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SHEAR DESIGN OF CIRCULAR CONCRETE SECTIONS ACCORDING TO THE EC2 TRUSS MODEL

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ABSTRACT

Shear design in Eurocode 2 is generally developed for rectangular sections or T-sections that have clearly defined tension reinforcement, concentrated in the cross-sectional tension zone, and an unambiguous width of compressed diagonals. In circular sections, which are also frequent in practice, the reinforcement is evenly distributed along the circumference of the section, while the width of the section changes continuously along the height.

Several proposals for the shear design of circular sections can be found in the literature, based on a relatively limited experimental database, which generally provide different structural resistances. This paper aims to enable the practical application of the Eurocode 2 variable-angle truss model in the shear design of elements of circular cross-section, such as columns or piles. It is intended to make a correct interpretation of the truss model with no intention to propose an improved procedure in accordance with the available experimental results.

Keywords: Eurocode 2; shear design; circular sections; truss model

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1. INTRODUCTION

The shear design rules in most codes were developed for rectangular elements. However, the shear behaviour of circular concrete elements is quite different from that of rectangular members.

Eurocode 2 (EC2, [1]) considers the following cases in shear design:

- Elements not requiring design shear reinforcement;
- Elements requiring design shear reinforcement, when shear resistance of concrete is exceeded;
- Maximum shear resistance, determined from the compressive strength of concrete.

Procedures regarding shear design in EC2 are also developed for elements with rectangular sections or T-sections. Tensile reinforcement due to bending in such elements is usually concentrated in the tension zone of the cross section. Also, the section width to be used with different design procedures can be easily determined.

However, circular sections are often used for concrete columns and piles. Apart from bending moments, these elements are usually subjected to axial forces. The axial compressive force can also be very large, so that the entire section can be in compression. The occurrence of axial tensile force is rarer, but not excluded. Bending moment often exhibits a "rapid" change in the zone that is interesting for the shear design (ends of the columns, part of the pile next to the pile cap).

A relatively small number of studies have been published on the shear behavior of circular concrete elements. Code rules and guidelines for shear design of circular concrete elements are quite rare. EC2, apart from general instructions, practically does not provide any specific guidelines for the shear design of circular sections. In recent study [2], the EC2 truss model for shear design is extended to circular columns, using both experimental and theoretical data. Relatively simple and explicit guidelines for shear design of circular cross-section elements can be found in AASHTO LRFD [3].

The paper presents the shear design procedure of circular concrete sections. This paper aims to enable the practical application of the EC2 variable-angle truss model in the shear design of elements of circular cross-section, such as columns or piles. It is intended to make a correct interpretation of the truss model with no intention to propose an improved procedure in accordance with the available experimental results.

2. ELEMENTS NOT REQUIRING DESIGN SHEAR REINFORCEMENT $V_{Ed} < V_{Rdc}$

EC2 provides the procedures for elements with cracks (A) and elements without cracks (B) in the design zone. The first method (A) is general and can be applied to both reinforced concrete and prestressed concrete elements. The application of the second method (B) is formally limited to prestressed elements where it is possible to prove that the tension edge stress (ULS) does not exceed the defined limit f_{ctd}.

Provided expressions for the design shear resistance of the element without shear reinforcement for cracked elements (A), V_{Rdc} ([1], (6.2a,b)), are semi-empirical and not suitable for circular sections. The main reasons are:

- There is no clearly defined - concentrated tensile reinforcement;
- Therefore, the structural depth of the section is not obvious, and
- The width of the section changes along the section height.

Therefore, if it is not possible to fulfill the requirements for the application of the second method (B), the design shear force V_{Ed} should be resisted by the reinforcement. In general, the shear capacity of concrete V_{Rdc} according to (A) is moderate and shear reinforcement is often necessary [4].

The second method (B) (for elements without cracks) is based on the principal tensile stress and can be consistently applied to all cross-sectional shapes. V_{Rdc} is given as ([1], (6.4)):

$$V_{Rd,c} = \frac{I \cdot b_w}{S} \sqrt{f_{ctd}^2 + \alpha_1 \cdot \sigma_{cp} \cdot f_{ctd}} \tag{1}$$

which, for a circular section, becomes

$$V_{Rd,c} = \frac{3\pi \cdot r^2}{4} \sqrt{f_{ctd}^2 + \sigma_{cp} \cdot f_{ctd}} \tag{2}$$

where:

- r is the cross-section radius;
- f_{ctd} is the design tensile strength of concrete, $f_{ctd} = f_{ctk,0.05}/\gamma_c$, $f_{ctk,0.05}$ is 70% of the mean tensile strength of concrete f_{ctm} and $\gamma_c = 1.50$;
- σ_{cp} is the mean axial stress, $\sigma_{cp} = N_{Ed}/A_c$, where N_{Ed} is the axial force and A_c is cross-sectional area.

The shear resistance V_{Rdc} of rectangular and T concrete sections obtained by the second method (B) is usually significantly bigger than that obtained by the first method (A). However, as already said, the application of method (B) is limited to prestressed concrete elements ([1], 6.2.2(2)). The authors are of the opinion that method (B) can also be applied to reinforced concrete elements with axial compression, provided that the internal forces (bending moments, axial forces) are determined in a reliable way - that is, their values are not questionable.

3. ELEMENTS REQUIRING DESIGN SHEAR REINFORCEMENT $V_{Ed} \geq V_{Rdc}$

When the concrete shear capacity V_{Rdc} is exceeded, EC2 adopts a truss model in which the inclination of the compression diagonals can be selected within the specified limits. When applying the truss model, there should be a zone of compression and tension in the sections of the element. If the entire cross-section is in compression, and, provided that the internal forces are reliably determined, the procedure for uncracked elements explained in Chapter 2 could be applied.

In order to create a truss model, it is necessary to determine the position of the center of pressure and the center of tension and to adopt the inclination of the compressed diagonals. Closed circular stirrups perpendicular to the element axis are considered as shear reinforcement. The resulting expression, with the provided modification in Chapter 3.3, is also applicable in the case of spiral reinforcement.

3.1. Calculation of the internal lever arm

The radius of the cross-section of the element is denoted by r, Fig. 1. It was assumed that the longitudinal reinforcement is continuously distributed in a circle with a radius of r_l, while the radius of the stirrup is r_v. The block diagram at the part of $0.8x$ was used to model the pressure in the compression zone of the section (valid for $f_{ck} \leq 50$MPa), where x is the depth of the compression zone (position of the neutral axis).

The center of pressure C_c (compressed truss chord) is located in the center of the pressure zone (up to $0.8x$). The effect of compressed reinforcement is neglected (this approximation has no significant effect on the position of the center of pressure). The center of tension C_t (tensioned truss chord) is adopted at the center of the arch segment of the reinforcement located below the neutral axis. This assumption is on the safe side because part of the reinforcement near the neutral axis is in the elastic region and the calculated center of tension is closer to the center of pressure (the calculated internal lever arm z is somewhat smaller than formally correct one).

The distance between C_c and C_t is the internal lever arm z (truss height). Calculated dimensionless values of the internal lever arm z/r in relation to the height of the compressed zone x/r, and for the three selected "depths" of the longitudinal reinforcement r_l/r = 0.80, 0.85 and 0.90, are shown in the Fig. 2.

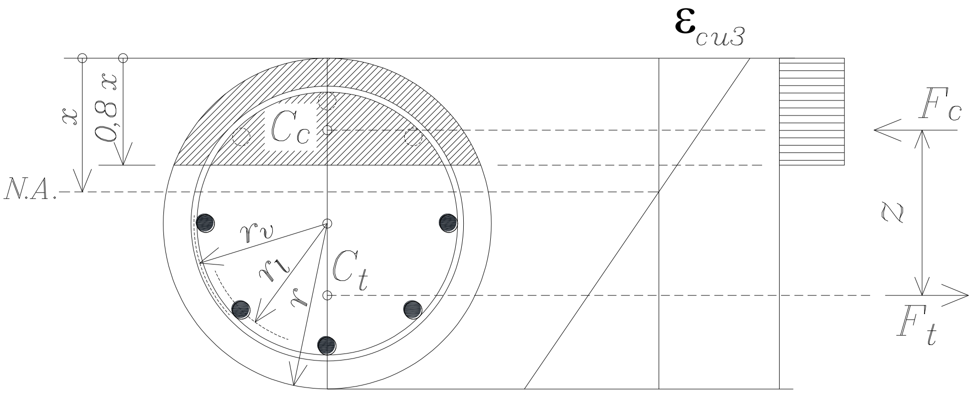

Fig. 1. Cracked cross-section notation

It can be shown that in the case of a circular section, when there is no axial compressive force (pure bending), even with a relatively small longitudinal reinforcement (for example, 0.6% of the concrete section area), the compressed zone is not below x/r = 0.3, for the commonly used concrete strength classes. Based on this, an approximation (Eq. (3)) for the dimensionless value z/r is made:

$$\frac{z}{r} \cong \frac{2}{3} \cdot \frac{r_l}{r} + 0.5 \tag{3}$$

which is also shown in Fig. 2.

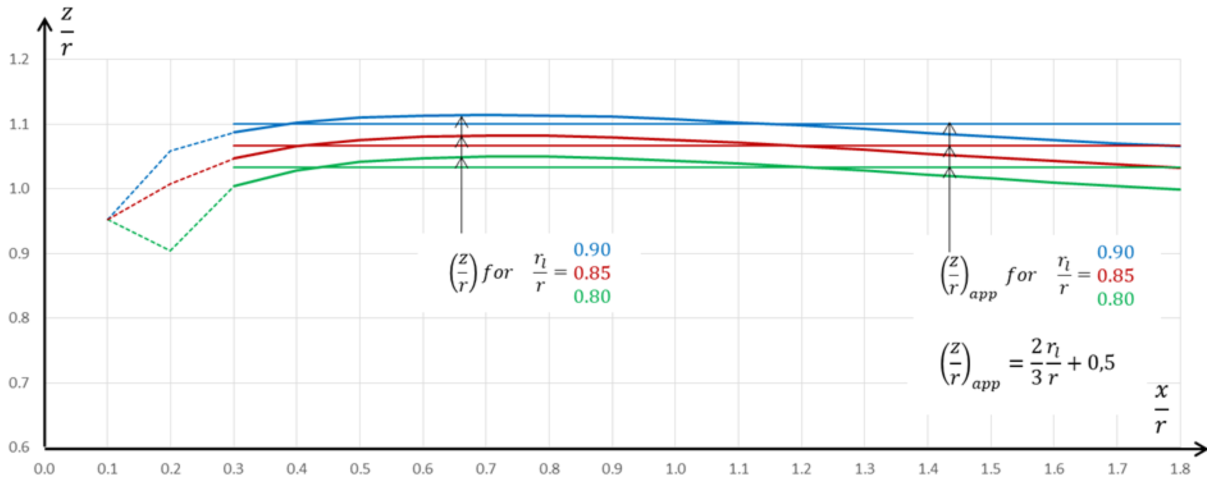

Fig. 2. Calculated and approximate values of z/r

3.2. Shear capacity of transverse reinforcement

In Fig. 3 (right), the inclination of the compressive strut with the selected slope θ is shown. The shear force is resisted by stirrups along the length $z \cdot \mathrm{ctg}\theta$.

Only part of the force in the stirrups resists the transverse force. The direction of the force in the stirrup F_v (Fig. 3, left) depends on the position where the plane at an angle θ "cuts" the stirrup. The component of the force in the stirrup in the direction of the shear force is $F_v \cdot \cos\zeta$. Here ζ denotes the central angle that describes the place where the plane at an angle θ intersects the stirrup (Fig. 3). The angle ζ is measured from the line through the centroid of the section which is parallel to the neutral axis.

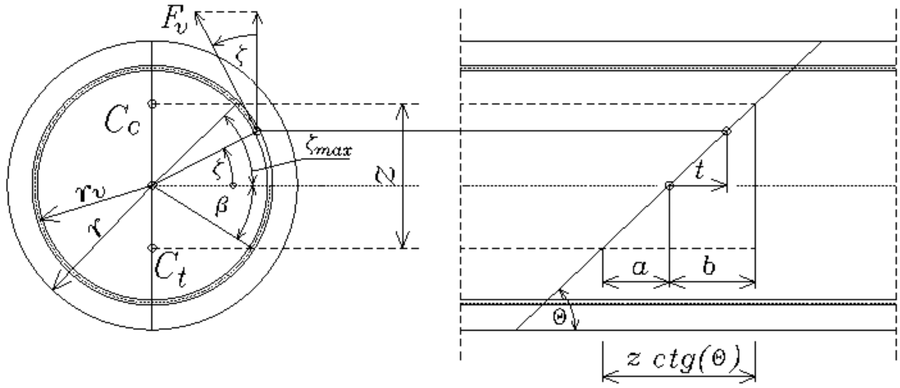

Fig. 3. Calculation of the stirrup force

It is necessary to sum the components of the forces in the stirrups along the length $z{\cdot}\cot\theta$, which is divided into parts a and b by the intersection of the center line and the inclined plane, Fig. 3 right.

If the stirrups are considered as a continuous sheet (tube) of thickness $A_{sv}/2/s$ along the element, the sum is calculated using the integral. Here, $A_{sv}/2$ denotes the cross-sectional area of the stirrup, while s is the stirrup spacing. The variable of integration is t, which represents the distance along the axis of the element, Fig. 3 right.

$$V_{Rds} = \int_{-a}^{b} F_v \cdot \cos\zeta \cdot dt = \int_{-a}^{b} \frac{A_{sv}}{s} \cdot f_{ywd} \cdot \cos\zeta \cdot dt \tag{4}$$

where f_{ywd} is the design yield strength of stirrups.

The variables t and ζ are related. If t is expressed in terms of ζ, V_{Rds} becomes:

$$V_{Rds} = \int_{-\beta}^{\zeta_{max}} \frac{A_{sv}}{s} \cdot f_{ywd} \cdot \cos\zeta \cdot d(r_v \cdot \cot\theta \cdot \sin\zeta) = \frac{A_{sv}}{s} \cdot f_{ywd} \cdot r_v \cdot \cot\theta \int_{-\beta}^{\zeta_{max}} \cos^2\zeta \cdot d\zeta \tag{5}$$

Eq. (5) can be written as:

$$V_{Rds} = \frac{A_{sv}}{s} \cdot f_{ywd} \cdot r_v \cdot \cot\theta \cdot J_1 \tag{6}$$

where J_1 is the value of the integral:

$$J_1 = \int_{-\beta}^{\zeta_{max}} \cos^2\zeta \cdot d\zeta \tag{7}$$

The integral J_1 in the Eq. (7) can be calculated. The limits of integration can take on different values depending on the position of the center of compression and the center of tension of the selected section along the length $z{\cdot}\cot\theta$. The calculated values are shown on Fig. 4.

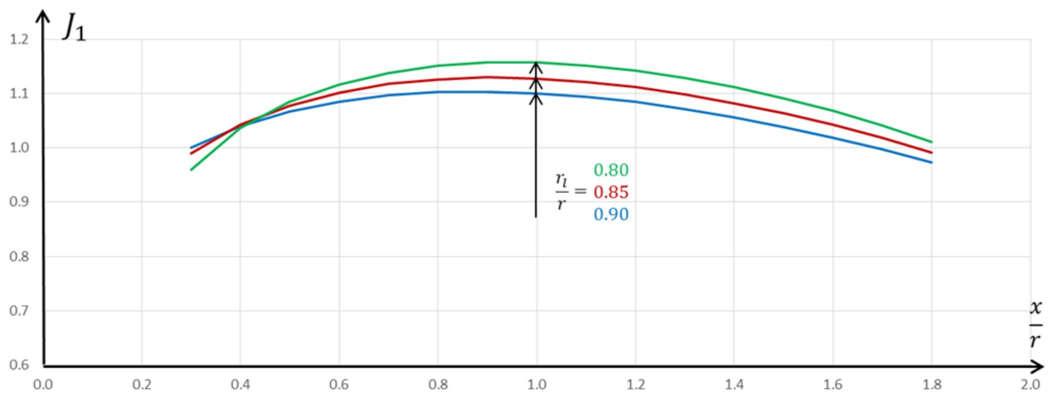

Fig. 4. Calculated values of J_1 (Eq. (7))

Approximation of the values of the integral shown on Fig. 4 requires a complex function. However, if the zone $x/r \geq 0.3$ is considered, a simple approximation, which is at the safe side, is about 1.0 It should be emphasized that, in the case of a "rapid" change of the bending moment in the observed segment of the element (corresponding to a large value of the shear force), with a constant axial force (usually in columns and piles) - the size of x (from section to section along the length $z{\cdot}\cot\theta$) can change significantly. Therefore, the value of J_1 can vary accordingly. This means that the smallest appropriate value of the integral should be taken, so that the approximation by the proposed constant value is suitable.

The expression Eq. (6) for the shear force resisted by the stirrups finally becomes:

$$V_{Rds} = \frac{A_{sv}}{s} \cdot f_{ywd} \cdot r_v \cdot \cot\theta \tag{8}$$

3.3. Spiral links

In the case of spirally reinforced circular sections, the force in the stirrup is inclined in two directions regarding to the longitudinal axis of the element. The corresponding force component in the stirrups can be determined similarly to closed transverse stirrups with an additional decomposition. The multiplier used to achieve this is included in Eq. 9.

$$V_{Rds,spiral} = \frac{A_{sv}}{p} \cdot f_{ywd} \cdot r_v \cdot \cot\theta \cdot \frac{1}{\sqrt{\left(\frac{p}{2r_v\pi}\right)^2 + 1}} \tag{9}$$

where p denotes the pitch of the spiral.

4. ADDITIONAL TENSILE REINFORCEMENT

The additional tensile force in the longitudinal reinforcement due to shear V_{Ed} is ([1], (6.18)):

$$\Delta F_{td} = 0.5 \cdot V_{Ed} \cdot \cot\theta \tag{10}$$

The required additional tensile reinforcement is $\Delta F_{td}/f_{yd}$, where f_{yd} is the design yield strength of the longitudinal reinforcement. Since the reinforcement is usually distributed uniformly along the circumference of the cross-section, it is necessary to increase the additional reinforcement in order to achieve the appropriate increase in the tensile zone. Additional reinforcement, for the entire section, can be determined using the central angle of the tensile zone ω, Fig. 5:

$$\omega = 2 \cdot \arccos \frac{x - r}{r_l} . \tag{11}$$

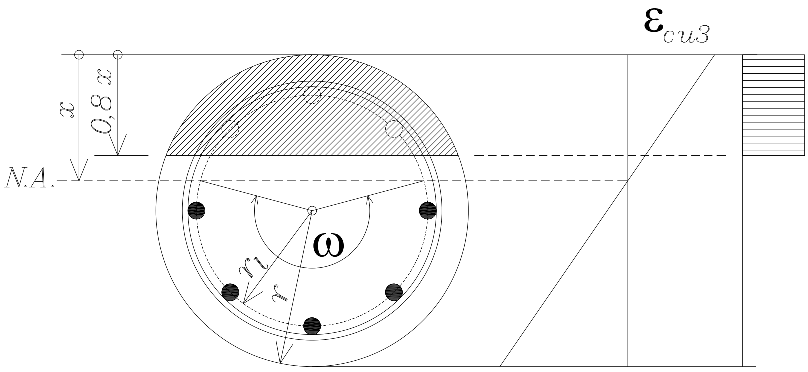

Fig. 5. Tensile reinforcement of the circular section

The required additional longitudinal reinforcement ΔA_{sl}, for the entire circumference, is:

$$\Delta A_{sl} = \frac{\Delta F_{td}}{f_{yd}} \cdot \frac{2\pi}{\omega} . \tag{12}$$

The total reinforcement (reinforcement due to the bending moment plus the indicated additional reinforcement ΔA_{sl}) should not be greater than the reinforcement corresponding to the maximum moment in the considered zone along the element.

5. MAXIMUM SHEAR FORCE

Unlike V_{Rds}, the determination of the maximum shear force which can be sustained by an element $V_{Rd,max}$, limited by the crushing of compression diagonals, is an issue seldom discussed in the literature. Since the width of the section is continuously changing along the height, the problem is to determine the relevant width b_w of the compressed diagonals.

The maximum shear force $V_{Rd,max}$ is given by Eq.(13) ([1], (6.9)):

$$V_{Rd,\max} = \alpha_{cw} \cdot b_w \cdot z \cdot \nu_1 \cdot f_{cd} / (\cot\theta + \tan\theta) \tag{13}$$

where α_{cw} = 1.0 for non-prestressed elements, $\nu_1 = 0.6 \cdot (1 - f_{ck}/250)$, $f_{cd} = f_{ck}/\gamma_c = f_{ck}/1.5$ and f_{ck} is the characteristic compressive strength of concrete.

Formally, the smallest width b_w in the region between the tension chord and the neutral axis should be used in Eq. (13). Paper [2] used the similar approach to determine EC2-compliant b_w, but without analyzing the results thus obtained. However, for columns and piles (which are the most common elements of circular cross-section), in the shear design zone, the axial force is almost constant, while the bending moment generally changes "rapidly". The position of the neutral axis changes and thus the heights of the compressed and tensioned cross-sectional zones along the compressed diagonal $z \cdot \cot\theta$ change.

The width of the compressive diagonal $b_{eff} = b_w$ has been considered depending on the height x of the compression chord. The smaller of the two values is selected: the width of the section at the level of neutral axis and the width at the level of the center of tension C_t (in paper [2] the smaller of the width of the section at the level of the center of pressure C_c and the width at the level of the center of tension). The obtained results for the dimensionless width b_{eff}/r in relation to the height of the compressed zone x/r, for three values of the "depth" of the longitudinal reinforcement r_l/r, are shown in Fig. 6.

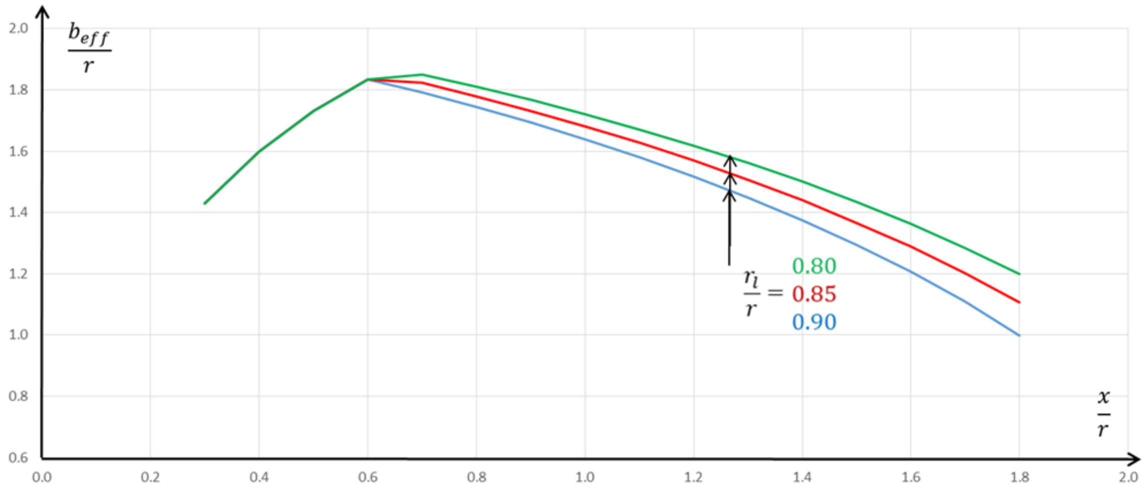

Fig. 6. Effective width of compressed diagonals b_{eff}

The smallest value of b_{eff} should be adopted along the compressed diagonal, in accordance with changing the position x of the neutral axis. According to Fig. 6, if values for x are not considered in detail, one can always adopt $b_{eff} = r$, on the safe side.

The previous approach is in formal agreement with the provisions of EC2's chapter 6.2.3. However, it should be emphasized that the obtained values are conservative compared to other approaches that can be found in the literature.

If the equivalent rectangular beam is used, whose section height is equal to the height of the tension zone of the circular section, the width b_{eff} is derived by equalizing the areas of the corresponding rectangle and the circular section below the neutral axis. In that case, resulting b_{eff} is about 1.6r [5]. The authors obtained a similar result when b_{eff} is adopted as the mean value of the section width at the level of the center of pressure C_c and the width at the level of the tension center C_t. In that case, b_{eff} is not below 1.5r, again for the range of x/r values.

AASHTO LRFD provides an explicit expression ([3], 5.8.3.3-2) for the maximum shear force $V_{\max}$ (resistance) of a circular section, which applies a width equal to the section diameter $b_v = D$ ([3], 5.8.2.9) and the internal lever arm d_v ([3], C5.8.2.9-2):

$$V_{\max} \leq 0.25 \cdot f_c^{'} \cdot b_v \cdot d_v \tag{14}$$

which can be rewritten using the notation from this paper

$$V_{\max} = 0.25 \cdot f_{ck} \cdot (2r) \cdot [0.9 \cdot (r + 2r_l / \pi)] \tag{14a}$$

and, for $r_l = 0.85r$

$$V_{\max} = 0.69 \cdot r^2 \cdot f_{ck} \tag{14b}$$

EC2's expression (13), for concrete class C25, $r_l = 0.85r$ and $\theta = 45°$ gives

$$V_{Rd,\max} = 0.32 \cdot r^2 \cdot f_{ck} \tag{13a}$$

Although the ULS load safety factors are different in [1] and [3], the value Eq. (13a) is significantly smaller than Eq. (14b).

Experiments studying the shear failure of circular sections are mainly focused on the shear resistance of elements without, or with small or moderate shear reinforcement. In those cases, the crushing of the concrete diagonals is not registered. In a recent study [6], circular concrete elements with heavy shear reinforcement were investigated. The ratio of the observed to calculated shear limit load according to the AASHTO procedure was also analyzed. In cases where the governing criterion in [3] is crushing of compressive diagonals - Eq. (14), the ratio was in the interval from 1.05 to 1.34, so it was concluded that the AASHTO procedure is also conservative. However, one should have in mind that the specimens in these experiments have been loaded with no axial force. The elements fulfilled the condition for the application of the constraint from Eq. (14), but it was not explicitly indicated in [6] whether the observed failure in these cases was due to the crushing of compressed diagonals. Also, the confinement effect of the heavy shear reinforcement delays the failure of the compressed concrete, which is not included in the design model.

The new version of EC2 (prEN 1992-1-1:2021, [7]) provides somewhat more detailed instructions for the shear design of concrete elements with a circular cross-section. No explicit expression is given for b_w (calculation is required), but a wider range is allowed for choosing the size of b_w.

Considering the very limited number of experiments related to the maximum shear resistance $V_{Rd,max}$, the authors are of the opinion that the provisions of the current version of EC2 [1] regarding the choice of b_{eff} should still be formally respected, although the experimental research so far suggests that this is a conservative approach. The conducted numerical analysis indicates that in practical calculations this conservatism is not a limiting factor in most cases.

6. CONCLUSIONS

This paper is intended to make a correct interpretation of the EC2's truss model for the shear design, with no intention to propose an improved procedure in accordance with the available experimental results.

The base of experimental data related to the shear design of elements of circular cross-section is still limited. Some design items (for example, crushing of compressed concrete diagonals) are practically not found in published experiments.

Eurocode 2 does not provide guidance for the shear design of circular cross-section elements - the given expressions are intended for the design of rectangular and T-sections. These instructions can only be partially adapted for the practical design of circular sections: approximations are needed to formulate procedures that are simple enough for practical application.

The expressions given in EC2 for the shear resistance of cracked elements without shear reinforcement are semi-empirical and not adaptable to circular sections. The procedure for uncracked elements can be adapted, but EC2 limits its use to prestressed concrete elements. For cracked elements, it is possible to use a truss model with a variable inclination of compressed diagonals.

The paper presents expressions for the shear resistance of stirrups and spiral reinforcement that are in accordance with the EC2 model. A practical procedure for the calculation of additional tensile reinforcement due to shear force is offered. The maximum shear resistance corresponding to the crushing of compressed diagonals is analyzed and compared with AASHTO LRFD recommendations.

Simple expressions for the shear design of circular cross-section concrete elements are offered. The expressions are suitable for practical application.

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