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Macro-mechanical strut and tie model for analysis of fibrous high-strength concrete corbels

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Abstract Reinforced concrete (RC) corbels becoming a frequent attribute in the building construction with the increasing use of pre-cast high-strength concrete (HSC). The use of fibrous high-strength concrete (FHSC), increases corbel ductility and thus defines the mode of failure of the corbels, depending on the fiber parameters. In this paper a macro-mechanical strut and tie model is proposed for analysis of fibrous high-strength concrete corbels. In this model the fibers can be used as a replacement of horizontal stirrups, due to increasing of shear friction of (FHSC). The analytical macro-mechanical model takes into consideration the effect of fiber volume, fiber length, and fiber diameter, random distribution of fibers, fiber HSC interface and shear span-to-depth ratio, respectively. This model is compared with available experimental results found in literature and a good agreement is obtained. The parametric study is performed to examine for different parameters affecting the analysis of (FHSC) corbels using the proposed macro-mechanical strut and tie model.

1. Introduction

The use of high-strength concrete is widespread in modern structures. Many researchers focused on the shear friction behavior of high-strength concrete [1–4] and use this behavior in corbels as a structural application. Corbels are designed mainly to provide for vertical reaction and sometimes for horizontal forces. The reinforcement of the corbels is primary tension steel and horizontal bars. From the test results, it was found that corbels display several modes of failure [2]. The most common are the yielding of tension reinforcement, crushing or splitting of compression strut and localized bearing or shearing failure under the loading plate, respectively. The cracking pattern near failure load of high-strength reinforced concrete corbel is shown in Fig. 1. The current codes philosophy [5,6] of the design of corbels is based on shear–friction theory. In the code provision of design of corbels all the tensile stresses are carried by main reinforcement and horizontal hoops while the concrete tensile strength is totally neglected.

The uneven crack faces slide past one another, the projections on the crack faces over one another and force the crack apart, stretching any reinforcement crossing the crack to yield. The tensile force developed in the reinforcement is assumed to

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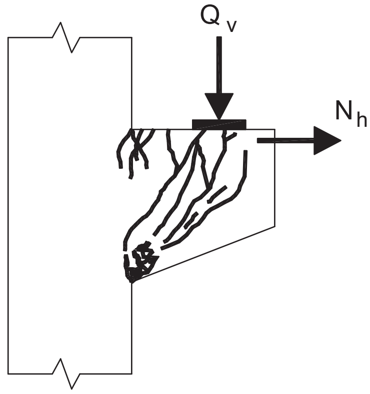

Figure 1 Cracking pattern near failure load for high-strength reinforced concrete corbels.

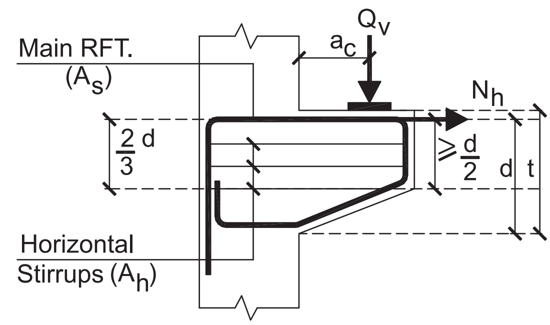

Figure 2 Details of steel reinforcement arrangement and applied forces on the reinforced concrete corbels.

compress the crack faces together which results frictional resistance across crack plan [1]. Many test results [7–12] are performed to predict the ultimate shear strength of fiber high-strength concrete (FHSC). Most of these tests are performed on the corbels and the other is localized on puss-off specimens. These test results reflect the influence of FHSC on shear friction strength. This means there is a need for design equation to evaluate the contribution of (FHSC) on the shear friction. The available experimental results [7–11] found in literature are performed on the corbels without horizontal ties and using fibers as partial or full replacement of horizontal ties. In the present paper, the evaluation of the contribution of fiber high-strength concrete (FHSC) corbels is presented through proposed simplified macro-mechanical model. The analytical macro-mechanical model takes into consideration the effect of fiber volume, fiber length, and fiber diameter, random distribution of fibers, fiber HSC interface and shear span to depth ratio. The analytical model compared with experimental results found in literature shows acceptable agreement. Different studies are preformed on the FHSC corbels include effect of fiber volume fraction, fiber length over fiber diameter, shear span-to-depth ration and FHSC strength, respectively.

2. Code provisions for design of corbels

The code previsions for design of RC corbels [5,6] approved that the shear force is transmitted through a defined plan by shear friction mechanism. The philosophy of the Egyptian Code (ECP 203-2007) [5] for shear friction provided that the shear force is transmitted by the reinforcement and neglecting the concrete shear strength. The reinforcement required to resist shear friction (A_{sf}) is given by the following relationship as:

$$A_{sf} = \frac{Q}{\mu_f(f_y/\gamma_s)} + \frac{N_h}{(f_y/\gamma_s)} \quad (1)$$

where (Q_v) and (N_h) are respectively, the vertical force and horizontal force transmitted through shear plan, as shown in Fig. 2. The value of (f_y/γ_s) is the yield stress of the reinforcement over the strength reduction factor of the reinforcing steel, on condition that the yield stress of the reinforcement is not greater than (400 MPa). The friction coefficient (μ_f) is taken as (1.20) for monolithic concrete, (0.80) for construction jointed concrete with rough surface greater than (5 mm) and (0.50) for construction jointed concrete with rough surface less than (5 mm), respectively. The shear friction stress (Q_v/bd), as shown on Fig. 2, should not exceed the value ($0.225f_{cu}/\gamma_c$); with maximum limit (5 MPa) as shown in Fig. 2, where (b) is the corbel width, (d) is the corbel depth, (f_{cu}) is the characteristic cube strength of concrete and (γ_c) is the strength reduction factor of concrete, respectively [5].

The reinforcement configuration of the corbels according to codes requirements [5,6] is shown in Fig. 2. The Egyptian Code [5] defines the corbels that have the value of (a_c/d) not greater than unity. The main reinforcement of the corbel (A_s) is shown in Fig. 2 and can be calculated according to (ECP 203-2007) [5], as the greater value of the following two equations as:

$$A_s = A_n + A_f \quad (2a)$$

or

$$A_s = A_n + (2/3)A_{sf} \quad (2b)$$

where the value of the main steel area (A_f) is the reinforcement required to resist flexure at the face of support and (A_n) is the value of main steel area required to oppose horizontal tension force (N_h), and can be calculated as:

$$A_n = N_h/(f_y/\gamma_s) \quad (3)$$

The main steel reinforcement ratio (A_s/bd) should be taken not less than ($0.03f_{cu}/f_y$). The horizontal stirrups (A_h) are parallel to the main reinforcement (A_s) and distributed over (2/3) of the section depth nearby main reinforcement, can be calculated as:

$$A_h = 0.50(A_s - A_n) \quad (4)$$

3. Mechanical properties of fibrous concrete

Due to the fiber improvement of the mechanical properties of (HSC), it is considered suitable material to use specially in corbels. The compressive and tensile behavior of fibrous concrete is highly dependent on fiber properties, mixing, curing and concrete matrix [13–15]. The stress is transmitted from the matrix to fiber by shear deformation at the fiber–matrix interface as a result of the different mechanical properties of the fibers and the matrix. This explains why fibers can be used as a full replacement of horizontal stirrups in FHSC corbels.

Under uniaxial compressive behavior, many experimental studies and numerical models are carried out to study the effect of fiber addition to normal and high-strength concrete