Influence of concrete strength on the behavior of steel tubular columns filled by concrete

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***Abstract*—**This paper deals with the effectiveness of using circular steel columns filled by high strength concrete in case of structural members subjected to compression. The paper was worked out within the research programme focused on true behavior of steel tubular columns filled by concrete. Attention is focused on influence investigation of concrete strength on the behavior of columns. The paper includes the interpretation and evaluation of the results of experimental analysis, initial results of numerical model and sensitivity analysis. Circular steel tubes filled by normal concrete and circular steel tubes filled by high-strength concrete have been taken into account within the solution. The behavior of tubular columns filled by concrete is compared based on the results of experimental analysis. The behavior of columns without concrete is included into comparison. Numerical model has been developed in order to ensure consistency of the output of the numerical calculation and the data obtained at the test specimens. Finally sensitivity analysis is presented which gives some information about influence of input parameters on the buckling strength. At the conclusion parameters with the greatest influence on the buckling resistance are discussed whereas the efficiency of using high-strength concrete is observed.

***Keywords*—**steel tubes filled by concrete, buckling resistance, sensitivity analysis, composite columns.

I. INTRODUCTION

STEEL tubular columns filled by concrete are used mainly as structural members subjected to compression. Examples of such structural members can be columns of buildings as well as braces of bridge structures. The advances in technology lead to the increase of the utilization of high-strength materials also in the field of composite columns. This raises the question about efficiency of high-strength concrete in the case of circular steel tubular columns filled by concrete.

The combination of circular tubes and high-strength concrete seems to be one of the most effective ways to use the high-strength concrete because of eliminating the lack of tensile strength. In the case of high-strength concrete the tensile strength is growing not in proportion to compressive strength, but more slowly. This means that a large increase in compressive strength is not accompanied by a corresponding increase in tensile and shear strength in comparison with normal strength concrete. Confinement of concrete core by steel shell leads to prevention of shear or tension failure, whereas high compressive strength can be activated.

Research programme discussed in this paper was carried out in order to investigate the effect of the concrete strength on buckling resistance of steel tubular columns filled by high-strength concrete. Experimental analysis of compressed circular tubes filled by concrete was conducted. The solution includes development of numerical model and sensitivity analysis. Parameters with the greatest influence on the buckling resistance are searched within the solution.

II. EXPERIMENTAL ANALYSIS

Steel tubes filled by concrete subjected to buckling compression are under investigation. For the loading tests the tubes of the diameter of 159 mm and the thickness of 4.5 mm with the buckling length of 3 000 mm were used. Total of 18 test specimens were tested within the analysis. One half of the test specimens were tubes of steel grade S235, other specimens were tubes of steel grade S355. The specimens were divided into three groups of six pieces. The first group of specimens was tested without concrete, second group of specimens was filled by concrete of class C55/67 and third group of specimens was filled by concrete class C80/95. In combination with the two classes of steel strength six partial experiments were achieved. Overview of arrangement of columns is given in Table I.

To investigate the real geometry of test specimens the basic geometric parameters of steel members were measured using geodetic methods before concreting. The following geometric characteristics were measured: deviations of the member axis from the directness lengthwise and deviations of cross-section parts from the nominal dimensions. It is assumed that the buckling will occur in the direction of the maximum geometric imperfection, which is important for the orientation of test specimens in the test set-up and for the measurement of transverse deformations during the loading tests.

The test specimens were loaded by axial pressure in a vertical position and were oriented so that the bearing edge was perpendicular to the expected plane of buckling. Test

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specimens were loaded gradually. The size of a load step of 100 kN was chosen in view of a creep and with respect to the expected resistance of the specimen (theoretically calculated). The load test was terminated when there was an increase of vertical displacement and horizontal deflection without increasing load. So if the load exceeded the ultimate strength of the tested element. The buckling resistance of the specimen is given by maximum load achieved. Illustration of the test realization is shown in Fig. 1.

Table I Arrangement of test specimens

Group of the test specimens	The composition of the column
1	Tube without concrete
	Steel grade S235
2	Tube without concrete
	Steel grade S355
3	Tube filled by concrete
	Steel grade S235
	Concrete strength class C55/67
4	Tube filled by concrete
	Steel grade S355
	Concrete strength class C55/67
5	Tube filled by concrete
	Steel grade S235
	Concrete strength class C80/95
6	Tube filled by concrete
	Steel grade S355
	Concrete strength class C80/95

Real material properties were measured on material specimens in order to compare values of buckling resistance achieved experimentally and numerically determined values. The material properties were as follows: the steel yield strength was measured on 6 material specimens and the mean value was 344 MPa in case of steel grade S235 and 475 MPa in case of steel grade S355; the mean value of concrete cube strength was 70.9 MPa in case of concrete class C55/67, modulus of elasticity was 36.2 GPa; the mean value of high-strength concrete cube strength was 97.7 MPa in case of concrete class C80/95 and modulus of elasticity was 45.3 GPa. The concrete cube strength was measured at the age of 28 days.

Three different values of buckling load for each specimen are considered to evaluate the results of load tests. $N_{exp,\ max}$ is maximal load achieved on the specimen during the testing. $N_{Rk,\ nom}$ is ultimate load with respect to the buckling calculated according to EN 1994-1-1 [15] with use of nominal material properties. N_{real} is the same ultimate load but with use of real measured material properties. Overview of these three values for all groups of specimens is given in Table II. N_{real} was calculated using concrete cylinder strength, which was converted from concrete cube strength in case of concrete C55/67 by coefficient 0.8 and in case of concrete C80/95 by coefficient 0.85.

Table II Overview of ultimate load values

Group of the test specimens	$N_{exp,\ max}$ [kN]	Mean value of $N_{exp,max}$ [kN]	$N_{Rk,\ nom}$ [kN]	N_{real} [kN]
1	672,1	707,4	459,8	634,5
	738,0			
	712,2			
2	869,8	858,9	650,5	806,1
	849,9			
	857,1			
3	1350,9	1422,8	1150,0	1268,4
	1509,1			
	1408,3			
4	1710,0	1706,7	1274,2	1374,6
	1704,6			
	1705,5			
5	1557,3	1524,2	1364,9	1483,5
	1500,9			
	1514,6			
6	1767,0	1744,5	1457,0	1565,6
	1710,9			
	1755,5			

III. RESULTS OF EXPERIMENTAL ANALYSIS

All partial tests were conducted in a standard way. During loading process the loading force, vertical displacement in bearing and transversal deflection in middle of the length of specimens was measured.

When testing specimens filled by high-strength concrete, crashes were heard caused by a sudden failure of the specimen. In case of these specimens with high-strength concrete low ductility was observed, buckling occurred suddenly without a clear plastic phase as it was in cases of specimens without concrete or with concrete C55/67. It can be stated that the specimens with a high-strength concrete showed brittle behavior.

Mean values, standard deviations and variation coefficients of values observed are given in Table III. Load deflection relationships are depicted in Fig. 2. Comparison of maximal load measured for each groups of specimens can be seen in Fig. 3. The graph in Fig. 3 shows that the use of high-strength concrete has very little effect on the increase in buckling resistance. The increase in buckling resistance is expressed as a percentage in Table IV. The base (100%) is taken always buckling resistance of the tube without concrete. Filling tubes of steel grade S235 by concrete C55/67 leads to increase of buckling load capacity by 101% compared to the empty tube.

Steel tube of the same strength filled by concrete of strength class C80/95 gives increase in buckling resistance by 115%. In case of tubes of steel grade S355 is a buckling resistance increased by 99% for filling by C55/67 concrete and by 103% when using concrete C80/95.

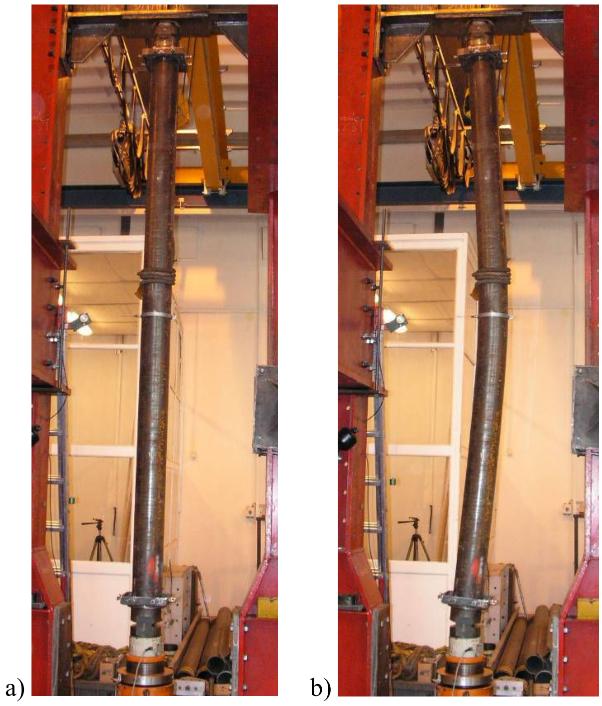
a) b)

Fig. 1 Test arrangement and realization

Table III Results of experimental analysis

Group of the test specimens	Mean value [kN]	Standard deviation [kN]	Variation coefficient
1	707,4	27,1	0,04
2	858,9	8,2	0,01
3	1422,8	65,39	0,05
4	1706,7	2,39	0
5	1524,2	24	0,02
6	1744,5	24,16	0,01

Table IV Results of experimental analysis

Circular tube 159/4.5	Group of the test specimens	Mean value [kN]	Increase in resistance
Steel grade S235	**1 - *without concrete***	707,4	0%
	3 - *filled with C55/67*	1422,8	101%
	5 – *filled with C80/95*	1524,2	115%
Steel grade S355	**2 - *without concrete***	858,9	0%
	4 - *filled with C55/67*	1706,7	99%
	6 – *filled with C80/95*	1744,5	103%

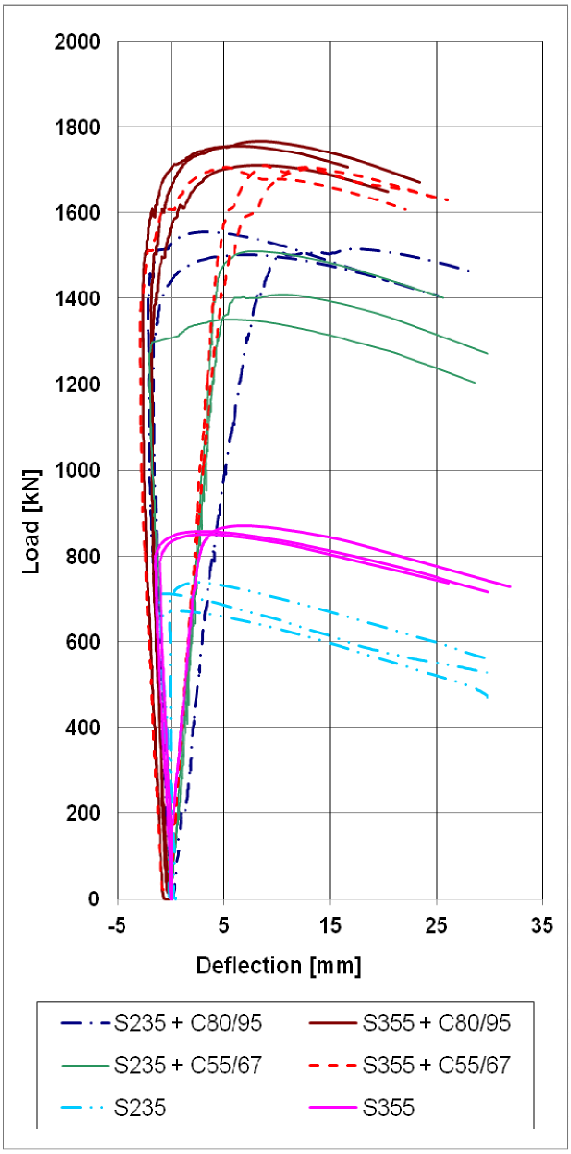

Fig. 2 Load – deflection relationships

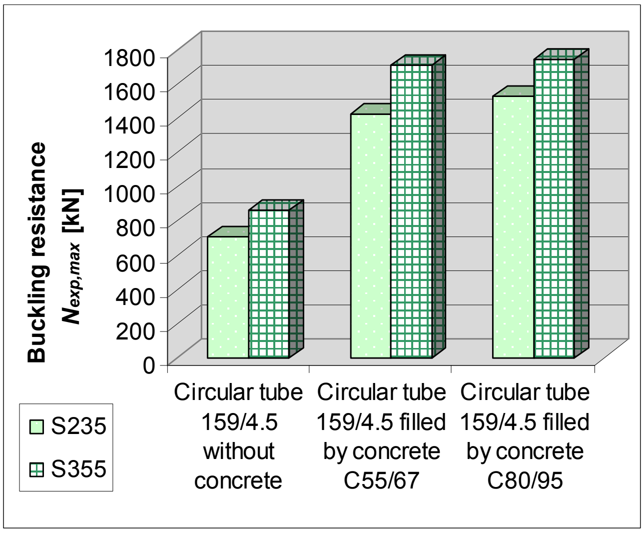

Fig. 3 Maximal measured load of specimens

The direction of deflection corresponds to the direction of the initial maximum deflection rather random. It seems to be unpredictable as well as the size of deflection, which is depicted in Fig. 4 for specimens with steel of strength grade S235 (three specimens for each group of the test specimens) and in Fig. 5 for specimens with steel strength grade S355. Deflections are shown that were obtained at maximum load

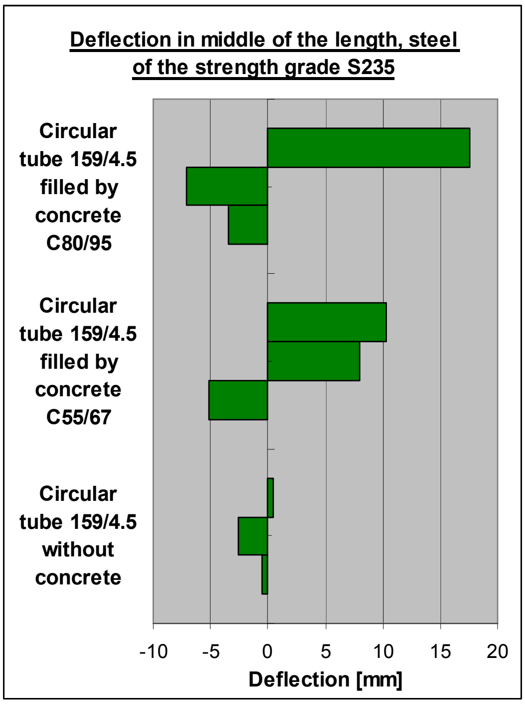

Fig. 4 Size of deflection, S235

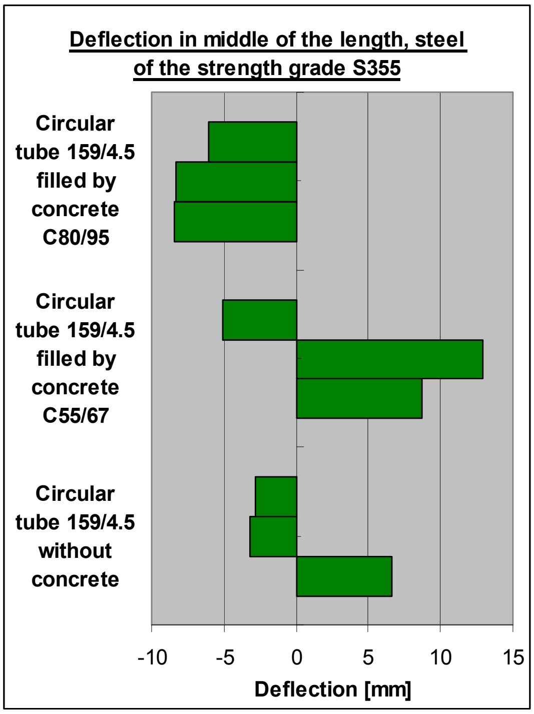

Fig. 5 Size of deflection, S355

IV. NUMERICAL MODEL

Numerical model has been developed in program ATENA 3D, which is determined for nonlinear finite element analysis of structures. This program is based on the deformation method and describes the nonlinear behavior of quasi-fragile materials by fracture mechanics. The steel tube and concrete core was generated by eight-sided column macro-elements because it is not possible to model the circular shape in ATENA. In order to better simulation of the test setup both ends of model were fitted up with steel plate, whereas supports were entered on the plates. Line supports were applied to assume pinned supports in the plane of bending as compared with experiment, where pinned joint was presented by bearing with cutting edges. Values of steel yield strength, steel modulus of elasticity, concrete strength and concrete modulus of elasticity determined from material tests were entered in definition material type. The Fig. 6 shows the numerical model in the phase of pre-processor (a), in the phase after calculating (b) and plotting iso-areas of normal stresses (c) where darker areas indicate compressive stress, the lighter the tensile stress.

In this time only initial results from numerical model are known. Results of a numerical model for the tubes filled with concrete are presented in the form of load-deflection response in Fig. 7 – Fig. 10. Load-deflection responses of circular steel tube filled by concrete predicted by the numerical model are compared with corresponding experimental results. It can be seen that the numerical model results are in good agreement with behavior of the test specimens observed during the experimental analysis.

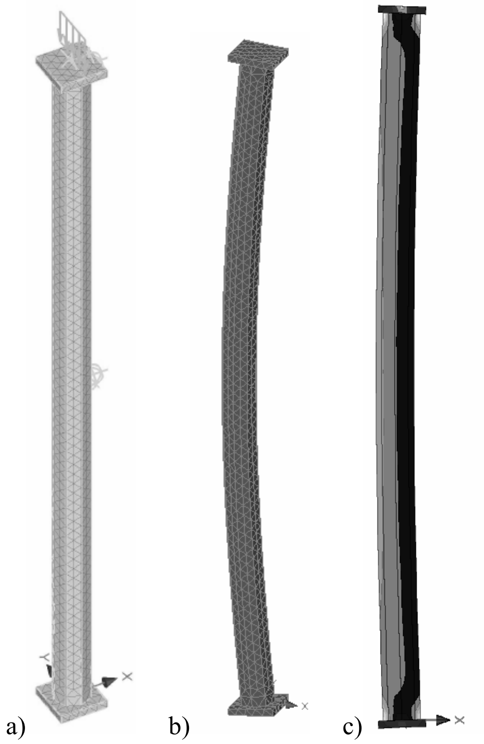

Fig. 6 Numerical model

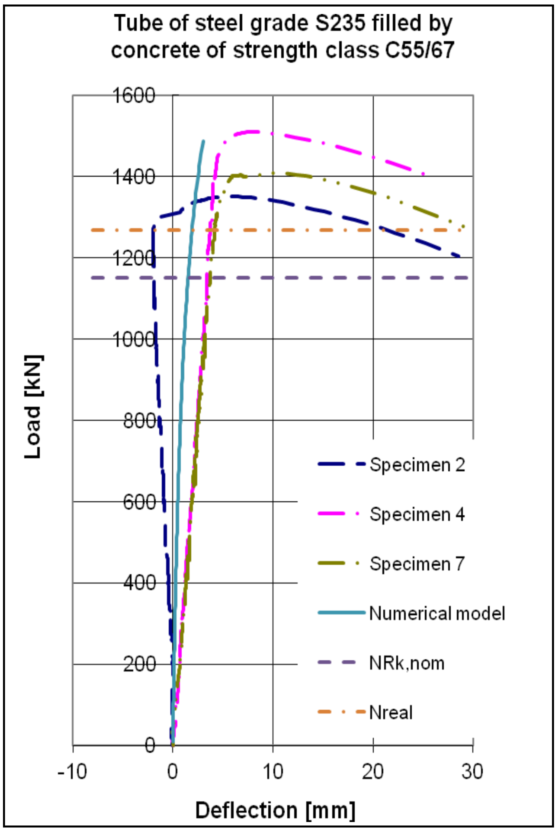

Fig. 7 Verification of numerical model (Group 3)

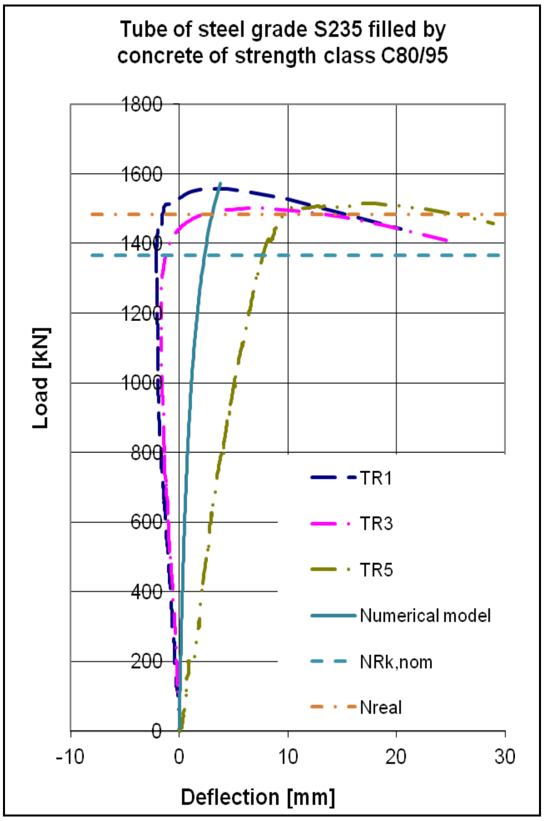

Fig. 8 Verification of numerical model (Group 5)

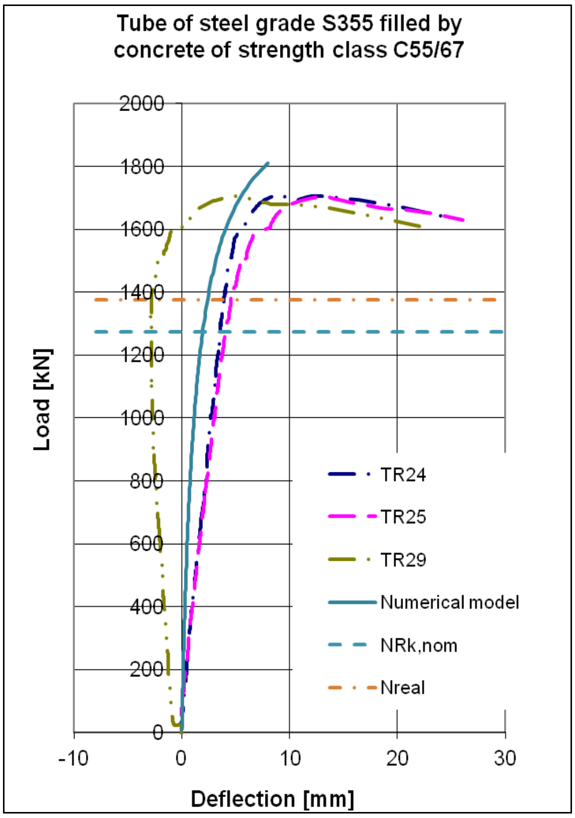

Fig. 9 Verification of numerical model (Group 4)

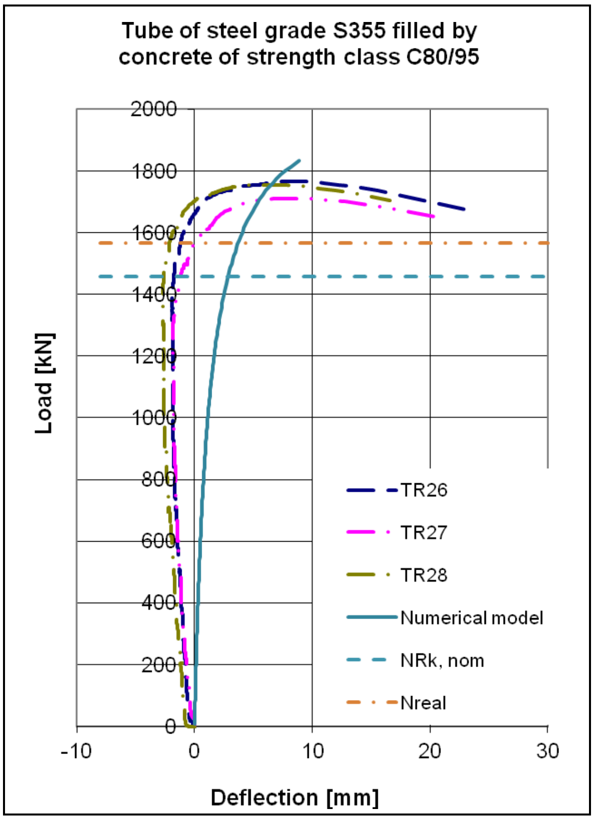

Fig. 10 Verification of numerical model (Group 6)

Numerical model gives the values for the graph in Fig. 11 illustrating the nonlinear dependence of transverse strain of concrete to longitudinal strain of concrete. Poisson's ratio, which is ratio of transverse strain to longitudinal strain, is not constant but increasing after reaching some value of loading. This effect can be explained by inception of micro-cracks. After the creation of cracks volume of material is increasing by the area of cracks.

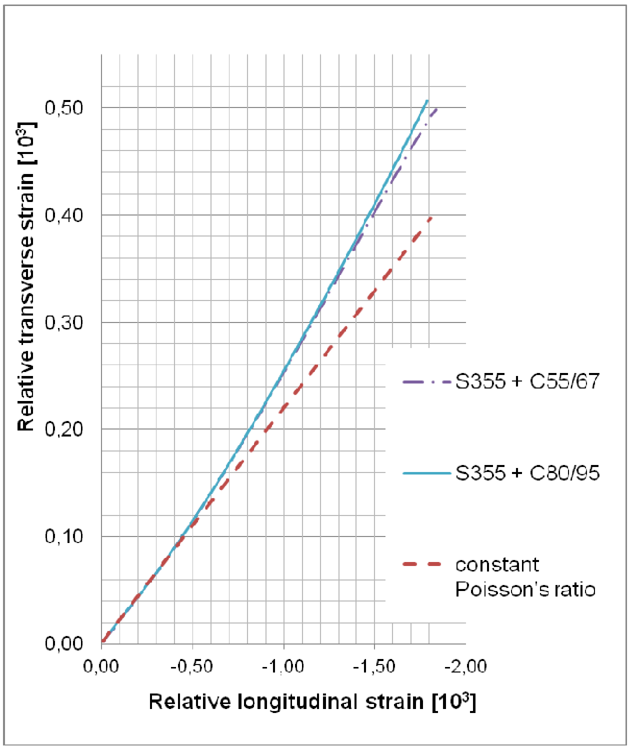

Fig. 11 Dependence of transverse strain of concrete to longitudinal strain of concrete

V. SENSITIVITY ANALYSIS

A. Inputs Parameters

The inputs parameters for sensitivity analysis are geometrical characteristics and strength characteristics of the test specimens whereas probabilistic and statistical quantities were obtained from measurements. Statistical values and probabilistic distribution unknown from measurement were entered according to the recommendation on web of Joint Committee on Structural Safety [14]. In agreement with this recommendation log-normal distribution was input in case of strength characteristics of steel and concrete as well as standard deviations of concrete strength characteristics. Only mean values of concrete cube strength are known from material concrete tests. Recalculated values corresponding to the cylinder strength were entered into analyzed model. Overview of the input strength characteristics can be seen in Table V. Geometrical characteristics are listed in Table VI.

Table V Mean values and standard deviations of strength characteristics

i	Parameter		Distribution φ (x_i)	Mean μ_i	Std σ_i
1	Steel yield strength S235 f_y	[MPa]	Log - normal (2 par)	344,39	15,41
2	Steel modulus of elasticity S235 E_a	[MPa]	Log - normal (2 par)	209200	11,99
3	Steel yield strength S355 f_y	[MPa]	Log - normal (2 par)	475,39	12,03
4	Steel modulus of elasticity S355 E_a	[MPa]	Log - normal (2 par)	199800	7,68
5	Concrete strength C55/67 f_c	[MPa]	Log - normal (2 par)	56,72	4,254
6	Concrete modulus of elasticity C55/67 E_c	[MPa]	Log - normal (2 par)	36200	5,43
7	Concrete strength C80/95 f_c	[MPa]	Log - normal (2 par)	83,05	5,862
8	Concrete modulus of elasticity C80/95 E_c	[MPa]	Log - normal (2 par)	45300	6,795

Table VI Mean values and standard deviations of geometrical characteristics

i	Parameter		Distribution φ (x_i)	Mean μ_i	Std σ_i
1	Tube diameter d	mm	Normal	158,7	0,38
2	Tube thickness t	mm	Normal	4,5	0,1
3	Tube length L	mm	Normal	3000	20

B. Results of the Sensitivity Analysis

Using the input parameters calculate process was programmed for evaluation of buckling resistance according to the EN 1994-1-1 [15]. Buckling strength curve *a* was entered into calculation (coefficient of imperfections α = 0,21). Then numerical simulations were performed by means of statistical methods: Monte Carlo and Latin Hypercube Sampling. Results of both methods for various numbers of simulations are presented for comparison.

Correlation coefficients are calculated between all random input variables and response variable i.e. buckling resistance. These coefficients show the relative influence of random variables on value of buckling resistance. The correlation coefficient is higher, the buckling resistance is more dependent on the parameter. A positive coefficient represents a direct dependency (the higher strength of concrete, the higher buckling resistance of composite column). If the correlation coefficient is negative, buckling resistance is inversely proportional to the variable (the higher buckling length, the lower buckling resistance). For each group of specimens sensitivity is introduced for corresponding characteristics (concrete strength and steel yield strength according to the composition of specimens in the group).

In Table VII correlation coefficients are presented for five parameters with the greatest influence on the buckling resistance. It can be seen that correlation coefficients for particular parameters are very similar using different simulation method and different number of simulations. In general, more accurate results are expected in a higher number of simulations. Simulations performed by means of Latin Hypercube Sampling method should give more accurate results than the Monte Carlo simulation. Fig. 11 shows graphic presentation of correlation coefficients obtained in simulation by method Latin Hypercube Sampling when number of simulation was 10 000.

Table VII Correlation coefficients

Parameter	Method of simulation, number of simulations	S235 + C55/67	S355 + C55/67	S235 + C80/95	S355 + C80/95
Strength of concrete	**MC, 1000**	0,798	0,701	0,82	0,724
	MC, 100 000	0,811	0,718	0,82	0,716
	LHS, 10 000	0,809	0,711	0,819	0,714
Steel yield stress	**MC, 1000**	0,347	0,239	0,247	0,169
	MC, 100 000	0,356	0,247	0,261	0,178
	LHS, 10 000	0,358	0,245	0,263	0,179
Tube thickness	**MC, 1000**	0,325	0,469	0,324	0,432
	MC, 100 000	0,321	0,468	0,317	0,434
	LHS, 10 000	0,323	0,469	0,318	0,434
Tube diameter	**MC, 1000**	0,206	0,27	0,23	0,293
	MC, 100 000	0,184	0,251	0,227	0,289
	LHS, 10 000	0,186	0,248	0,231	0,293
Buckling length	**MC, 1000**	-0,187	-0,289	-0,258	-0,354
	MC, 100 000	-0,182	-0,291	-0,249	-0,352
	LHS, 10 000	-0,185	-0,293	-0,253	-0,357

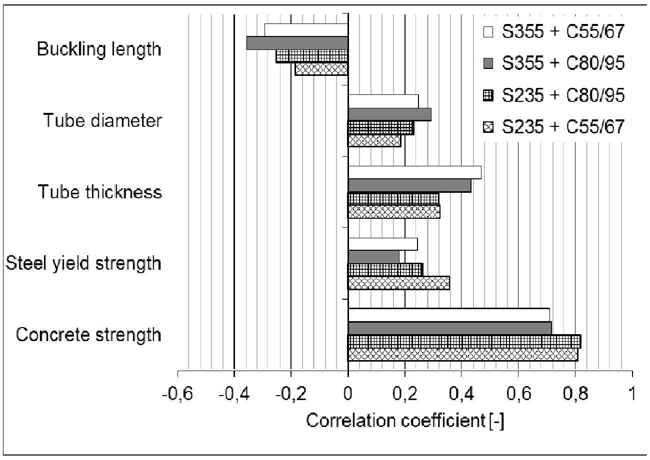

Fig. 12 Graphic presentation of correlation coefficients

VI. CONCLUSIONS

Experimental analysis of 18 test specimens was carried out within the research programme. The common parameter is the length of the specimens of 3.0 m, the diameter of tubes of 159 mm and the thickness of 4.5 mm. Variable is the yield stress of the steel tube and the concrete strength. Specimens were subjected to buckling compression whereas maximum achieved load was observed. Attention was paid to the effect of the concrete strength on the buckling strength. The results of the experimental analysis can be compared with earlier investigations, see e. g. [8], [9].

Based on the test results it can be stated that the use of high-strength concrete is inefficient in case of steel circular tube with diameter of 159 mm and thickness of 4.5 mm. The question is what extend of increase in concrete strength is worthwile in case of circular steel tube filled by concrete. Fig. 13 shows comparison of experimental and theoretical values of buckling resistance investigated within the experimental analysis. Obtained points are slightly scattered around the median line of the quadrant. This means that the normative recommended calculation of buckling resistance corresponds to the actually observed values for all groups of specimens. The largest deviation from the ideal line show tubes of steel grade S355 filled with concrete. Experimental part of research programme presented in this paper will be continued by using some of the method based on statistical or probabilistic approach, in particular the methods of the design assisted by testing (see [7], [10]).

Numerical model has been developed in order to ensure consistency of the output of the numerical calculation and the data obtained at the test specimens. The aim of the numerical model is to replace some of the tests performed actually in order to provide data for developing of buckling curves for tubular columns filled by high-strength concrete. First phase of numerical analyses is presented in this paper. Numerically predicted load-deflection relationships are in good agreement with relationship observed during experimental analysis. The results of the numerical model uncovered the fact that Poisson's ratio is not linear during loading. It seems that it is a specific phenomenon of steel tube filled with concrete.

In this paper results of sensitivity analysis are presented. The aim of sensitivity analysis was to find out which of input parameters has the greatest influence on the buckling resistance of composite column made by steel tube filled with concrete. Four models were analyzed differing in grade of steel and strength of concrete. In this case, it was found out that the choice of a simulation method does not affect the results.

It can be seen from the results of sensitivity analysis in Fig. 12 that the strength of concrete has the greatest positive influence on buckling resistance. Influence of strength concrete is twice greater than influence of steel yield strength. As for the geometrical parameters the greatest is the influence of tube thickness which is greater by tubes of steel grade S355 than that of steel grade S235 according to the expectation.

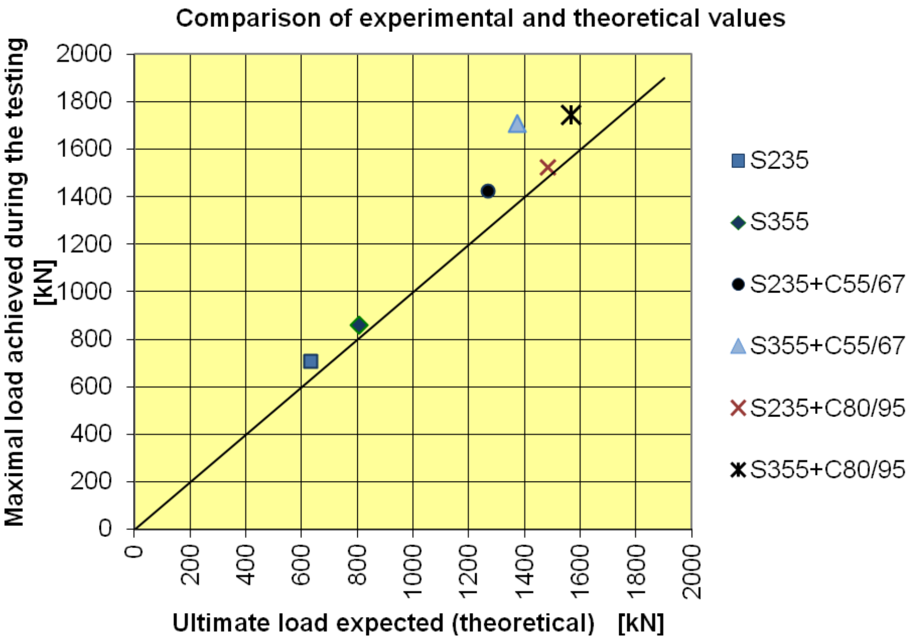

Fig. 13 Comparison of experimental and theoretical values

Negative influence on the buckling resistance has the length of tube which corresponds to the critical length of member when considering pinned ends of columns. The critical length has greater influence in case of models with using steel of grade S355. The results of sensitivity analysis confirm the influence of concrete strength on the buckling resistance of the column.

The research programme presented in this paper includes experimental analysis, numerical model and sensitivity analysis. Research will be continued by extending the group of specimens. The aim of further investigation is to contribute to knowledge about the behavior of tubes filled with concrete, especially tubes filled with high-strength concrete.

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