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# Analysis of behaviour for concrete-filled steel tubular beams

*Audronis Kazimieras Kvedaras[1], Gintas Šaučiuvėnas[2], Arūnas Komka[3] and Ela Jarmolajeva[4]

*[1], [2], [3] Department of Steel and Timber Structures, [4] Department of Structural Mechanics, VGTU, Vilnius 10223, Lithuania*
*[1] audronis-kazimieras.kvedaras@vgtu.lt*

## 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 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) of (CEN 1994) 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.

## 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 effectively may be used in buildings and bridges. 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 development results (Uenaka and Kitoh 2011) a wide application of them in bridge piers as well as in columns, beam-columns and beams for buildings is looked forwards too. Study (Oyawa *et al.* 2004) seeks 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. Some information about possibilities of

[1] Professor
[2] [3] [4] Associate Professor

application of concrete-filled double skin circular hollow section composite members is presented in (Montague 1978; Zhao *et al.* 2002).

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) with test data has showed a good agreement. It is usual to suppose 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 more high efficiency for slender differently loaded hollow members against short ones and it is in some contradiction with the limitation of (EN 1994-1-1:2004) 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 $M_{\mathrm{Ed}}$ / $N_{\mathrm{Ed}}$ 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 be existing under different loading conditions – uniaxial and eccentric compression and tension, bending etc. It is a custom to think that the concrete-filled steel tubes are most useful in those buildings where mainly great compression forces are acting. However, the research data and building practice show that being also efficient under other actions as those for circular composite beams evidently confirms the research data presented in (Matzumoto *et al.* 1976).

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 2003) recommends the use of a four-parameter failure criterion, also known as the Ottosen 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 no design recommendation for them exists 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 is still studied not sufficiently especially those manufactured from the steel circular 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 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 uniaxial moment resistance of circular composite concrete-filled steel tubular beam is calculated using the ideally plastic material models for concrete and steel. The design moment resistance $M_{pl,Rd}$ is defined by the plastic axial resistance $N_{pl,Rd}$ of the steel cross-section and a design eccentricity $e_u$, which depends on the type of member cross-section:

$$N_{pl,Rd} = A_a \cdot f_{ud} \quad (1)$$

$$M_{pl,Rd} = N_{pl,Rd} \cdot e_u \quad (2)$$

For definition of 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 (Kvedaras1983 and 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 expression (1) for different types and dimensions of members may vary; therefore it is marked further as $f_a$.

$$\text{If } k_a \cdot k_w < f_y, \textit{ then } f_a = \eta_a f_y \quad (3)$$

$$\text{If } f_y < k_a \cdot k_w < f_u, \textit{ then } f_a = \eta_a \cdot f_{\mathrm{mod}} \quad (4)$$

$$\text{If } k_a \cdot k_w > f_u, \textit{ then } f_a = \eta_a \cdot f_u \quad (5)$$

Where:

$$k_a = 0.5 \cdot E_c \cdot A_c / E_{a\cdot} \cdot A_a \le 1 \quad (6)$$

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

$$k_w = f_y \cdot W_p / W \quad (7)$$

$$f_{\mathrm{mod}} = k_a \cdot k_w \quad (8)$$

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

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. 1.

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 fully concrete-filled steel tubular beams.

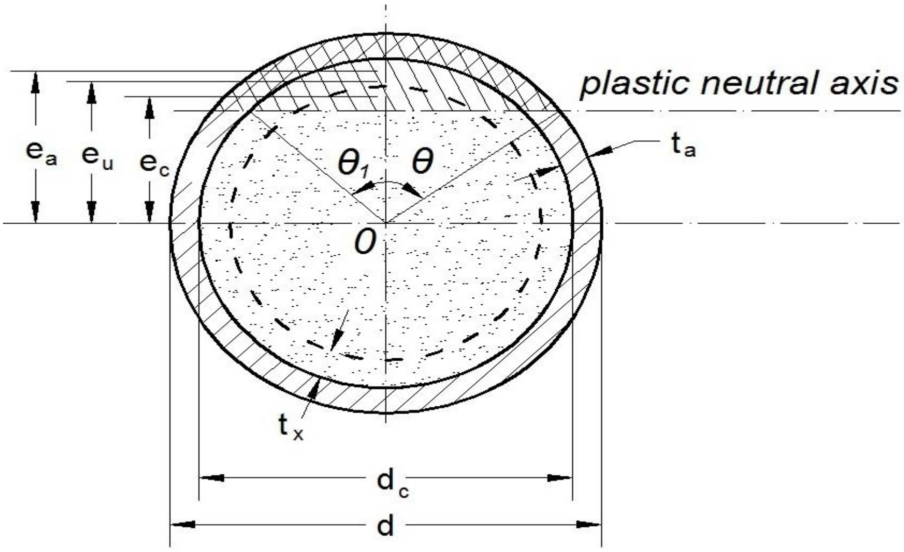


Fig.1. Dimensions of cross-section of circular solid concrete-filled steel tubular beam and position of plastic neutral axis; $t_x$ – thickness of relative circular steel core to which the solid concrete core is reduced

*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. 2.

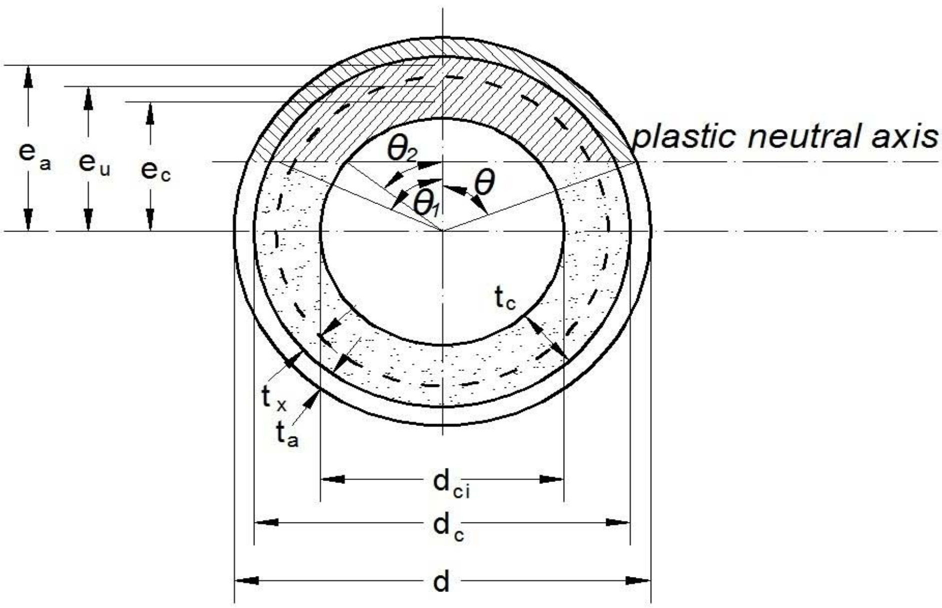


Fig.2. Dimensions of cross-section of partially concrete-filled circular steel tubular beam and position of plastic neutral axis; $t_x$ – thickness of relative circular steel core

## 3. NATURAL AND NUMERICAL EXPERIMENTS OF COMPOSITE BEAMS

Composite steel and concrete elements have been tested using 4-point bending (see Fig. 3). The samples were tested until the loss of load bearing capacity. During the tests the stresses of middle section of the beam and vertical displacement has been recorded. The obtained test results were compared with results obtained by numerical simulation and analytical calculation.

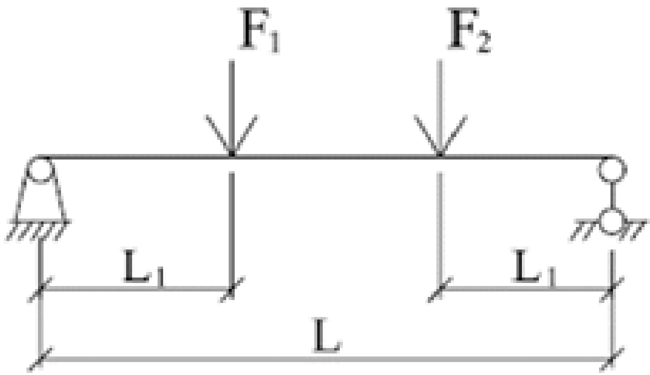


Fig. 3. Test specimen model using 4-point bending

### *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 – 450 MPa. Class of concrete core according EN 206-1 was C20/25.

### *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 3.60 m, the distance between supports was 3.0 m and the distance between the load adding points –1.0 m. Mean values of steel strength were such: yield strength – 250 MPa and 283 MPa and ultimate tensile strength – 374 MPa and 332 MPa, respectively. Nominal cylindrical strength of concrete was 30.0 MPa and about 28.0 MPa, respectively.

### *3.3 Numerical experiment of composite beams*

Numerical simulation of bending composite elements has been done using software (COMSOL 2010). Interaction of concrete core and the steel shell was modelled using the Ottosen's parameters, and Murnaghan's and Lame's parameters for nonlinear analysis were used. The 3 main parameters were compared – load bearing capacity, beam deflections and the neutral axis position.

## 4. COMPARISON OF ANALYTICAL AND EXPERIMENTAL RESULTS

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

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 $M_{u.theor}$ | $M_{u.exp} / M_{u.theor}$ |
| **Steel tube Ø108×2.25 mm, 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 |
| **Steel tube Ø219×1.6 mm, 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 |
| **Steel tube Ø219×4.5 mm, 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 |
| Note: $\eta_a$ = 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); $f_y$ and $f_u$ are the nominal values of steel yield and ultimate tensile strengths, respectively. $f_{\text{mod}}$ is some intermediate value between $f_y$ and $f_u$ or just the value of $f_u$ . | | | |

It is found that supper thin-walled steel shell during bending of composite simple beam may be used until the ultimate steel strength is reached at failure. Therefore, such simple hollow concrete-filled circular steel tubular beams may be more effective than the similar composite short columns. Therefore, possibility exists for the simple beams made of supper thin-walled CHS with hollow concrete core to be more competitive than the steel and reinforced concrete flexural members of more effective than CHS forms. The failure of elements of CHS with concrete core is not sudden, so their maintenance is on the safe side. In addition, with the methods based on main principals and presumptions of the theory of plasticity of small elastic--plastic strains, the possibility exists of quite exact theoretical definition of ultimate load of composite elements and avoidance their overloading during service time.

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

– For composite beam with Ø108×2.25 mm steel tube and solid concrete core when the experimental value of ultimate bending moment is 14.4 kNm, the value of the same moment received by numerical simulation is 13.65 kNm;

– For composite beam with Ø219×1.60 mm steel tube and hollow concrete core 30.0 mm thick when the experimental value of ultimate bending moment is 33.1 kNm, the value of the same moment received by numerical simulation is 34.40 kNm;

– For composite beam with Ø108×2.25 mm steel tube and solid concrete core when the experimental value of ultimate deflection is 44.5 mm, the value of the same deflection received by numerical simulation is 42.5 mm.

## 5. CONCLUSIONS

The experimental and analytical data on the hollow and solid concrete-filled circular steel tubular simple beams showed their structural and constructional efficiency. The fairly high effect of an interaction between steel tubes and 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 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.

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