Steel and Composite Structures, *Vol. 19, No. 2 (2015) 293-308*
DOI: http://dx.doi.org/10.12989/scs.2015.19.2.293

Analysis of behaviour for hollow/solid concrete-filled CHS steel beams

Audronis Kazimieras Kvedaras *, Gintas Šaučiuvėnas [a],
Arūnas Komka [b], and Ela Jarmolajeva [c]

Department of Steel and Timber Structures, *2Department of Structural Mechanics*,
Vilnius Gediminas Technical University, *11 Sauletekio ave*, *Vilnius 10223*, *Lithuania*

(*Received June 27, 2014, Revised November 25, 2014, Accepted June 01, 2015*)

Abstract. Interaction between the external thin-walled steel tube and the internal concrete core significantly increases the bending resistance of composite beams and beam-columns in comparison with the steel or concrete members. There is presented a developed method for design of hollow and solid concrete-filled steel tubular beams based on test data, which gives better agreement with test results than EC4 because its limitation to take an increase in strength of concrete caused by confinement contradicts the recommendation of 6.7.2(4) that full composite action up to failure may be assumed between steel and concrete components of the member. Good agreement between the results of carried out experimental, numerical and theoretical investigations allows recommending the proposed method to use in design practice.

Keywords: composite steel-concrete beams; concrete-filled circular steel tubes; hollow and solid concrete cores; design based on test data

1. Introduction

One of the most effective ways for industrialization of construction and realization of the main structural materials (steel and concrete) is the widening of the use fields of composite steel and concrete structures. The use of composite steel and concrete members consisting of relatively thin-walled circular or rectangular steel tubes and ordinary concrete is conceivable as means of economic improvement of the strength and ductility for structural members and their connections. Some composite steel-concrete members may also be produced by the means of centrifugal force. The centrifuging process allows developing composite steel and concrete members with an effective hollow concrete core which may be used in buildings and bridges efficiently. In some countries hollow composite steel and concrete members are now more widely used as foundation piles (Matzumoto *et al*. 1976), but according to our test data and other development results

---

∗Corresponding author, Professor, E-mail: audronis-kazimieras.kvedaras@vgtu.lt
[a] Ph.D., Associate Professor
[b] Ph.D., Associate Professor
[c] Ph.D., Associate Professor

http://www.techno-press.org/?journal=scs&subpage=8 ISSN: 1229-9367 (Print), 1598-6233 (Online)

(Uenaka and Kitoh 2011) a wide application of them in bridge piers as well as in columns, beam-columns and beams for buildings is expected too. Oyawa *et al*. (2004) seeks for the alternative polymer-based fill materials to the much-limited cement concrete used in concrete-filled steel tubular structures, especially for circular steel beams subjected to pure bending. Montague (1978); Zhao *et al*. (2002) present some information about possibilities of application of concrete-filled double skin circular hollow section composite members.

The comparison of results of resistance calculations for short concrete-filled steel tubular elements in compression on the base of criteria of small elastic-plastic strains (Kikin *et al*. 1974) has showed a good agreement with test data. It is usual to suppose that an existing the functional relationship expressing the magnitude of increase in resistance of composite member upon its mechanical geometrical parameter (Luksha 1977), or upon the steel contribution factor according to the Eurocode 4 (CEN 2004)

The obtained own test data show higher efficiency for slender differently loaded hollow members against short ones and it is in some contradiction with the limitation of (CEN 2004) that for the concrete-filled tubes of circular cross-section, account may be taken of increase in strength of concrete caused by confinement provided that the relative slenderness $\bar{\lambda}$ does not exceed 0.5 and $e/d < 0.1$, where e is the eccentricity of loading given by M_{Ed}/N_{Ed} and d is the external diameter of the member. This contradicts with the recommendation given in 6.7.2(4) of CEN (2004) that full composite action up to failure may be assumed between the steel and concrete components of the member, because increase in strength of concrete and, perhaps, of steel caused by confinement should exist under different loading conditions – uniaxial and eccentric compression and tension, bending etc. It is usually believed that the concrete-filled steel tubes are the most useful in those buildings where mainly great compression forces are acting. However, the research data and building practice show that efficiency under other actions as those for circular composite beams evidently confirms the research data presented in (Matzumoto *et al*. 1976). It is also necessary to mention some further researches carried out in the field of various composite steel and concrete beams. First of all it is possible to mention the works of Elchalakani *et al*. (2001), Wheeler and Bridge (2011) and Han (2004). Among the latest investigations of composite beams reference to Jiang *et al*. (2013a, b) may be mentioned, who were studying the design of thin-walled centrifugal concrete-filled steel tubes for which an accurate finite element model was developed and verified against experimental results, but since the design bending resistance based on FEA model and exact parametric method are difficult to be calculate, empirical equations were proposed for simple predicting of the bending resistance with the reasonable accuracy. The flexural behaviour of thin walled steel-concrete composite sections as cross sections for beams was investigated by conducting an experimental study supported by applicable analytical predictions (Valsa Ipe *et al*. 2013).

This above mentioned full composite action means that 2D and/or 3D stress state arises in the steel and concrete components of differently loaded members of very different dimensions including the flexural ones. The Model Code (CEB-FIP 1993) recommends the use of a four-parameter failure criterion, also known as the Ottosen's failure criterion, to estimate the strength of concrete under multi-axial states of stress (Montoya *et al*. 2006, Pereira and Barros 2009). The problem of application of such composite concrete filled circular steel tubular beams also exists because there is no design recommendation for them in Code of Practice (CEN 2004).

Application of different technologies, materials, cross-section types for steel shells and in-fill cores of composite members, including double-skin shells and multi-layer cores, has very great influence on behaviour of differently loaded composite elements. The behaviour of composite steel and concrete beams isn't still studied sufficiently, especially of those manufactured from the circular steel hollow sections filled with solid or hollow concrete cores. Therefore, methods of practical design of such composite beams are not developed enough and most codes of practice being now in force do not include full scale of necessary recommendations for their design. Such situation stresses on necessity to carry out more natural and numerical experiments with concrete-filled steel tubular beams which might enable developing of practical methods of their design based on test data using together the postulates and presumptions of classical theory of plasticity.

2. Analytical definition of bending resistance

Usually the elastic plastic behaviour of composite concrete-filled steel tubular beam is fixed during natural and numerical tests. Such behaviour may be described by model presented in Fig. 1 for composite beam with hollow concrete core. In this model well-grounded by data of natural as well as numerical experiments the elastic core around the plastic neutral axis fixed by central angles θ is seen in diagrams of distribution of steel and concrete stresses while in other parts of these diagrams distribution of steel and concrete stresses is ideally plastic corresponding to the rectangular diagrams.

The self-regulating resistance property is characteristic for concrete-filled steel tubular members. That property in Fig. 1 is expressed by constraining factors η_a and η_c, which values for an external shell steel and hollow core concrete respectively may be taken η_a = 1.074 and η_a = 1.320. For solid core concrete the value of constraining factor may be taken η_a = 1.640. The above given values of constraining factors may be applied because the interaction between a steel tube and a concrete core at their interface occurring during concentric compression causes an increase in the compressive strength of both components and in the robustness of whole such composite members. However, the theoretical and experimental description of the interaction between these components is under discussion. Usually this description is based whether on the postulates of the mathematical theory of elasticity or on the theory of plasticity of small elastic-plastic deformations

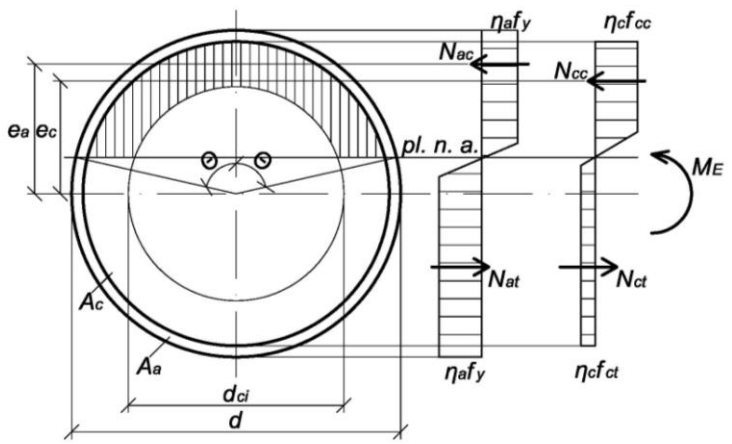


Fig. 1 Modelling of stress distribution in the steel and concrete tube cross-sections under bending for hollow concrete filled circular steel tubular beam

and it takes into account the different values of Poisson's ratio of component materials. A homologous definition of the strain criteria allows an exact definition of the robustness of concrete-filled steel tubular members evaluating their increase against the criteria determined by superposition of the resistances of these composite member components.

The structural behaviour of hollow concrete-filled circular steel tubular members under concentric compression is more complicated than that of composite members with solid concrete cores. The resistance analysis of composite concrete-filled circular steel tubular members may be based on the postulates of the theory of plasticity. Then from the generalized Hooke's law, the normal ultimate stresses of both media – external steel shell and internal concrete core – under either concentric compression or tension have to be expressed by the formula

$$\sigma_x = (4/3)E_{im}\left(\varepsilon_{x,y} + v \cdot \varepsilon_z\right) \tag{1}$$

where: v is Poisson's ratio, different values of which are observed for steel and concrete at different stages of loading; at ultimate state $v = 0.5$ for materials of both components of composite concrete-filled steel tubular members;

E_{im} – is the secant modulus of elasticity of the corresponding media;

$\varepsilon_{x,y}$ – the value of longitudinal strain of the external steel shell at the interface with concrete core (this strain therefore is the same for concrete core too) is expressed as

$$\varepsilon_{x,y} = 0.5\left(\varepsilon_z + \sqrt{3\left(\varepsilon_{iy}^2 - \varepsilon_z^2\right)}\right) \tag{2}$$

ε_Z – the value of tangential strain of the external steel shell at the interface with concrete core (this strain therefore is the same for concrete core too) is expressed as

$$\varepsilon_z = (\sigma_z - 0.5\sigma_x)/E_a \tag{3}$$

The structural behaviour of hollow concrete-filled circular steel tubular members under concentric compression is more complicated than that of composite members with solid concrete cores. Therefore the radial stress σ_Z of both media (of external steel shell and internal concrete core) interaction at their interface is expressed as:

- In case of the annular concrete core

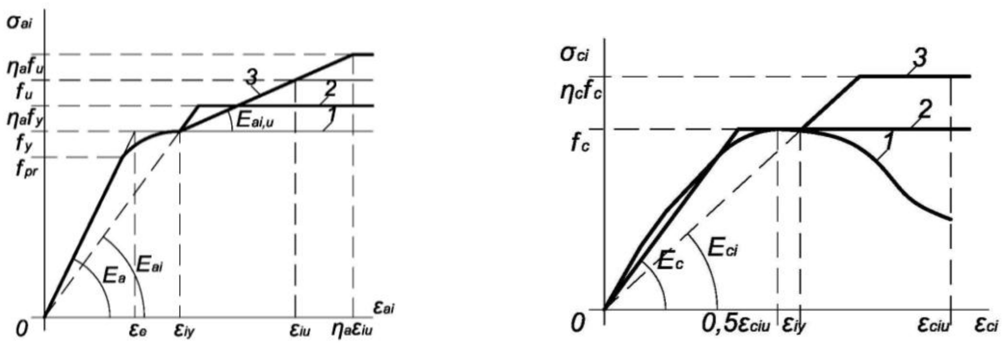
$$\sigma_z = 2\left(f_{cm}E_a - f_yE_c\right)/\left\{E_a(2\beta_i - 1)/(\beta_i - 1) - E_c\right\} \tag{4}$$

where $\beta_I = (d - t)/d_{ci}$ is taken as relational thickness of the annular concrete core;

- In case of the annular concrete core

$$\sigma_z = \left(f_{cm}E_a - f_yE_c\right)/\left(E_a - 0.5E_c\right) \tag{5}$$

Because the value of core concrete strength in tension is comparatively small in the practical strength analysis of composite steel and concrete members Eq. (1) not be used to determine this strength which by Eurocode 4 (CEN 2004) is usually recommended to take as negligible.



(a) External shell steel (b) Core concrete

Fig. 2 Generalised stress-strain relationship under unblocked (1), blocked typical (2) and bilinear blocked (3) deformations

Because of the assumed equality of biaxial stress state in a steel shell and in a concrete core (Kvedaras and Kudzys 2010), the ultimate value of the generalized strain ε_{iy} = 1.5f_y / E_a will be the same for both materials. Thus, the ultimate normal stresses of steel σ_{ax} in tension and compression and of concrete σ_{cx} in compression defined from Eq. (1) represent the modified values of steel and concrete strengths as follows

$$f_a = \sigma_{a,x} = \eta_{am} f_y \quad \text{and} \quad f_c' = \left(\sigma_{c,x} + f_c\right)/2 = \eta_{cm} f_c \tag{6}$$

where η_{am} and η_{cm} are the steel and concrete constraining factors as random variable values characterizing the interaction effect of the components of a composite member on its load-bearing capacity under compression (or tension), respectively;

f_y and f_c are the values of steel yield and concrete specified compressive strengths, respectively.

The positions of f_y and $\eta_a f_y$ for mild steel are presented in Fig. 2(a). When the thickness of a steel tube is less than its ultimate minimum, the critical steel strength f_{cr} has to be used instead of f_y in a compressed member. The value of the constraining factor for annular core concrete η_c is obtained taking into account the unequal distribution of the normal stresses through the wall thickness of the annular cross-section of the concrete core with its maximum value on the interface with the steel shell and the minimum one at the internal surface of its cavity. It is also required to evaluate by the value of η_c has also to evaluate the necessary jump from the 3D and 2D stress states to the 2D and 1D stress states, respectively, in the annular cross-section of the concrete core in the strength analysis due to the postulates of the theory of plasticity applied for a concrete-filled tubular steel member with components from materials with different Poisson's ratios.

In Fig. 2(a) strain ε_{iy} is fixing the point of beginning the steel's yielding expressed further by horizontal line 1. At this point the secant modulus E_{ai} of the starting of steel yielding also is fixing. The line 2 presents the blocked typical deformations at the level of modified steel strength $\eta_{am} f_y$. The line 3 inclined by modulus $E_{ai,u}$until modified value of the steel ultimate tensile strength $\eta_{am} f_y$ allows to evaluate the increased strength of shell's usually high-strength steel because of interaction effect between external circular steel shell and internal concrete core in the region between yield strength and ultimate tensile strength, which usually corresponds the lateral yielding of the shell's steel in circular concrete filled member under compression or tension.

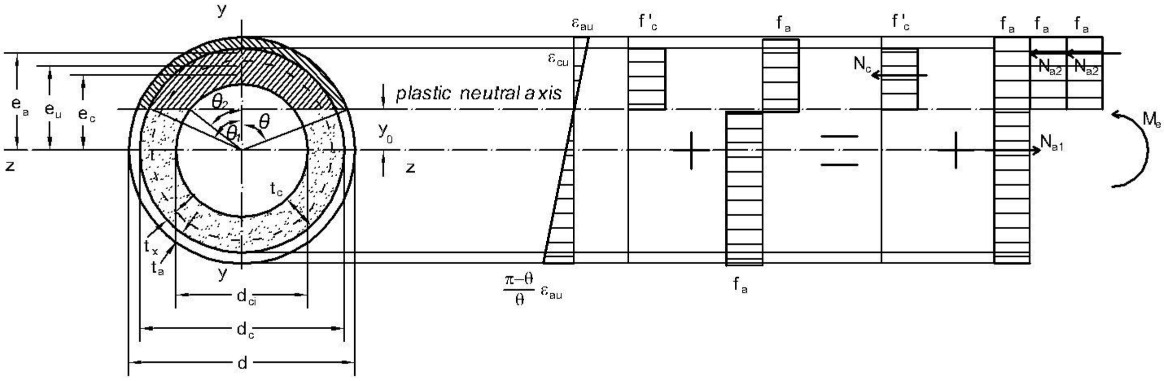


Fig. 3 Modelling of linear strain and ideally plastic stress distributions in the steel and concrete tubular cross-sections

The stress-strain relationships of concrete under different deformation laws are presented on Fig. 2(b).in which the strain ε_{iy} is fixing the point of beginning the steel's yielding but on these generalised stress-strain relationship curves for concrete core. At this point the secant modulus E_{ci} of core's concrete also is fixed.

The uniaxial bending moment resistance of circular composite concrete-filled steel tubular beam may be calculated using ideally plastic material models for concrete and steel (see Fig. 3).

The design moment resistance $M_{pl,Rd}$ is defined by the plastic axial tension resistance $N_{pl,Rd}$ of the steel cross-section and design eccentricity e_u, which depends on the type of member cross-section

$$N_{pl,Rd} = A_a \cdot f_{ud} \tag{7}$$

$$M_{pl,Rd} = N_{pl,Rd} \cdot e_u \tag{8}$$

For definition of the bending resistance of circular composite concrete-filled steel tubular beams estimating the strength of steel and concrete in such members under multi-axial state of stresses in this investigation the methods presented in (Kvedaras 1983, Kvedaras *et al*. 2013) and based on criteria of small elastic-plastic strains and on the law of generalized curves from the theory of plasticity (Kikin *et al*. 1974) were applied.

Therefore, the value of design ultimate tensile strength f_u applied in Eq. (7) for different types and dimensions of members may vary; as a result it is marked further by f_a

$$\text{If} \quad k_a \cdot k_w < f_y, \quad \text{then} \quad f_a = \eta_a \cdot f_y \tag{9}$$

$$\text{If} \quad f_y < k_a \cdot k_w < f_u, \quad \text{then} \quad f_a = \eta_a \cdot f_{\text{mod}} \tag{10}$$

$$\text{If} \quad k_a \cdot k_w > f_u, \quad \text{then} \quad f_a = \eta_a \cdot f_u \tag{11}$$

where

$$k_a = 0.5 \cdot E_c \cdot A_c / E_{a\cdot} \cdot A_a \leq 1 \tag{12}$$

If $t > t_{wu}$, then in all senses $k_a = 1$

$$k_w = f_y \cdot W_p / W \tag{13}$$

$$f_{\text{mod}} = k_a \cdot k_w \tag{14}$$

Here $\cdot W_p$ and W – plastic and elastic section modulus of steel shell, respectively.

Below in this investigation the circular composite beams with solid and hollow concrete cores were analysed.

2.1 Circular composite beams with solid concrete core

Dimensions of cross-section of circular fully concrete-filled steel tubular beam and position of plastic neutral axis are shown on Fig. 4. The corresponding relationships presented in (Kvedaras *et al*. 2013) are used to find the ultimate values of bending resistance including ones of axial resistance and ultimate eccentricity for all analysed circular concrete-filled steel tubular beams.

2.2 Circular composite beams with hollow concrete core

Dimensions of cross-section of circular partially concrete-filled steel tubular beam and position of plastic neutral axis are shown on Fig. 5.

One of the most important parameters characterizing the bending resistance of composite members is a distance of plastic neutral axis from the main sectional axis. If the position of the plastic neutral axis of composite cross-section and the material characteristics of composite member are known, it is possible to define the bending resistance of such member exactly. Kvedaras (1999) have suggested expressions for angle θ defining the position of the plastic neutral axis for circular composite beams with solid and hollow concrete core

$$\theta = \cos\left\{\left[1 - \frac{2\ (t + t_x)}{d}\right]^k \cos\left[\frac{A_c}{t_x\ (d - 2t - t_x) + 2t\ (d - t_x)}\right]\right\}^{-1} \tag{15}$$

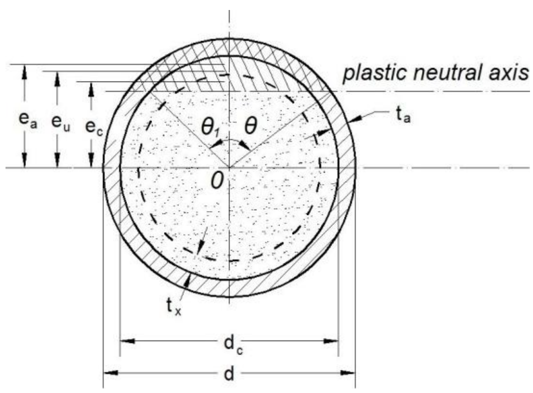


Fig. 4 Dimensions of cross-section of circular solid concrete-filled steel tubular beam and position of plastic neutral axis; t_x – thickness of relative circular steel core to which the solid concrete core is reduced

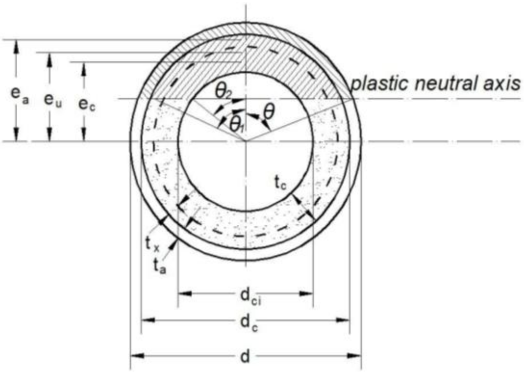


Fig. 5 Dimensions of cross-section of partially concrete-filled circular steel tubular beam and position of plastic neutral axis; t_x – thickness of relative circular steel core

Eq. (15) is derived for sections, presented in Figs. 4 and 5 modifying composite sections to hollow circular steel sections in which core thickness t_x represent thickness of relative steel hollow core by strength corresponding the solid or hollow concrete core. Application of the values of angle θ determined according to Eq. (15) gives possibility to calculate the ultimate values of bending resistance for circular composite beams with solid and hollow concrete cores but when using these values of angle θ it is impossible to determine exact value of distance between the plastic neutral axis and axis z – z of this composite section. Therefore, for this purpose the next expression for definition of angle θ of composite section proposed by Kvedaras and Kudzys (2010) was applied.

$$\theta = \frac{\pi \cdot \eta_a \cdot f_y \cdot A_a}{[2 \cdot \eta_a \cdot f_y \cdot A_a + 0.5 \cdot (1 + r_c / r_a) \cdot \eta_c \cdot f_c \cdot A_c]} \tag{16}$$

where $r_c = d_c / 2$ and $r_a = d / 2$ see in Figs. 4 and 5.

The distance of plastic neutral axis from the main z axis of the hollow circular composite section y_0 may be calculated using the next expression proposed by Kvedaras and Kudzys (2010)

$$y_0 = 0.5 \cdot d \cdot \sin\left(\frac{(0.5 \cdot \pi - \theta) \cdot 180}{\pi} \right) \tag{17}$$

Elchalakani *et al*. (2001) presented very similar expression for distance fixing position of plastic neutral axis of circular composite beams with solid concrete core

$$\gamma_0 = \frac{\pi}{4}\left(\frac{f_c r_i r_i}{f_y r_m t} \right) \Bigg/ \left[2 + \frac{1}{2}\left(\frac{f_c r_i r_i}{f_y r_m t} \right) \right] \tag{18}$$

where f_c - concrete cylinder strength; r_i - inside radius of the tube; f_y - measured yield stress of steel tube; r_i - mean radius of the tube; t - thickness of CHS wall.

Eqs. (17) and (18) for definition of the distance of plastic neutral axis from the main z axis of the circular composite section y_0 proposed by Kvedaras and Kudzys (2010) and Elchalakani *et al.* (2001) were used in comparison of results of analytical analysis and numerical simulation (see Chapter 4).

3. Natural and numerical experiments of composite beams

Circular composite steel and concrete elements have been tested using 4-point bending (see Fig. 6). The samples were tested until their loss of load bearing capacity. During the tests the stresses at the middle section of the beam and the vertical displacements have been recorded using for that the strain gauges fixed around this section and the inductive deflection measurers located beside the supports and under the points of load application, respectively. The obtained test results were compared with results obtained by numerical simulation and analytical calculation.

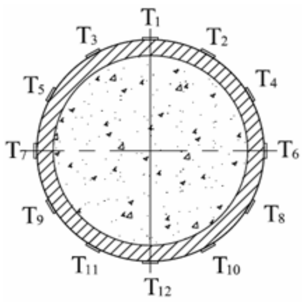
3.1 Circular composite beams with solid concrete core

Bending elements were made from steel tubes with external diameter 108 mm and thickness 2.25 mm filled with concrete. The length of beams was 2.0 m, the distance between supports was 1.8 m and the distance between the load adding points – 0.6 m. The calculations of load bearing capacity and numerical simulation were carried out using the actual strength values of tube steel and in-fill core concrete. Mean values of steel strength were such: yield strength – 400 MPa and ultimate tensile strength – 471 MPa. Class of concrete core according EN 206-1 was C20/25. More exact material data are given in Table 1.

3.2 Circular composite beams with hollow concrete core

Bending elements were made from steel tubes with external diameter 219 mm and thicknesses 1.60 mm and 4.50 mm filled with concrete. The length of beams was 3.40 m and 2.40 m, the distance between supports was 3.0 m and 2.10 m, respectively, the distance between the load adding points – 0.33 of span. Mean values of steel strength were such: yield strength – 250MPa and about 283 MPa and ultimate tensile strength – 374 MPa and about 350 MPa, respectively. Nominal cylindrical strength of concrete was 30.0 MPa and about 28.0 MPa, respectively. More exact data for materials used in specimens are given in Table 1.

(a) View on test specimen

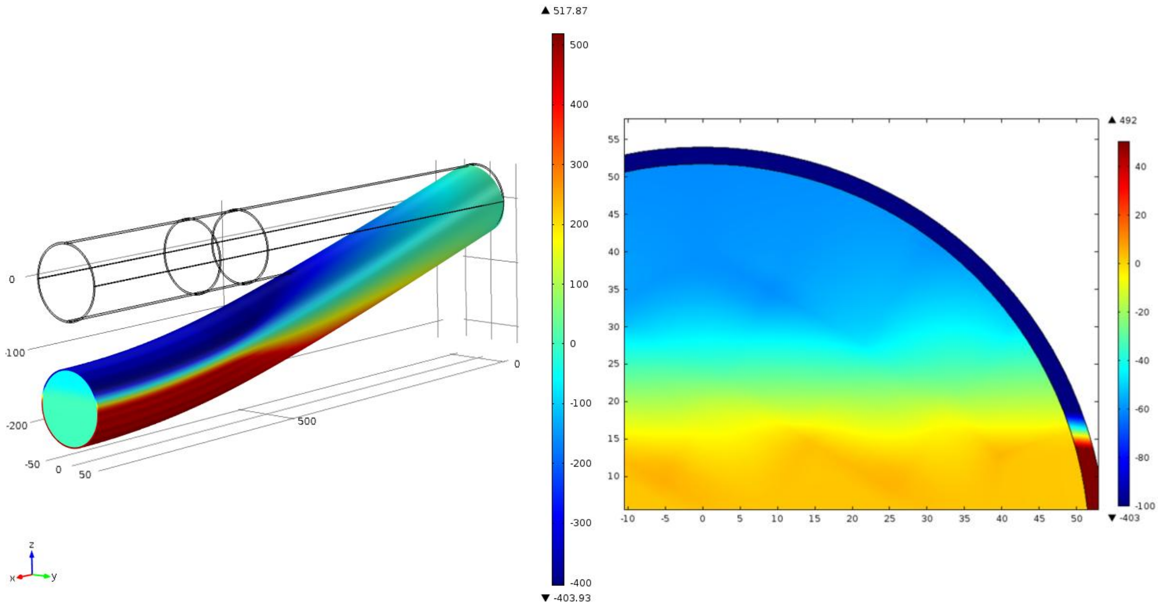


(b) Location of strain gauges

Fig. 6 4-point bending test of a solid concrete-filled CHS steel beam

3.3 Numerical experiment of composite beams

Numerical simulation of composite beams was done using software COMSOL 2010. Interaction of concrete core and the steel shell was modelled using the Ottosen's parameters, and for nonlinear analysis the Murnaghan's and Lame's parameters were used. The three main parameters were compared for beams – load bearing capacity, deflections and neutral axis position.



(a) In beam (b) In cross-section

Fig. 7 Stress distribution in circular composite beam with Ø 108 × 2.25 mm external steel tube and with the internal solid concrete core

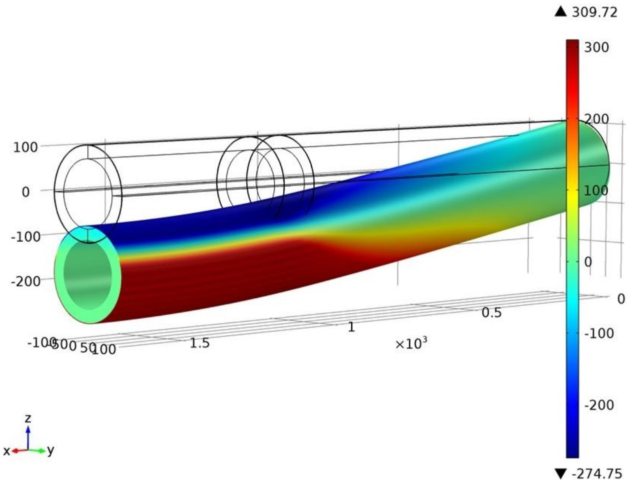


Fig. 8 Stress distribution and deflection shown in the half of circular composite beam with Ø 219 × 1.6 mm external steel tube and with the internal hollow concrete core

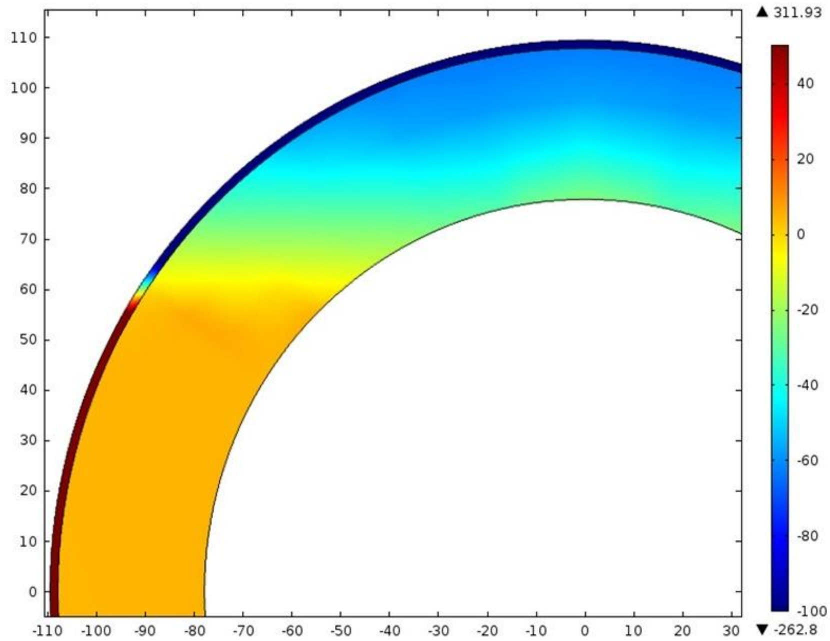


Fig. 9 Stress distribution and position of plastic neutral axis in cross-sections of circular composite beams in hollow cross-section of beam Ø 219 × 1.6 mm

In Fig. 7 the stress distributions received by numerical simulation in the half of circular composite beam with Ø 108 × 2.25 mm external steel shell and with solid concrete core and in beam's middle cross-section are presented.

In Fig. 8 the stress distribution and deflection along the half of circular composite simple beam with Ø 219 × 1.6 mm external steel shell and with the internal hollow centrifuged concrete core are presented.

In Fig. 9 the stress distributions and the position of plastic neutral axis in cross-sections of the circular composite beams with Ø 219 × 1.6 mm (Fig. 9) external steel shells and with the internal hollow concrete core are seen.

The results of carried out numerical simulation (see Figs. 7 and 9) show that the interaction between the external steel shell and the internal concrete core of circular composite simple beam has the great effect on the distribution of stresses in composite cross-section and on the resistance of members.

As it is seen from the Fig. 7(b), the position of the neutral axis in the cross-sections of the external steel thin shell and of the internal solid concrete core practically is in the same place and the value of stresses in the cross-section of the external steel shell because of and the internal concrete core's interaction has reached and even exceeded the value of ultimate tensile strength of steel, but as the experimental investigation (Kvedaras *et al*. 2013) shows the failure of the tested specimens hasn't happened yet.

Fig. 9(a) presents the case which is other than discussed above. Because of different strength characteristics of steel and concrete and different geometric characteristics of cross-sectional components the interaction between the external steel shell and the internal hollow concrete core in loaded circular composite beam is different than in beam given in Fig. 7. Therefore, slightly

Table 1 Properties of materials of tested and analysed circular composite beams

Specimen No.	Dimensions of tube $d \times d_a$ (mm)	Steel strength (MPa)		Concrete strength f_c (MPa)
		f_y	f_u	
Steel tube Ø 108 × 2.25 mm (D/t = 48), solid concrete core				
1.	108 × 2.25	400.6	471.1	30.1
2.	108 × 2.25	400.6	471.1	28.7
3.	108 × 2.25	400.6	471.1	30.1
Steel tube Ø 219×1.6 mm (D/t = 136.9), hollow concrete core 30 mm thick				
1.	219 × 1.6	250.0	374.2	23.7
2.	219 × 1.6	250.0	374.2	23.7
3.	219 × 1.6	250.0	374.2	25.9
Steel tube Ø 219×4.5 mm (D/t = 48.7), hollow concrete core 30 mm thick				
1.	219 × 4.5	296.0	349.3	31.9
2.	219 × 4.5	273.2	347.1	32.0
3.	219 × 4.5	283.5	353.0	39.9

different result is fixed: the value of stresses in steel shell is greater than the value of the yield strength of steel, but lower than the value of its ultimate tensile strength.

As it is seen from Fig. 9, misalignment of positions of neutral axis in cross-sections of Ø 219×1.6 mm external steel shell and internal hollow concrete core of composite beam is slightly greater than that fixed in cross-sections of Ø 108 × 2.25 mm external steel shell and internal solid concrete core of composite beam (see Fig. 7(b)).

3.4 Properties of materials of tested and analyzed composite beams

Properties of materials of tested and analysed circular composite beams with solid and hollow concrete cores are presented in Table 1.

In tests the tubes from structural and high-strength steel were used. The values of steel yield and ultimate tensile strengths were defined experimentally by tensile testing the specimens of standard dimensions cut out from the steel shells of circular composite beams and using standard tensile testing procedures. These values for steels of different test groups were different.

The strength of cores' concrete of composite beams of different groups was also different. The concrete mix in solid cores of beams with steel CHS shell of minimal outer diameter Ø 108 mm was compacted using the steel rod. The concrete mix in hollow cores of circular composite specimens was compacted by centrifuging. The values of concrete strengths given in Table 1 have been determined by testing due to standard compression testing procedures. The solid or hollow cylinders were cut out of concrete cores of circular composite beams just before the moment of carrying the bending tests with the beams. On test cylinders the strain gauges on four perpendicular sides were fixed and from registered data of longitudinal and lateral strains the values of some physical properties of cores' concrete were determined. From those parameters, for instance, the values of modulus of elasticity of cores' concrete were used in analytical calculations and numerical simulations. All specimens were kept in the laboratory room conditions with temperature about +20–22°C and humidity 50–75%. Additionally all specimens were put into the plastic slipcovers to keep for all of them more similar wet curing conditions.

4. Comparison of analytical, experimental and numerical simulation results

The experimental values of ultimate bending moment $M_{u.exp}$ and analytical ones $M_{u.theor}$ for investigated concrete-filled steel CHS beams are given in Table 2.

It is found that ultrathin-walled circular steel shell during bending of composite simple beam may be used until the ultimate steel strength is reached at failure of concrete-filled steel tubular composite section. Therefore, such simple hollow concrete-filled circular steel tubular beams may be more effective than the similar composite short columns, and the possibility exists for the simple beams made of ultrathin-walled CHS with hollow centrifuged concrete core to be more competitive than the steel and reinforced concrete flexural members of even more effective than CHS forms. The failure of flexural elements of CHS with concrete core is not sudden, so their maintenance is on the safe side.

In addition, with the methods based on the main principals and presumptions of the theory of

Table 2 Comparison of the results of experimental and theoretical load bearing capacities

Specimen No.	Values of ultimate bending moments (kN.m)			Relationships	
	Experimental $M_{u,exp}$	Analytical $M_{u,theor}$	Numerical simulation $M_{u,num}$	$M_{u,exp}/M_{u,theor}$	$M_{u.exp}/M_{u,num}$
Steel tube Ø 108 × 2.25 mm (D/t_{eff} = 42.59), solid concrete core, $f_a = \eta_a f_{mod}$*					
1.	14.4	12.85		1.121	
2.	14.4	12.82		1.123	
3.	12.9	12.85		1.004	
Mean value	13.90	12.84	13.77	1.083	1.009
Steel tube Ø 219 × 1.6 mm (D/t_{eff} = 110.38), hollow concrete core 30 mm thick, $f_a = \eta_a f_{mod}$*					
1.	27.0	26.61		1.015	
2.	27.0	26.61		1.015	
3.	33.1	32.39		1.022	
Mean value	29.03	28.55	31.25	1.017	0.929
Steel tube Ø 219 × 4.5 mm (D/t_{eff} = 43.90), hollow concrete core 30 mm thick, $f_a = \eta_a f_y$*					
1.	-	66.28		-	
2.	59.9	61.50		0,974	
3.	62.7	64,43		0,973	
Mean value	61.3	64.07	–	0.9735	–

• η_a*: η_a = 1.074 is the constraining factor as random variable value characterizing the interaction effect of the components of a composite concrete-filled member on its resistance under compression or tension. (Kvedaras and Kudzys 2010, Goode *et al*. 2010);

f_y and f_u: nominal values of steel yield and ultimate tensile strengths, respectively, f_{mod} some intermediate value between f_y and f_u or just the value of f_u;

t_{eff}: thickness of composite section modified to steel tube wall thickness.

Table 3 Comparison of the distance y_0 of neutral plastic axis

Element	Distance of plastic neutral axis y_0 [mm] by			Relationship
	Eq. (17)	Eq. (17)/Numerical	Eq. (18)	Numerical simulation (Figs. 7 and 9)
Ø 108 × 2.25 (fully filled)	17,95	1.12	21.41	16.00
Ø 219 × 1.6 (hollow core)	68.45	1.10	–	62.00
Ø 219 × 4.5 (hollow core)	41.94	–	–	–

plasticity of small elastic-plastic strains, the possibility exists of quite exact theoretical definition of ultimate load of circular composite beams made from steel CHS with solid and hollow concrete core and avoidance of their overloading during the service time.

The partial results received by numerical simulation and analytical calculation may be illustrated by such data:

- For composite beams with Ø 108 × 2.25 mm steel tube and solid concrete core when the experimental mean value of ultimate bending moment is 13.90 kNm, the value of the same moment received by numerical simulation is 13.77 kNm and by analytical calculation – 12.84 kNm;
- For composite beam with Ø 219 × 1.60 mm steel tube and hollow concrete core 30.0 mm thick when the experimental mean value of ultimate bending moment is 29.03 kNm, the value of the same moment received by numerical simulation is 31.25 kNm and by analytical calculation – 28.55 kNm;

In Table 3 the comparison of the results of analytical calculation and numerical simulation of the distance y_0 of the neutral plastic axis from the section main z axis of circular composite beams with the solid and hollow concrete cores are presented.

Distances of plastic neutral axis which were calculated using Eq. (17) have a quite good correlation not only with the results received by numerical simulation but also with the distances of plastic neutral axis determined experimentally (Kvedaras *et al*. 2013).

For working-out the maximum values of deflections of tested simple beams next equation expressing the linear relationship between deflection and action effect may be used

$$w_{max} = 0.10 \cdot M_{Ek} l^2 / \left(E_a I_a + E_c I_c\right) \tag{19}$$

where M_{Ek} is the characteristic value of the bending moment acting on the composite beam; E_a, E_c and I_a, I_c are the elastic modulus of shell's steel and core's concrete and the second moments of steel shell's and concrete core's areas, respectively; l is the beam's span.

The ultimate value of deflection evaluating the plastic behaviour of the composite simple beam just before its failure may be expressed so

$$w_u = 0.33 \cdot M_{Ek} l^2 / \left(E_a I_a + E_c I_c\right) \tag{20}$$

For a composite beam with Ø 108 × 2.25 mm steel tube and solid concrete core when the maximum experimental value of the deflection is 44.5 mm, the value of the same deflection received by numerical simulation is 42.5 mm and by analytical calculation due to Eq. (19) is 21.9

mm, due to Eq. (20) – 72,3 mm. The maximum value of the deflection for composite beam with Ø 219 × 1.6 mm steel tube and hollow concrete core received by numerical simulation is 62.5 mm and from the experiments is 68.0 mm (the maximum value of the deflection received by analytical calculation due to Eq. (19) is 70.4 mm).

5. Conclusions

The experimental and analytical data on the hollow centrifuged and solid concrete-filled circular steel tubular simple beams showed their structural and constructional efficiency. The fairly high effect of an interaction between the steel tubes and the concrete cores on their constraining factors and the ultimate strength of flexural composite members were established.

Proposed analytical method gives good agreement with the natural and numerical test results with hollow centrifuged and solid concrete-filled circular steel tubular simple beams and that allows recommending presented method to use in design practice of such efficient composite beams.

The most rational composite section is standing up when its plastic neutral axis is laying both in steel shell's and concrete core's sections in the same level.

With increasing the thickness of steel shell its plastic neutral axis is falling down when concrete core's one is turning up. Such changes of the level of plastic neutral axis of composite section possibly depend on the different relationships between the strength and geometrical parameters of the steel shell and the concrete core.

Software with the module analyzed interaction of the concrete core and the steel shell using the Ottosen's parameters, and other nonlinear analysis like Muornaghan's and Lame's parameters gives quite reliable results of stress distribution and load bearing capacity of circular composite steel and concrete simple beams with solid and hollow concrete cores. But from a carried out investigation follows that results obtained from the numerical simulation are less safe in comparison with the results obtained by test and analytical calculation because the ultimate values of the action effects received by numerical simulation are greater and those of the deflections and of the distances of neutral plastic axis are lesser.

References

BS: 5400 (1979), Steel, Concrete and Composite Bridges; Part 5 Code of Practice for Design of Composite Bridges, British Standards Institution, London, UK.

CEB-FIB (1993), CEB-FIB: Model Code 1990 – Design Code; Thomas Telford.

CEN (2004), EN 1994-1-1: Design of Composite Steel and Concrete Structures – Part 1-1: General rules and rules for buildings, Brussels, Belgium.

COMSOL (2010), Multiphysics User's Guide, COMSOL AB.

Elchalakani, M., Zhao, X.L. and Grzebieta, R.H. (2001), "Concrete-filled circular steel tubes subjected to pure bending", *J. Construct. Steel Res.*, **57**, 1141-1168.

Goode, C.D., Kuranovas, A. and Kvedaras, A.K. (2010), "Buckling of slender composite concrete-filled steel columns", *J. Civil Eng. Manag.*, **16**(2), 230-237.

Han, L.H. (2004), "Flexural behaviour of concrete filled steel tubes", *J. Construct. Steel Res.*, **60**(2), 313-337.

Jiang, A-Y., Chen, J. and Jin, W-L. (2013a), "Bending strength of thin walled centrifugal concrete-filled

steel tubes", *Res. J. Appl. Sci. Eng. Technol.*, **5**(3), 801-811.
ISSN: 2040-7459; E-ISSN: 2040-7467, Maxwell Scientific Organization.

Jiang, L., Qi, J., Scanlon, A. and Sun, L. (2013b), "Distortional and local buckling of steel-concrete composite box-beam", *Steel Compos. Struct., Int. J.*, **14**(3), 243-265.

Kikin, A.J., Sanzharovsky, R.S. and Trull, V.A. (1974), *Concrete Filled Steel Tubular Structures*, Strojizdat Moscow, USSR. [In Russian]

Kvedaras A.K. (1983), *Metal Structures of Concrete Filled Tube*; Editorial Publishing Council of the Lithuanian Ministry for High Education, Vilnius, Lithuania. [In Lithuanian]

Kvedaras, A.K. (1999), "Light-weight hollow concrete-filled steel tubular members in bending", *Proceedings of Light-weight Steel and Aluminium Structures CSAS'99 Fourth International Conference on Steel and Aluminium Structures*, Espoo, Finland, June, pp. 755-760.

Kvedaras, A.K. and Sapalas, A. (1998), "Research and practice of concrete-filled steel tubes in Lithuania", *J. Construct. Steel Res.*, **49**(2), 197-212.

Kvedaras, A.K. and Kudzys, A. (2010), "Tubular composite beam-columns of annular cross-sections and their design practice", *Steel Compos. Struct., Int. J.*, **10**(2), 109-128.

Kvedaras, A.K., Šaučiuvėnas, G. and Jarmolajeva, E. (2013), "Behaviour of hollow and solid concrete-filled circular steel tubular simple beams", *Proceedings of International Conference on Design, Fabrication and Economy of Metal Structures*, Miskolc, Hungary, April, pp. 569-576.

Luksha, L.K. (1977), *Strength of Pipe-Concrete*, Higher School, Minsk, USSR. (In Russian)

Mäkeläinen, P. and Maliska, M. (1997), "Design tubular composite columns according to the Finnish Code and comparison with Eurocode 4", *Proceedings of Concrete Filled Steel Tubes. A Comparison of International Codes and Practices*, pp. 39-58.

Matzumoto, Y., Fukuzawa, K. and Endo, H. (1976), "Manufacture and behaviour of hollow composite member", *Final Report of 10^{th} Congress of IABSE*, Tokyo, September, pp. 389-394.

Montague, P. (1978), "The experimental behaviour of double skinned, composite, circular cylindrical shells under external pressure", *J. Mech. Eng. Sci.*, **20**(1), 21-34.

Montoya, E., Vecchio, F.J. and Sheikh, S.A. (2006), "Compression field modelling of confined concrete: constitutive models", *J. Mater. Civil Eng., ASCE*, **18**(4), 510-517.

Oyawa, W.O., Sugiura, K. and Watanabe, E. (2004), "Flexural response of polymer concrete filled steel beams", *Construct. Build. Mater.*, **18**(6), 367-376.

Pereira, E.B. and Barros, J.A.O. (2009), "3D behaviour of a 4 parameter isotropic nonlinear hardening plasticity model for concrete", *Proceedings of CMNE 2009 – Congress on Numerical Methods in Engineering*, Barcelona, Spain, pp. 1-20.

Sanjayan, J.G. and Setunge, S. (2001), „Complete triaxial stress-strain curves of high-strength concrete", *J. Mater. Civil Eng., ASCE*, **13**(3), 209-215.

Uenaka, K. and Kitoh, H. (2011), "Mechanical behaviour of concrete filled double skin tubular circular deep beam", *Thin-Wall. Struct.*, **49**(2), 256-263.

Valsa Ipe, T., Sharada Bai, H., Manjula Vani, K. and Iqbal, M. (2013), "Flexural behavior of cold-formed steel concrete composite beams", *Steel Compos. Struct., Int .J.*, **14**(2), 105-120.

Wheeler, A. and Bridge, R. (2011), "Flexural behaviour of concrete-filled thin-walled steel tubes with longitudinal reinforcement", *Proceedings of Engineering Foundation Conference Composite Construction in Steel and Concrete VI, ASCE*, New York, NY, USA, pp. 225-236.

Zhao, X.L., Grzebieta, R. and Elchlakani, M. (2002), "Tests of concrete-filled double skin CHS composite stub columns", *Steel Compos. Struct., Int. J.*, **2**(2), 58-98.

CC