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State-of- the Art and practice of Concrete Structures Reinforced with FRP Bars

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Abstract: Fiber reinforced polymer (FRP) bars have been widely used in civil engineering used as a substitute for steel reinforcement because it has many advantage such as high strength, light weight and no corrosion. Moreover, the productive technology becomes more and more mature and industrialized so that FRP has become one economic and competitive structure material. Based on the recent researches, this paper mainly introduces progress in the studies on concrete structures reinforced with FRP bars. These contents in this paper include the bond performance of FRP bars in concrete, shear resistance, flexural behavior and ductility of concrete structure reinforced with FRP bars in the past few years in the world.

Introduction

Infrastructure deterioration owing to corrosion of steel reinforcement is one of the major challenges. The use of concrete structures reinforced with FRP composite materials has been growing to overcome the common problems caused by corrosion of steel reinforcement. The application of FRP bars in civil engineering can be divided into two classes. One is to substitute steel bars in concrete structures, and the other one is to maintain and strengthen old structures. In the past few years, with the development of FRP material technique, more and more scholar began to focus on the application research work on FRP. This paper mainly introduces progress in the studies on concrete structures reinforced with FRP bars. These contents in this paper include the bond performance of FRP bars in concrete, shear resistance, flexural behavior and ductility of concrete structure reinforced with FRP bars in the past few years in the world.

Bond performance of FRP bars in concrete

The development length of FRP bars The bond performance of FRP bars in concrete, which is the basic mechanical behavior, is the main factor of the mechanical performance, failure mode, serviceability, crack width, deformation and structure analyses and design. The bond performance of 82 concrete specimens with FRP bars are investigated by GAO et al. [1], and the development length and modified coefficient are presented. Ehsani et al. [2] did extensive research on both straight and hooked embedded GFRP bars of 102 specimens, and the constraint coefficient considering the concrete cover depth and the position of FRP bars is suggested. The results from these studies were used to compile the constants for use in the ACI440.1R-03 [3] equation for development length of a straight embedded FRP bar in concrete. Nathan Newman et al. [4] collected the database set of 48 test specimens from the open literature and emulated a specific bar size and embedment length for various scenarios, and a refined design equation for development length of FRP bars was resulted. The following equation 1 of development length is recommended by ACI440.1R-03:

$$l_{bf} = \frac{A_{f,bar} f_{fu}}{\pi d \mu_f} \tag{1}$$

Where, $l_{bf}, d, A_{f,bar}, f_{fu}$ is the development length, diameter, area, ultimate strength stress of FRP bar respectively.μ_f is the average bond stress in the interface between FRP bar and concrete.

Bond strength and its factors The mechanics of bond stress transfer between FRP reinforcement and concrete has been investigated extensively. Bond stress is the shearing stress whose direction is parallel to the interface plane of FRP bars and concrete. The bond of an embedded bar, regardless of material, resists pull-out via three main mechanisms. The first is chemical adhesion between the two materials at their interface. The second is the friction bond which is due to coarseness in the surface of the bar. The third mechanism contributing towards the bond is mechanical bearing, such as that generated from the lugs on reinforcing bars upon the surrounding concrete [4]. Based on the studies on concrete reinforced with FRP bars, the factors that influence the bond strength can be divided to several classes below:

The strength of concrete 130 pull-out specimens were tested by Zenon et al[5]. In this experiment, different strength of concrete was adopted, and the results presented that concrete strength influenced the failure mode of concrete specimen reinforced with FRP bars. When the strength is higher than 30MPa, the interface of bond failure occurs on the surface of FRP bars, and the bond strength of FRP bars is independent on the strength of concrete. When the strength is around 15MPa, the bond failure mode changes, and that is to say, concrete strength influences directly the bond performance of FRP bars. Pull-out test of normal-strength concrete and high-strength concrete was performed by Gao et al[6], and the results show that the conclusion that bond strength of concrete reinforced with FRP bars is linear to the square root of compressive strength of concrete is hard to determine. The new ACI 440.1R-06 guidelines [7] use a different approach that relies on the equilibrium equation of anchored bars and an empirically derived expression for average bond stress normalized with respect to the square root of the compressive strength of the concrete.

Embedded length of FRP bars Pull-out tests were performed by Zenon et al. [5], and the results presented that if the diameter remain constant, the larger the embedded length of the FRP bars in the specimens are, the less uniform the distribution of bond stress, and the ratio of the average bond stress to the actual maximum bond stress when the specimen fails, that is to say, the bond strength of the specimens increases with the increase of embedded length. Therefore, the embedded length of FRP bars has great influence on bond strength of concrete with FRP bars. The new ACI 440.1R-06 guidelines [7] recommends embedded length of 5db to study the average bond strength of FRP bars and design the development length of FRP bars.

Diameter of FRP bars The studies on bond performance of FRP bars in concrete present that when the embedded length of FRP bars remain constant, the bond strength decreases with the increase of the diameter of FRP bars. During the pull-out test, the peak bond stress moves gradually from the loaded end towards the unloaded end of the bar, while the bond stress value at the loaded end decreases considerably, having a nonlinear distribution of stresses along the bar. Tighiouart et al. [8] held the view that larger bar diameters develop bigger gaps between the concrete and FRP bars, and these gaps could induce the decrease of bond strength of FRP bars in the concrete. Tastani

[9] did an experiment of 30 directly pull-out test, and the variables include surface treatments, diameter and relative bond area of FRP bars, and induced the modified equation of bond-slip model based on the test results.

Types and surface treatments of FRP bars Javier [10] investigated the bond behaviors of GFRP bars of four types which have different surface treatments. The study presented that formula recommended by ACI 440 seems to be very conservative. Furthermore, the bond strength increase with the increase of the transverse constraint, and in the same condition of constraint, the bond strength of normal steel bar and concrete is a little larger than that of FRP bars and concrete. B. Benmokrane et al. [11] did experiments on the mechanical properties and bond strength of carbon fiber fiber reinforced polymer on the mechanical properties and bond strength of new generation of carbon fiber reinforced polymer (CFRP) reinforcing bars used as nonprestressed reinforcement for concrete structures. Two types of CFRP reinforcing bars, namely, 9-mm-diameter CFRP ribbed bars and 9.5-mm-diameter CFRP sand-coated bars, were investigated. Both types of the CFRP bars exhibited almost the same bond strength to concrete similar to steel bars. The minimum bond development length for the two types of CFRP bars seemed to be equal to about 20db for the sand-coated bars and 30db for the ribbed bars.

Analytical modeling of bond behavior

When concrete structures with FRP bars are analyzed numerically, the bond-slip relation should be considered. However, a general bond-slip law has not been proposed up to now because of the many factors that exert an influence, including the different behaviors and mechanisms involved in the different types of rebar. Currently, several bond-slip models including BPE model, modified BPE model [12], Malvar [13] model and CMR [12] model and continuous curve mathematical model have been proposed and modified BPE model has been applied to the analysis of concrete structure reinforced with FRP bars. The double branch model, proposed in Cosenza et al. [13] as a modification of the BPE model [12], consists of an ascending and a softening branch for the pre- and post-peak bond behavior, respectively. These two branches are given by the following equations:

$$\frac{\tau}{\tau_{\max}} = \left(\frac{s}{s_1}\right)^{\alpha} \tag{2}$$

$$\frac{\tau}{\tau_{\max}} = 1 - \frac{p \cdot (s - s_1)}{s_1} \tag{3}$$

Where α is a curve fitting parameter that must be no larger than 1 to be physically meaningful, s_1 is the slip at peak bond stress, and p is a parameter based on curve-fitting of experiment data.

Shear resistance of RC beams with FRP bars

As FRP bars are linearly elastic material and the transverse serviceability and elastic modulus are lower, the shear strength of FRP-reinforced concrete beams is different from that of steel bar RC beams. M. Guadagnini et al [14] investigated the shear behavior of 6 beams with FRP bars. The results of this study showed that the approaches of current proposal by the ACI and the Institution of Structural Engineers of U.K underestimate the contribution of the concrete and the shear reinforcement to the total shear capacity of FRP RC beams. El-Sayed et al [15] compared five methods, including ACI 440.1R-06, CSA-S806-02, ISIS-M03-07, the British Institution of

Structural Engineers guidelines and mendation of the Japan Society of Civil Engineers. A modified compression field theory approach was compared with the experiment database obtained from the literature. Islam [16] investigated the shear strength contribution of carbon fiber reinforced polymer (CFRP) bars attached with concrete beams using a near surface mounted (NSM) technique. Four concrete beam were cast with regular steel reinforcement in flexure. The performance of the NSM technique was found to be very effective with no occurrence of delamination, debonding or fracture of FRP. A new formula to calculate the nominal shear strength provided by NSM CFRP bars has also been proposed by Islam as follows equation.

$$V_n = V_c + V_s + V_f \tag{4}$$

Where Vn stands for shear capacity of RC beam, *Vc* stands for the nominal shear strength provided by concrete, and *Vs* and V_f stand for the nominal shear strength provided by steel and FRP bars, respectively.

Flexural behavior of RC beams with FRP bars

*Nonprestressed concrete structur*e Alsayed et al. [17] investigated flexural behaviors of FRP reinforcement RC beams and normal RC beams and compared the results of both. The test results show that the structural behaviors of FRP reinforced concrete are similar to normal RC in many aspects. However, with the low elastic modulus of FRP, the deflection of FRP reinforcement RC beam increases immediately after the beam starts to crack. To the concrete beams with the same size and ultimate flexural serviceability, the deflection of FRP bars RC beams is 2-4 times as the steel RC beams. Currently there are two calculating models to calculate the deflection of FRP RC structure. The first model is to utilize the effective moment of inertia. Different methods used to calculate the effective moment of inertia were presented by Issa [18]. The general idea is to combine the uncracked moment of inertia and cracked moment of inertia and calculate the deflection of the bended structure through elastic analysis. The second model is to consider the interaction between FRP bars and concrete.

Prestressed concrete(PC) structure Due to the low elastic modulus of FRP bars, the deflection and crack width of FRP RC beams are too large for nonprestressed concrete structure, and the high strength of FRP could not be fully utilized. One effective way to solve this problem is to use FRP bars as prestressed bars. The flexural behavior is the basic character of prestressed concrete structure reinforced with FRP bars, and a lot of studies have been investigated by many researchers. Based on the position of FRP bars in concrete beams, the PC beams can be classified into three types, which include internal bonding, internal unbonded, external PC structure. To internal bonding FRP bars PC beams, the prestress is mainly provided by the bond between FRP bars and concrete. The flexural strength can be calculated. Since 1992, Luc R et al. [19] started to study the feasibility to use GFRP bars in PC structure, and three 2-meter long GFRP bar PC beams and one 20-meter PC beam were tested. The results demonstrated that the load-deflection relationship of FRP bars PC beams is linear before the crack and doublely linear after the crack, as the stiffness of the beams decrease. To unbonded PC beams, the prestress is mainly provided by the anchorage at the ends of FRP bars. As the FRP bars can move relatively against concrete beams, the relative deflection of FRP PC beams is larger and the serviceability is lower. Xue [20] and Zhang [21] did researches on internal unbonded PC beams reinforced with FRP bars, and the results demonstrated that the effective prestress and crack width can be calculated by current design code. Compared to internal unbonded FRP bars PC beams, external PC beams can produce quadratic effect as the effective eccentricity decreases with the change of the deflection after the beams are bent. Robert [22] did experiments on strengthening behavior and the results pointed out that the strengthed beams got great improvement on crack moment, deflection and ultimate serviceability.

Ductility

Due to the linear elastic brittle behavior of FRP bars, the flexural behavior of FRP-reinforced concrete beam exhibits no ductility. In order to improve the ductility of such composite systems, it is proposed to add a certain amount of steel rebars in FRPRC systems such that the brittleness of FRP rebars can be compensated by the ductile nature of the additional steel reinforcement. Lau [23] did experiments on 12 specimens consisting of plain concrete beams, steel-reinforced concrete (SRC) beams, pure FRPRC beams and hybrid FRPRC beams, and the test results showed the hybrid FRPRC beams behave in a more ductile manner when compared with the pure FRPRC beams. Also, it is pointed out that a higher degree of over-reinforcement in the beam specimen resulted in a more ductile FRPRC beams; that is to say, over-reinforcement is a preferred approach in the design of FRPRC members. Xu et al. [24] did research on bending resistance of reinforced concrete beam strengthened with near-surface mounted FRP bars. The test results presented that the bearing capacity of structure reinforced with near-surface mounted FRP depend on the adhesive property between concrete and phenol-formaldehyde resin, and edge distance and separation distance influence the mode of failure and bearing capacity. In addition, the bearing capacity increases with the increase of the anchorage length.

Summary

With 20 years' studies on the mechanical behaviors of FRP bars RC structure, great progress has been made, and lots of design codes have been published worldwide. However, there are still a lot of problems to be solved, especially the over-large deflection. Hybrid FRP bars are fabricated and might be an effective method. In the same time, the bond behaviors of FRP bars and concrete still need to be investigated as it affects the failure modes, serviceability, crack width and deflection of FRP bars RC beams, and it is the main factor in the structure analysis and design. A general bond-slip law has not been proposed up to now. Therefore, studies are still needed to be investigated on the FRP bars RC structures, especially bond behaviors.

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