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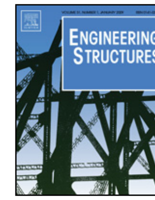

Shear strength of heavily reinforced concrete members with circular cross section

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ABSTRACT

Reinforced concrete members with circular cross section are used frequently in practice. Despite this fact, only limited research on the shear behaviour of such structural members has been published. Further, code rules and guidelines for shear design of circular concrete members are almost non-existent. Most code rules are based on shear models for rectangular members. The shear behaviour of circular members is, however, quite different from that of rectangular members. The difference is especially pronounced for members containing high shear reinforcement percentages. This paper presents the results of a test series on heavily shear reinforced circular concrete members. The specimens had shear reinforcement percentages up to more than three times the maximum percentage found in existing tests. The test results indicate that it is possible to obtain shear strengths which exceed the upper limit usually imposed on rectangular members. The test results are compared with a recently developed plasticity-based shear model for circular members. Satisfactory agreement was found. Comparisons were also made with calculations using the AASHTO LRFD design code. It was found that the AASHTO LRFD design code gives reasonable results for members with small amounts of shear reinforcement while it underestimates the shear strength for heavily shear reinforced members.

1. Introduction

Reinforced concrete members with circular cross section are often used in civil engineering structures, for instance as laterally loaded bridge piers and piles. Despite their frequent occurrence in practice, only limited research on the shear behaviour of circular members has been carried out. Shear design rules in codes are based on models for rectangular members. In practice, these rules are also applied to circular members by the use of an equivalent rectangular cross section. The accuracy of such an approach is questionable because circular hoops contribute differently to the shear strength compared with rectangular stirrups.

Only a few shear models specially developed for circular members can be found in the literature. Ang et al. [1] developed a model for members subjected to cyclic loading. This model consists of a purely empirical concrete contribution and a classical shear reinforcement contribution, where the inclination of the shear crack is determined by the use of a lower bound plasticity model. The Ang et al. model has been subjected to a number of modifications over the years [2–4]. A shortcoming of these models is that they do not account for size effects. This was pointed out by Collins et al. [5], who instead have advocated for the application of the Modified Compression Field Theory (MCFT) [6] to deal with shear strength prediction of circular members. Application of the MCFT requires implementation of the calculation algorithms in a computer program. A simplified and design oriented version of the MCFT has been described by Bentz et al. [7]. This simplified model forms the basis of the shear design rules described in AASHTO LRFD [8], which also contains rules for shear design of circular members. An analytical study of shear truss analogy for concrete members with solid and hollow circular cross section has recently been reported by Turmo et al. [9]. This study, however, is only focused on the contribution of the shear reinforcement.

Similar to the theoretical research, experimental studies on the shear capacity of circular members are also quite limited. Fewer than 250 test results have been found in the literature [1,2,10–17]. The published tests only cover circular members with mechanical shear reinforcement degrees up to $\psi \sim 0.10$. Tests on heavily shear reinforced specimens, i.e. specimens with shear reinforcement contribution several times the concrete contribution, have not been found in the literature. Such tests have been requested by, for example, Feltham [18] for a better understanding of the hoop contribution in circular members.

Heavy shear reinforcement is required in practice when a member, for instance a bridge column or pile, is short and is subjected to large transverse loads. For slender members designed to fail in flexure, the zones of the plastic hinges are often detailed with

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Nomenclature

Roman letters

a	Shear span
a_g	Maximum aggregate size
b_v	Effective width
d_{sh}	Cross sectional diameter of one hoop leg
d_v	Effective depth
f_c	Uniaxial cylinder compressive strength
f_{tef}	Effective tensile strength of concrete
f_y	Yield stress of longitudinal reinforcement
f_{ys}	Yield stress of shear reinforcement (hoops)
f_u	Tensile strength of longitudinal bars
h	Depth of beam
k	D'/D
m	Total number of longitudinal reinforcement bars
n	Number of legs in a hoop
s	Spacing of hoops along the longitudinal axis
s_{xe}	AASHTO LRFD crack spacing parameter
u	Relative displacement
v_u	$V/b_v d_v$
x	Horizontal projection of diagonal crack
A_c	Concrete cross sectional area
A_s	Flexural reinforcement area in tension
A_{sh}	Cross sectional area of hoop reinforcement
A_v	Cross sectional area of shear reinforcement within distance s
$A_{v,\min}$	Minimum shear reinforcement according to AASHTO LRFD
C	Correction factor
D	Diameter of cross section
D'	Diameter of hoop
E_s	Young's modulus for steel
L	Span of test specimen
L_o	Width of loading or support saddle
P	Point load
P_{cr}	Cracking load
P_R	Vertical projection of yield force in the hoops crossed by the crack
P_u	Theoretical shear strength
$P_{\exp}$	Experimental shear strength
M	Sectional moment
N	Sectional axial load
V	Sectional shear force
V_c	AASHTO LRFD concrete contribution to the shear capacity
V_s	AASHTO LRFD shear reinforcement contribution to the shear capacity
V_n	AASHTO LRFD nominal shear strength
W_E	External work
$W_{I,c}$	Internal work, concrete
$W_{I,s}$	Internal work, reinforcement

Greek letters

α	Angle between yield line and the displacement direction
β	AASHTO LRFD factor
ε_x	Longitudinal strain at mid-depth of the cross section
φ	Angle of internal friction
θ	Inclination of diagonal compression field
ν_0	Effectiveness factor taking into account micro cracking and softening
ν_s	Sliding reduction factor
ρ_l	Reinforcement ratio based on the total area of longitudinal reinforcement
τ_c	$\frac{1}{2}\nu_s\nu_0\left(\sqrt{5}-2\right)f_c$
$\tau_{\exp}$	$P_{\exp}/A_c$
τ_u	P_u/A_c
ψ	Mechanical shear reinforcement degree

confining hoops in such amounts that these zones also may be classified as heavily shear reinforced. Although designed for a flexural collapse mode, it is also important in such cases to be able to calculate the shear strength accurately. One of the reasons for this is that confining hoops often provide an enhanced flexural capacity, which in turn could make the member shear critical if there is an insufficient margin between the flexural and the shear capacity.

The purpose of this paper is to present results from a shear test series with heavily shear reinforced circular members. The test results are compared with calculations based on the AASHTO LRFD approach. Analysis of the test results using the plasticity-based Crack Sliding Model is also carried out. It is shown that the AASHTO LRFD approach only yields good agreement for tests with small degrees of shear reinforcement whereas the Crack Sliding Model gives good agreement within the whole range of shear reinforcement degrees tested.

2. Experimental programme

Shear tests on 16 circular specimens were carried out at the University of Southern Denmark [19]. Four specimens were without shear reinforcement while the remaining specimens were designed with ψ varying between 0.075 and 0.333. The specimens had a cross sectional diameter D of 250 mm and a total length of 1800 mm. All specimens were simply supported and subjected to a point load at mid-span. For the majority of the specimens the center to center distance between the supports was $L = 1000$ mm, corresponding to an M/VD ratio of 2. For specimens SDU1, SDU3 and SDU4, L was 750 mm, 1250 mm and 1500 mm, respectively. This corresponds to M/VD ratios of 1.5, 2.5 and 3.0.

The shear reinforcement consisted of closed hoops. Three specimens were provided with "single hoops" while nine specimens had "double hoops", (single hoop = hoop with one turn, double hoop = hoop with two turns); see Figs. 1 and 2. The hoops were made of deformed bars and had yield stress, f_{ys}, varying between 573 MPa and 587 MPa. The spacing of the hoops was varied between 100 mm and 125 mm, corresponding to an s/D ratio between 0.4 and 0.5. The main reason for choosing the relatively large hoop spacing was to obtain similar s/D ratios to those used in many of the tests on lightly shear reinforced members published in the literature. Furthermore, the chosen hoop spacing also ensures sufficient free space between the double hoops. Details of the specimens including hoop spacing and strength parameters are given in Table 1.

For specimens SDU1 to SDU4, the longitudinal reinforcement consisted of sixteen 10 mm diameter deformed bars. The bars were evenly distributed, as shown in Fig. 3 (left). For specimens SDU5 to SDU16, eight DYWIDAG 20 mm diameter thread bars with nominal $f_y = 900$ MPa and $f_u = 1100$ MPa were used together with eight 10 mm diameter deformed bars. The DYWIDAG bars were placed at the bottom and at the top, as shown in Fig. 3 (right), in order to obtain a sufficient margin between the flexural capacity and the expected shear capacity. To prevent unexpected anchorage failure in the heavily shear reinforced specimens, an anchorage length of 400 mm beyond the supports was provided and combined with anchor nuts installed on the threaded bars; see Fig. 4.

The specimens were produced at a manufacturer of precast concrete elements. The cement type was Ordinary Portland Cement and the water/cement ratio was 0.55. The maximum aggregate size was limited to 8 mm due to the dense reinforcement arrangement. Fabrication of the specimens took place on two consecutive days. Eight specimens were cast simultaneously each day. The specimens were cast vertically in formwork made of hard cardboard tubes (the same material as used in the precast concrete industry). The tubes were delivered with both the inner surface and the outer surface wax treated in order to enhance the curing conditions of