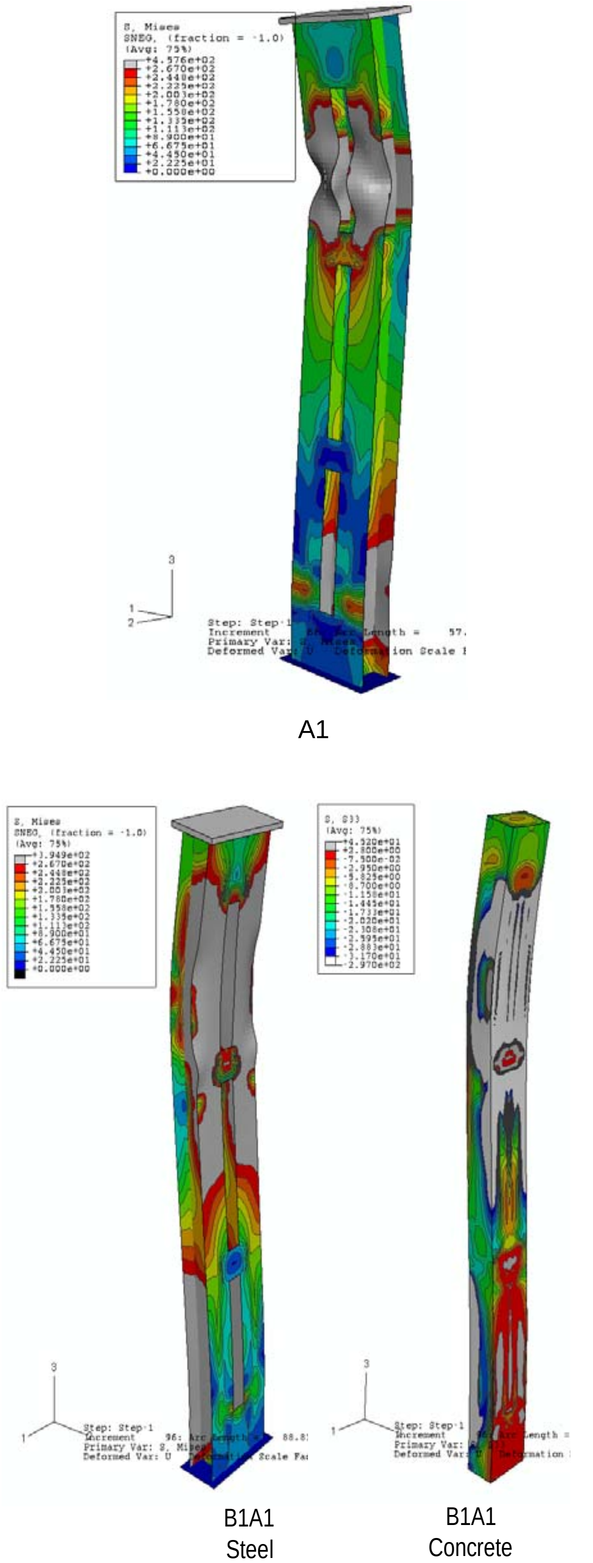
where:

$$\sigma_T = \sigma_E(1+\varepsilon_E), \quad (4)$$

$$\varepsilon_T = \ln(1+\varepsilon_E), \quad (5)$$

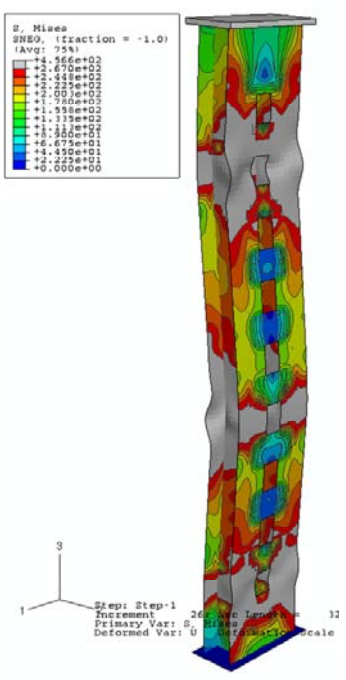
σ_E, ε_E – nominal value of stresses and strains.

a)



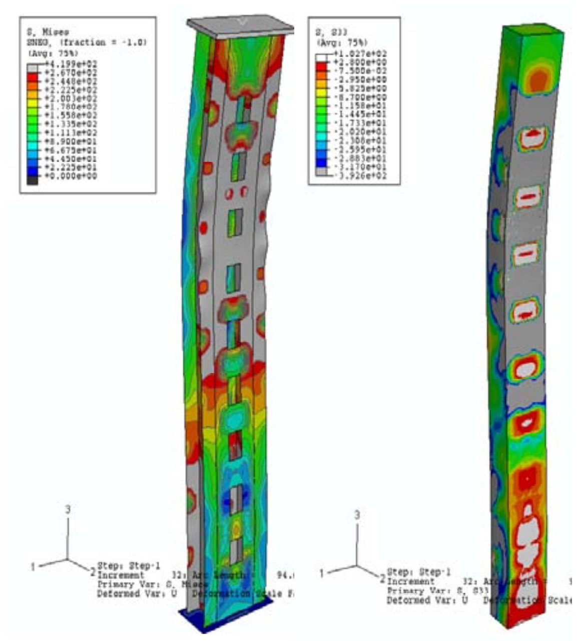
b)

Fig. 10. The form of destruction of the columns type: a) A1 and b) B1A1



A2

a)



C1A2
Steel

C1A2
Concrete

b)

Fig. 11. The form of destruction of the columns type: a) A2 and b) C1A2

The results of the analysis concerning the bearing capacity and character of performance of the tested columns confirmed the results of the experimental research. For the elaborated numerical models of concrete filled columns, similar increases of bearing capacity related to the models of steel columns were obtained. The accordance of analysis refers to both adopted spacing of battens.

In Figs. 10 and 11, an exemplary comparison of the character of failure of models of steel columns and steel columns filled with the C 20/25 grade concrete are presented. It reflects the real form of the failure observed during the laboratory research.

4. Summary

The results of the carried research explicitly reveal a very significant influence of concrete filling on the load carrying capacity of built-up steel columns. Already for the lowest concrete strength class, recommended for composite concrete – steel structures in existed codes, the increase of the ultimate load came to about 50%.

The shorter distance between battens noticeably influences on the increase of load capacity of the columns filled with weaker concrete, which was not observed in the case of applying of the C50/60 concrete strength class. The described increase for the C20/25 class came to about 10% (see Table 1 column 7). The validity limits of the conclusions are: the strength class of concrete from C20/25 to C50/60, distance between battens from 240 mm to 780 mm, steel grade S235 (see Table 1).

The influence of distance between battens described above, is confirmed in (Montuori and Piluso 2009). This article presents results of tests conducted on the reinforced concrete elements strengthened by battens and hoops. Interestingly, the value of cubic resistance of confined concrete was between 25 MPa – 32 MPa, which corresponds with concrete strength class C20/25.

The analysis of the deformation curves in the tested columns sections indicates that steel and concrete deform more uniformly in higher grade of concrete and bigger distance between battens.

Results received from the described tests were compared with the researches conducted earlier on the axially compressed encased single I-shape HE160A. As it comes from analysis, for the same concrete strength class, the load capacity of filled built-up steel columns is twice as load capacity of encased columns consisted of single I-shape, while the cross-section is about 30% smaller.

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KOLONŲ IŠ STANDŽIŲ PLIENINIŲ SKERSPJŪVIŲ, UŽPILDYTŲ BETONU, LAIKOMOSIOS GALIOS TYRIMAS

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S a n t r a u k a

Straipsnyje pristatomi plieninių kolonų, užpildytų dviejų tipų betonu, eksperimentiniai ir skaitiniai tyrimų rezultatai. Laboratoriniai bandymai ir skaitinė analizė buvo atliekami naudojant bendrosios paskirties baigtinių elementų programą ABAQUS. Remiantis šiame straipsnyje pateiktais tyrimo rezultatais, galima daryti prielaidą, kad kolonos iš standžių plieninių skerspjūvių, užpildytų betonu, yra labai ekonomiškos. Kolonos, užpildytos C20/25 betonu, laikomoji galia padidėjo 42 %, o elemento, užpildyto C50/60, – daugiau negu 100 %. Kai atstumas tarp sutvirtintų vietų trumpesnis, galima padidinti didžiausiąją apkrovą (naudojant betono klasę C20/25 – apie 8 %). Skaitinė analizė patvirtino padidėjusią kolonų laikomąją galią. Geriausia koreliacija tarp eksperimentinių ir skaitinių rezultatų buvo gauta esant tariamam 1 mm ekscentricitetui. Be to, didesnis šių elementų standumas, palyginti su plieninėmis kolonomis, nėra susijęs su išlaidų padidėjimu. Šis mokslinis tyrimas buvo mokslinio projekto Nr. 4TO7E01528, kurį inicijavo Lenkijos studijų ir aukštojo mokslo ministerija, dalis.

Reikšminiai žodžiai: ABAQUS, kolonos, užpildytos betonu, kompozitinės kolonos, laikomoji galia, dviejų tipų kolonos.

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