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Minimum shear reinforcement for ultra-high performance fiber reinforced concrete deep beams

Ahmed M. Yousef [a,*], Ahmed M. Tahwia [a], Nagat A. Marami [a,b]

[a] *Structural Engineering Department, Faculty of Engineering, Mansoura University, Mansoura 35516, Egypt*
[b] *Zawia University, Zawia 16418, Libya*

HIGHLIGHTS

- The Stirrups have slight effect on the ultimate shear strength of UHPFRC beams.
- The recommendations of AFGC and KCI are conservative more than the codes.
- The maximum spacing between stirrups of EC-2 and ECP-203-2017 is applicable.
- The requirements of ACI318-2014 for $S_{v,max}$ between stirrups should be increased.
- The proposed numerical model provides accurate predictions for V_u.

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ABSTRACT

This research aimed to study the minimum requirements of shear reinforcement for ultra high performance fiber reinforced concrete deep beams. The experimental results showed that increasing the provided vertical web reinforcement ratio has slight effect on the diagonal cracking strength and the ultimate shear strength. The maximum spacing between the vertical web reinforcement required by ACI 318-2014 for reinforced concrete beams (*d/5*) is not suitable for ultra-high performance fiber reinforced concrete deep beams, while for the EC-2 (*2b*) and that required by the Egyptian code ECP-203-2017 (200 mm) is applicable. The recommendations of AFGC-2013 and KCI-2012 are safe and conservative more than that required by ACI 318-2014.

1. Introduction

The use of Ultra High-Performance Fiber Reinforced Concrete (UHPFRC) enables designers to create thinner sections and longer spans. Its excellent mechanical behavior, in the form of high compressive strength of values greater than 150 MPa and a design value of tensile strength more than 8 MPa, and its high durability reduces the maintenance requirements and extends the service life. Many investigations have studied the material properties of UHPFRC, including mechanical strength, shrinkage behavior and bond performance [1–4].

Deep beams are commonly used as transfer girders in tall buildings, foundations, offshore structures and others. Experimental tests on the shear behavior of UHPFRC shallow and deep beams with and without web reinforcement have been reported [5–8]. In order to avoid sudden failure in deep beams, vertical and horizontal web reinforcement in a proper spacing should be provided, even when shear reinforcement is not necessary according to computation. All the international codes such as ACI 318-2014 Building Code [9], the Eurocode 2 (EC-2) [10] and the Egyptian code (ECP-203-2017) [11] require a minimum vertical and horizontal shear reinforcement in reinforced concrete deep beams. However, these codes do not contain provisions for design of UHPFRC beams. The first design recommendations for UHPFRC has been reported in 2002 by the France Association of Civil Engineers (AFGC-2002) [12] and revised in 2013 (AFGC-2013) [13]. Another design recommendation for UHPFRC has been proposed by the Japan Society of Civil Engineers (JSCE-2008) [14] and also by the Korea Concrete Institute (KCI-2012) [15].

* Corresponding author.
E-mail addresses: ahmyousef@mans.edu.eg (A.M. Yousef), atahwia@mans.edu.eg (A.M. Tahwia).

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In this paper, shear tests of UHPFRC deep beams provided with minimum shear reinforcement has been reported. The applicability of the recommendations of AFGC-2013 and also that of KCI-2012 for the shear design of UHPFRC beams has been examined. Numerically model for predicting the shear strength and deformations of UHPFRC deep beams is proposed using a three dimensional finite element program.

2. Minimum shear reinforcement required by the international codes for R/C deep beams

2.1. ACI 318-2014

Deep beams in this code are members that strut-like compression elements can develop between the loads and supports and satisfy that clear span does not exceed four times the overall member depth h, or concentrated loads exist within a distance $2h$ from the face of the support.

The area of the minimum vertical web reinforcement $A_{v,\min}$ and the minimum horizontal web reinforcement $A_{h,\min}$ are given as follows:

$$A_{v,min} = 0.0025\ b\ s_v \quad (1.a)$$

$$A_{h,min} = 0.0025\ b\ s_h \quad (1.b)$$

where b is the width of the beam, s_v is the spacing between vertical web reinforcement and s_h is the spacing between the horizontal distributed skin longitudinal reinforcement. The web reinforcement should be provided such that s_v and s_h do not exceed the lesser of $d/5$ or 300 mm, where d is the effective depth.

2.2. ECP-203-2017

This code defines the beam with effective span to depth ratio (l_n/d) less than or equal to 4 as deep beam. The area of the minimum vertical web reinforcement $A_{v,\min}$ and the minimum horizontal web reinforcement $A_{h,\min}$ are given as follows:

$$A_{v,min} = 0.0030\ b\ s_v \ \text{ for mild steel } 240/350 \quad (2.a)$$

$$A_{v,min} = 0.0025\ b\ s_v \ \text{ for high grade steel} \quad (2.b)$$

$$A_{h,min} = 0.0030\, b\, s_h \ \text{ for mild steel } 240/350 \quad (3.a)$$

$$A_{h,min} = 0.0025\ b\ s_h \ \text{ for high grade steel} \quad (3.b)$$

The web reinforcement should be provided such that s_v and s_h should not exceed 200 mm.

2.3. EC-2

The EC-2 defines the beam with span to the overall section depth ratio (l_n/h) less than 3 as deep beam. The area of the minimum vertical web reinforcement $A_{v,\min}$ and the minimum horizontal web reinforcement $A_{h,\min}$ are given as follows:

$$A_{v,min} = 0.001\, A_c \quad (4.a)$$

$$A_{h,min} = 0.001\, A_c \quad (4.b)$$

where A_c is the area of the concrete section. The web reinforcement should be provided such that s_v and s_h do not exceed the smaller of $2b$ or 300 mm.

3. Shear design recommendations for UHPFRC beams

3.1. AFGC-2013

The design shear strength V_d of UHPFRC is obtained as follows:

$$V_d = V_c + V_{fb} + V_s \quad (5)$$

For beams with loads within a distance $0.5d \le a_v \le 2.0d$, the contribution of this load to the shear force may be reduced by $\beta = a_v/2d$.

The shear strength provided by the cement matrix V_c is given as follows:

$$V_c = \left(0.21/\gamma_{cf}\gamma_E\right)k\sqrt{f'_c}\,bd \quad (6)$$

where $f_c^{'}$ is the compressive cylinder strength, γ_{cf} is a partial safety factor on fibers and is taken 1.30, γ_E is a safety coefficient, $\gamma_{cf}\,\gamma_E$ is equal to 1.5, and k is a factor for the case of prestressing. The contribution of steel fibers V_{fb} can be calculated from the following equation:

$$V_{fb} = (A_{fv}\sigma_{Rd,f}/tan\theta) \quad (7)$$

where A_{fv} is the area of fiber effect and is assumed equal to $b\ z$ for rectangular sections, z is equal to $0.9d$, θ is the angle between the principal compression stress and the beam axis taken with a minimum value of 30° , and $\sigma_{rd,f}$ is the residual tensile strength calculated from the following expression:

$$\sigma_{Rd,f} = (1/k\sigma_{cf}) \times (1/w_{lim}) \int_0^{w_{lim}} \sigma_f(w)\,dw \quad (8)$$

where w_{lim} = max ($\underline{w_u}$, w_{max}), K is the fiber orientation factor taken equal to 1.25, $\sigma_f\,(w)$ is a function of the tensile stress and crack width, w_{max} is the maximum crack width.

The shear strength by vertical shear reinforcement V_s is computed from the following equation:

$$V_s = A_v/s_v z f_{yv} \cot\theta \quad (9)$$

3.2. KCI-2012

The design shear strength V_d is given by the same equation No. (5), while the term V_c is given as follows:

$$V_c = \phi_b\, 0.18\sqrt{f'_c}\, b\, d \quad (10)$$

where ϕ_b is the member reduction factor equal to 0.77. The value of V_{fb} is:

$$V_{fb} = \phi_b(f_{vd}/tan\beta_u)bz \quad (11)$$

where f_{vd} is the design average tensile strength in the direction perpendicular to diagonal tensile crack, β_u is the angle between the diagonal tensile crack plane and axial direction of the beam and shall be larger than 30°, z is equal to $d/1.15$. The value of f_{vd} is given by:

$$f_{vd} = (1/w_v)\int_0^{w_v} \phi_c\sigma_k(w)dw = (1/w_v)\int_0^{w_v} \sigma_d(w)dw \quad (12)$$

where w_v= max (w_u, 0.3 mm), w_u is the ultimate crack width at the peak stress on the outer fiber, ϕ_c is the material reduction factor taken equal to 0.8, $\sigma_k\,(w)$ is the tension softening curve. The term V_s can be calculated from:

$$V_s = \phi_b(A_v f_{yv}(sin\alpha_s + cos\alpha_s)/s)d \quad (13)$$