



## THE USE OF ANNULAR AND CIRCULAR CROSS-SECTION MEMBERS IN TRANSPORT AND POWER ENGINEERING BUILDING CONSTRUCTION

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**Abstract.** The problem of evaluating the bearing capacity of the reinforced concrete elements of circular cross-section is considered. Strength calculation of these reinforced concrete elements differs from strength calculation of the elements of the rectangular cross-section. A method of calculation similar to that used for strength calculation of annular cross-section elements is suggested. The bearing capacity of circular cross-section elements, calculated based on the use of this method, matches the bearing capacity determined by testing.

**Keywords:** circular cross-section, annular cross-section, plain and reinforced concrete elements, strength, bearing capacity, longitudinal reinforcing bars, eccentric compression.

### 1. Introduction

Solid circular columns are very popular for bridge pier design because the construction is simple and its strength characteristics under wind and seismic loads are similar in any direction. Furthermore, circular elements are also widely used as columns in buildings or as piles for foundations. Hollow core circular concrete members are much less structurally used than solid circular cross sections. Though, these can be found in concrete chimneys, concrete pipes and elevated water tanks, as well as in large bridge columns and offshore platforms (Turmo *et al.* 2009).

Hollow core circular concrete elements are economically and conveniently manufactured using spin casting technique. Spin casting is an effective method to produce concrete pylons, masts or pipes. Through the centrifugation process the concrete is compacted and the desired shape, mostly round or ellipsoidal, is obtained (Abeles 1973; Bacsa 1979; Bacsa 1981; Kaufmann, Hesselbarth 2007; Kvedaras, Šapalas 1999; Wesley, Wong 2002).

Normally, the load-bearing reinforced concrete structures of buildings and other engineering constructions are of a circular (round) shape (Fig. 1). The use of structural elements of this shape in building construction in the areas of transport and power engineering has some advantages. Since the buildings intended for use in transport and power engineering are constructed in the open areas, their structures are exposed to weather (Dilger *et al.* 1996; Šelih 2010).

The perimeter of a circular cross-section is by 12.8% smaller than the perimeter of the rectangular cross-section of the same area. Therefore, the surface area of circular cross-section elements exposed to weather is smaller than the surface area of the rectangular (square) cross-section elements.

Another factor ensuring higher durability of the considered structures is that they have a smooth surface without any ribs, typical of round elements. Field tests of long-service power transmission lines aimed at determining the technical state of electric power pylons have shown that the characteristic cross cracks were formed in the corners of the rectangular cross-sections near the longitudinal reinforcing bars (Kliukas *et al.* 2003; Vadlūga, Kliukas 2000). The tests have shown that the technical state of the spun concrete pylons of annular cross-section was much better than the state of concrete members of the rectangular cross-section made of concrete compacted by vibration.

As shown by numerous experimental and theoretical studies (Kvedaras, Kudzys 2006; McAteer *et al.* 2004; Mei *et al.* 2001; Pellegrino, Modena 2010; Šelih 2010; Wang, Wu 2008), higher durability of structures is achieved by applying an external cover, typically of circular shape, which may be made of metal, plastic or reinforced concrete.

Concrete generally has to be reinforced with steel bars which are susceptible to corrosion. Furthermore, the placement of the steel reinforcement is time-consuming



The pillars of the airport's runway  
(www.airliners.net)



Bridge pier shafts

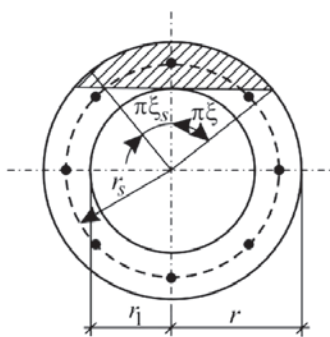


Carrier poles (author's photo)

**Fig. 1.** Modelling of annular cross-section for reinforcement concrete elements

and hence expensive. The structural elements of this type are rather thick and heavy. The application of short-fiber reinforced cement of carbon or polyvinyl alcohol (Doma-gala 2011; Kaufmann *et al.* 2005) is a suitable alternative for such slightly bended elements.

Codes do not provide calculation methods suitable in all cases to evaluate the strength (shear strength) of circular cross-section elements of reinforced concrete (ACI 318-05:2005 *Building Code Requirements for Structural Concrete*; BS8 100:1985 *Structural Use of Concrete: Part I: Code for Practice for Design and Construction*; EHE 1998:1998 *EHE Instruction for Structural Concrete*; CEB-FIP 1990:1993 *CEB-FIP Model Code*; SNiP 2.05.03-84:1985 *Building Code. Bridges and Pipes*; Rodgers *et al.* 1983). The calculation of the reinforced concrete members of circular cross-section is more complicated than the calculation of the rectangular cross-section elements. The circular shape of the cross-section and the uniform distribution of the reinforcing bars along the perimeter impart some specific features to the evaluation of the stress-strain state of the members (Harajli 2006; Mander *et al.* 1988; Pantazopoulou, Mills 1995). Since the longitudinal bars are uniformly distributed along the cross-section perimeter, the variation of their stress-strain state is accompanied not only by the variation of the parameters of the compressed zones, but the ratio of the areas of the longitudinal bars found in the compression and tension zones as well.



**Fig. 2.** Modelling of annular cross-section for reinforcement concrete elements

Reinforced concrete elements of circular (solid) cross-section and the elements of annular (hollow) cross-section are usually compressed. Therefore, both their strength and stability, depending on flexural stiffness ( $EI$ ) are important. In this respect, the second moment of area ( $I$ ) of the solid circular cross-section elements is by about 4.5% smaller than that of the elements of the rectangular cross-section having the same area (Arslan, Cihanli 2010; Kliukas *et al.* 2010; Kudzys, Kliukas 2010; Kvedaras, Kudzys 2010). This difference may be smoothed by using annular cross-section elements, whose ratio of the second moment of area and cross-section area is higher, when the ratio of their internal and external diameters is higher (Fig. 2).

A feasibility study of using annular cross-section reinforced concrete elements in building construction in transport was described in two articles published earlier in the *Baltic Journal of Road and Bridge Engineering* (Kudzys, Kliukas 2008a; 2008b). In the present paper, a relatively simple method of calculating reinforced concrete members of circular cross-section, based on the main principles used in calculating annular cross-section elements, is described.

## 2. The main assumptions of the method of calculation

In calculating the bearing capacity of reinforced concrete structures by the limiting state method, it is assumed that the element is at the stage of failure, but concrete behaviour under tension is not taken into account. For the sake of calculation simplicity, the diagram presenting concrete stresses in the compressed zone of the element by curves is replaced with a diagram of arbitrary rectangles. The same principle is also used in the *EN 1922-1:2004 Eurocode 2. Design of Concrete Structures – Part 1: General Rules and Rules for Buildings*.

Unlike the rectangular cross-section elements, whose longitudinal reinforcing bars are located as close as possible to the most highly stressed layers of the compression and tension zones, the longitudinal reinforcing bars of the circular cross-section elements are usually uniformly distributed along the circular cross-section perimeter. The

diagrams of the reinforcement stresses in the compression and tension zones of such elements at the stage of failure are curve diagrams, i.e. the strength of the reinforcement is used depending on its position in the cross-section. The bearing capacity of an element may be evaluated by a universal method of strength calculation, presented in the Lithuanian construction specifications STR 2.05.05:2005 *Design of Concrete and Reinforced Concrete Structures*, based on the previously valid structural design codes and specifications CHuII 2.03.01-84. However, the calculation based on the considered method is complicated and rarely used.

### 3. Bayes theorem in revised reliability analysis

In actual calculations, the curve diagrams of concrete and reinforcement stresses (Fig. 3) are replaced with the diagram of arbitrary rectangles (Vadlūga 2007). The compressed cross-section zone is defined by its sector portion. In this case, the position of the neutral axis, i.e. the relative value  $\xi$  (Fig. 2) is hard to determine. The problem is solved by using the successive approximation method. The solution is complicated because the relative value  $\xi_s$  describing the compressed part of the reinforcement of the element cross-section does not match the value  $\xi$ .

The relationship between these values is expressed by the formula:

$$\xi_s = \frac{\arccos\left(\frac{r}{r_s} \cos \pi \xi\right)}{\pi} = k \xi. \quad (1)$$

The values of the coefficient  $k$ , characterizing the relationship between  $\xi_s$  and  $\xi$ , depend on the ratio  $\frac{r}{r_s}$ . They are given in Table 1.

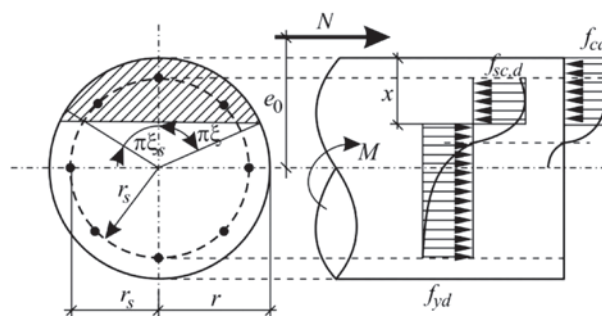


Fig. 3. Modelling of stresses in the steel reinforcement and concrete of eccentrically loaded circular cross-section elements

As shown by the data given in Table 1, the difference between  $\xi_s$  and  $\xi$  is the greatest, when the ratio  $\frac{r}{r_s}$  increases. When the relative size of the compressed zone is in the range of  $\xi = 0.3-0.7$ , the value of the coefficient  $k$  does not differ from unity by more than 10% even for the worst case (when  $\frac{r}{r_s} = 1.20$ ). In the case of concrete-filled members with tubular reinforcement (Šaraškinas, Kvedaras 2000), the values of  $\xi_s$  and  $\xi$  match each other.

The value of  $\xi$ , characterizing the compressed cross-section area of the member, is determined from the equilibrium condition, stating that the sum of all axial (internal and external) forces is equal to zero:

$$f_{cd} A_c + f_{sc,d} A_{sc} - f_{yd} A_{st} - N = 0, \quad (2)$$

where  $f_{cd}$  – the calculated compression strength of the concrete,  $f_{sc,d}$  and  $f_{yd}$  denote the calculated compressive and tensile

Table 1. The values of the coefficient  $k$  describing the relationship between  $\xi_s$  and  $\xi$

$\xi$	$k$				
	when $\frac{r}{r_s}$				
	1.05	1.1	1.15	1.2	1.25
0.10	0.1679	–	–	–	–
0.15	0.7660	0.6360	–	–	–
0.20	0.8846	0.7538	0.5974	0.3854	–
0.25	0.9346	0.8653	0.7910	0.7100	0.6197
0.30	0.9609	0.9207	0.8791	0.8360	0.7910
0.35	0.9767	0.9530	0.9290	0.9046	0.8798
0.40	0.9870	0.9740	0.9609	0.9477	0.9344
0.45	0.9944	0.9889	0.9832	0.97775	0.9719
0.50	1.0000	1.0000	1.0000	1.0000	1.0000
0.55	1.0046	1.0092	1.0138	1.0184	1.0230
0.60	1.0086	1.0173	1.0261	1.0349	1.0437
0.65	1.0126	1.0253	1.0382	1.0514	1.0647
0.70	1.0167	1.0340	1.0518	1.0703	1.0896
0.75	1.0218	1.0449	1.0697	1.0967	1.1268
0.80	1.0288	1.0615	1.1006	1.1536	–
0.85	1.0413	1.017	–	–	–
0.90	1.0925	–	–	–	–

strength of the reinforcement, respectively, kN/m<sup>2</sup>;  $A_c$  – the compressed zone of the element's cross-section area, m<sup>2</sup>;  $A_{sc}$  and  $A_{st}$  – the cross-section areas of the longitudinal compression or tension reinforcing bars respectively, m<sup>2</sup>. They may be expressed as follows:  $A_{sc} = A_s \xi_s$  and  $A_{st} = A_s (1 - \xi_s)$ , where  $A_s$  – the total cross-section area of the element's reinforcement, m<sup>2</sup>;  $N$  – normal axial compressive force, kN.

The area of the compressed zone of the element's cross-section is described as the area of a segment of a circle:

$$A_c = \frac{r^2}{2} (2\pi\xi - \sin 2\pi\xi) = \pi r^2 \left( \xi - \frac{\sin \pi\xi \cos \pi\xi}{\pi} \right), \quad (3)$$

where  $\pi r^2$  – the total area of the element's cross-section.

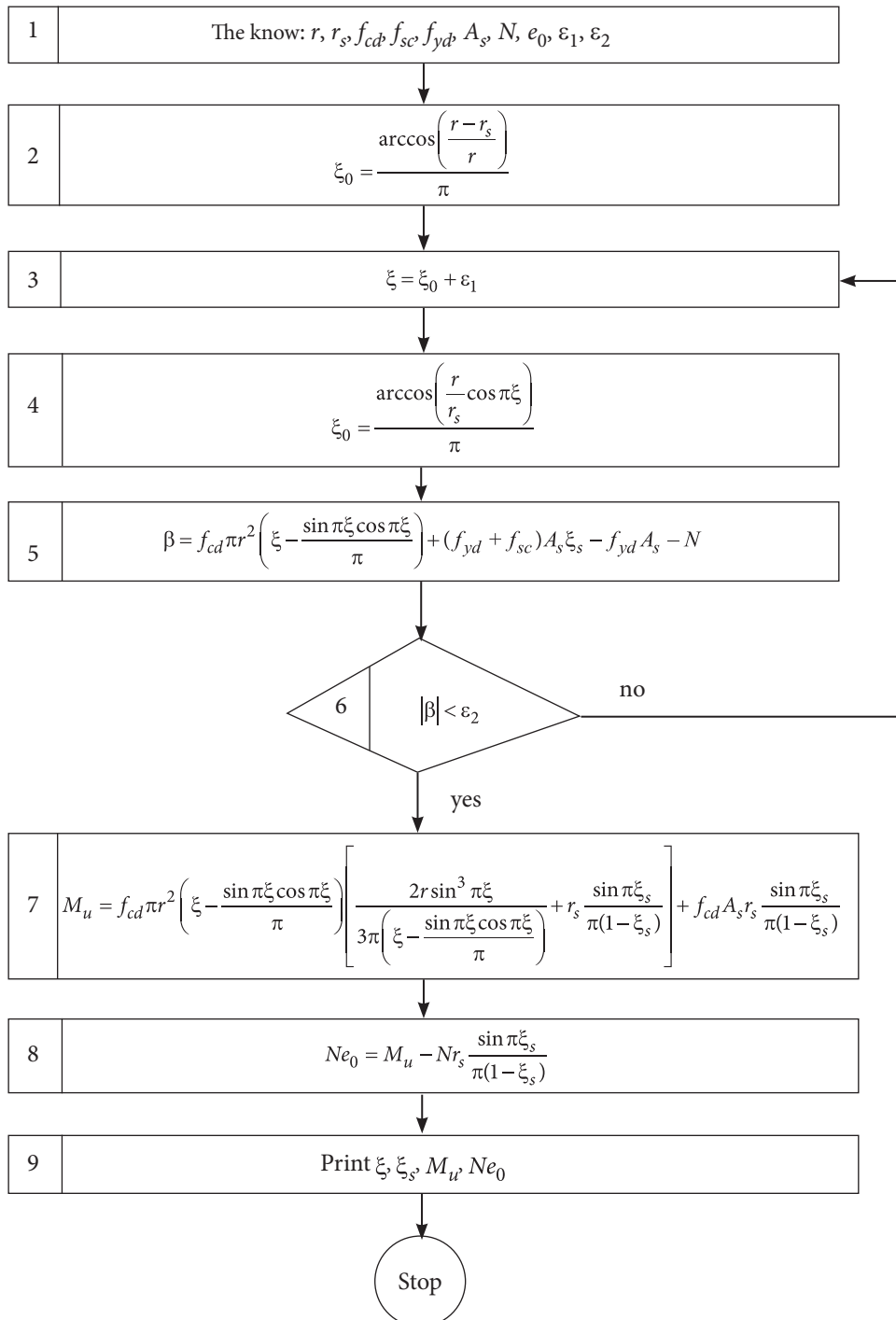


Fig. 4. The algorithm of evaluating the bearing capacity of the reinforced concrete elements of circular cross-section

By substituting the expressions for the above-mentioned characteristics into the Eq (2), the equation allowing us to calculate the value  $\xi$  characterizing the compressed part of an element's cross-section is obtained. The solution can only be made by using the successive approximation method. For this purpose, a computer program based on the algorithm presented in Fig. 4 can be made.

For practical calculations, a simplified approximate method can be used. The analysis has shown that, in the interval  $\xi = 0.3-0.7$ , the expression between the brackets of the Eq (3) may be replaced with a simpler expression rather accurately (Vadlūga 2007).

$$\xi - \frac{\sin \pi \xi \cos \pi \xi}{\pi} \approx 1.8\xi - 0.4. \quad (4)$$

Then, the equilibrium condition (2) may be rewritten as

$$f_{cd}A(1.8\xi - 0.4) + f_{sc,d}A_s\xi_s - \xi_{yd}A_s(1 - \xi_s) - N = 0 \quad (5)$$

or

$$f_{cd}A(1.8\xi - 0.4) + f_{sc,d}A_s k\xi - f_{yd}A_s(1 - k\xi) - N = 0. \quad (5a)$$

After solving the Eq (5a), the relative size of the compression zone of the element may be defined as follows:

$$\xi = \frac{0.4f_{cd}A + f_{yd}A_s + N}{1.8f_{cd}A + k(f_{sc,d} + f_{yd})A_s}. \quad (6)$$

The bearing capacity of the reinforced concrete members of circular cross-section is obtained based on the equilibrium condition. This means that the sum of the moments, which develop due to the action of the internal and external forces about the axis, passing through the centre of the member's cross-section, is equal to zero:

$$M_0 = (Ne_0)_u = \frac{2}{3}(f_{cd}r^3 \sin^3 \pi \xi) + (f_{yd} + f_{sc,d})A_s r_s \frac{\sin \pi \xi_s}{\pi}. \quad (7)$$

The suggested method has been checked by comparing the bearing capacity of eccentrically compressed

reinforced concrete members of circular cross-section, calculated using this method, with the experimental data presented in the literature on the problem (Šapalas 1978). It has been found that the suggested method is more suitable when the eccentricity  $\frac{e_0}{r}$  is smaller than 0.3. The comparative analysis has shown that the ratio of the calculated bearing capacity values of eccentrically compressed concrete elements of circular cross-section, obtained by using the suggested method, and the respective experimental data is as follows: the mean ratio value is  $m = 1.0686$ , and the mean square deviation is  $\bar{s} = 0.0709$ . The confidence interval of this ratio according to the Student  $t$ -test is 0.9918–1.1454 (Vadlūga 2007).

Further analysis of this problem has shown that the Eq (7) is not universal. This particularly refers to the calculation of the bearing capacity of the members eccentrically compressed with small eccentricity.

A general (universal) formula is obtained by considering the equilibrium of the moments about the axis, passing through the centre of the reinforcement zone subject to tension or slight compression. In calculating the bearing capacity of the concrete elements (without the longitudinal reinforcing bars), the equilibrium condition about the axis passing through the conventional centre of the concrete element's zone in tension is considered, i.e. it is assumed that  $r_s = r$ . It follows from the equilibrium condition that the sum (equal to zero) of the moments, which develop due to the action of the external and internal forces about the axis, passing through the element's cross-section reinforcement centre subject to tension or slight compression, is obtained as follows:

$$M_u = N \left( e_0 + r_s \frac{\sin \pi \xi_s}{\pi(1 - \xi_s)} \right)_u = \frac{2}{3}(f_{cd}r^3 \sin^3 \pi \xi) + \left[ f_{cd}r^2(1.8\xi - 0.4) + \frac{f_{sc,d}A_s}{\pi} \right] r_s \frac{\sin \pi \xi_s}{1 - \xi_s}. \quad (8)$$

The suggested method was checked by comparing the calculated bearing capacity of eccentrically compressed plain and reinforced concrete members of circular cross-section with the experimental data (Šapalas 1978, Docenko 1954). The results of the comparative analysis are presented in Tables 2 and 3.

**Table 2.** The results obtained in determining the ratio of the calculated and experimental bearing capacity of the elements

Method	Element	Quantity	Mean value $\rho_m = \left( \frac{M_{obs}}{M_{cal}} \right)$	Mean square deviation $s_p$	Variation coefficient $c_p$	$(k_{min})^*$	
						$\alpha = 2$	$\alpha = 3$
Eq (7)	reinforced concrete	24	1.089	0.120	0.110	1.179	1.373
	plain concrete	13	0.958	0.108	0.113	1.347	1.576
Eq (8)	reinforced concrete	24	1.051	0.048	0.045	1.046	1.101
	plain concrete	13	0.979	0.057	0.038	1.104	1.151

\* Note. The min confidence coefficient of the calculation method for the case, when the distribution  $\rho$  is assumed to be normal, is  $k_{min} = \frac{1}{\rho_m - \alpha s_p}$ , where  $\alpha$  is the number of mean square deviations.



**Table 3.** The confidence interval of the relative mean value ( $\rho_m$ )\* according to the Student *t*-test

Members	Probability		
	$p = 0.95$	$p = 0.99$	$p = 0.998$
reinforced concrete	1.031–1.071	1.024–1.078	1.009–1.093
plain concrete	0.957–1.002	0.948–1.010	0.935–1.023

\* Note. The calculated bearing capacity is obtained from Eq (8).

The analysis performed has shown that the method of calculating the bearing capacity of the considered members by the Eq (8) is more accurate and reliable. Based on the suggested method, the bending, compression and tensile strength of reinforced concrete and concrete members of circular cross-section may be calculated irrespective of the eccentricity value.

#### 4. The comparison of methods for calculating the bearing capacity of circular and annular cross-section members

In calculating the bearing capacity of the reinforced concrete elements of annular cross-section, a section of the compressed zone is described as the part of a sector rather than a ring section. This is done for the sake of margin (Kudzys 1975). The latter assumption does not suit when calculating the bearing capacity of circular cross-section elements. However, when the neutral axis of circular cross-section members does not cross the internal circumference of the ring (implying that the height of the compressed zone is smaller than the thickness of the ring (Fig. 3)) and the bearing capacity of annular cross-section members may be calculated similarly to the calculation of circular cross-section members.

#### 5. Conclusions

A relatively simple method of calculating the bearing capacity of circular cross-section reinforced concrete elements is suggested. It has been shown that this method is analogical to the method of calculating the bearing capacity of annular cross-section reinforced concrete elements. The suggested method may be used for calculating circular cross-section reinforced concrete elements in testing and design.

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