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Design approach for flexural capacity of concrete T-beams with bonded prestressed and nonprestressed FRP reinforcements

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ABSTRACT

Concrete beams with prestressed and nonprestressed fiber-reinforced polymer (FRP) reinforcements are commonly employed in field applications. However, available flexural strength design approaches mainly focus on rectangular concrete beams exclusively prestressed with FRP tendons. This paper, therefore, presents a simplified yet rational design approach for flexural capacity of concrete T-beams with bonded prestressed and nonprestressed FRP reinforcements. Firstly, a new transition region between tension- and compression- controlled sections was proposed in terms of ratio of provided-to-balanced reinforcement ($\rho_{e,b} < \rho_e \leq 1.5\rho_{e,b}$) based on a statistical analysis of an experimental database of 83 beams. Afterwards, numerical sectional analysis procedure of tension-controlled sections was developed by using an accurate stress block to approximate the nonlinear compressive stress distribution in concrete. Based on a detailed parametric study of over 160,000 sections, simplifed design equations for flexural capacity of tension-controlled section is derived from multiple regression analyses. Then, design equations were presented for flexural capacity of compression-controlled sections. Finally, the performance of the proposed approach was evaluated by comparing their predictions with experimental results of the 83 beams.

1. Introduction

The deterioration in concrete structures due to corrosion of steel strands and bars is one of the major challenges facing the construction industry. When exposed to deicing salts and marine environments, concrete structures are susceptible to corrosion. A promising solution to eliminate the corrosion-related problems associated with conventional prestressed and reinforced concrete structures is the application of fiber reinforced polymer (FRP) reinforcements [1,2]. FRP reinforcements exhibit several properties that include high resistance to corrosion, high strength-weight ratio, outstanding fatigue resistance, lower elastic modulus compared to steel, and a linear stress-strain relationship. Among FRPs, aramid FRP (AFRP) and carbon FRP (CFRP) are suited for prestressing tendons because of their higher strength and lower sensitivity to creep rupture. Glass FRP (GFRP) and Blast FRP (BFRP) are more widely used as nonprestressed bars because of their lower cost.

Although the use of FRP as structural reinforcement shows great promise in terms of durability, issues of its low elastic modulus and linear elastic to failure without yielding must be addressed in a practical manner [3,4]. In practice, the concrete beams exclusively prestressed with FRP tendons are rarely employed because of their lack of ductility and control of crack distribution. Combining prestressed and nonprestressed FRP reinforcement has been proven an efficient way to improve cracking behavior and minimize deflections at service loads while providing additional deformability [4,5]. To date, remarkable progresses have been made in field applications of prestressed concrete bridges with FRP reinforcements in North America, Europe, Japan and China [6–8].

Nowadays, considerable experimental studies have been devoted to investigate flexural response of concrete beams with bonded prestressed and nonprestressed FRP reinforcements [9–14]. Three flexural failure modes, including rupture of prestressed FRP, rupture of nonprestressed FRP, and concrete crushing, were observed in these experiments. Generally, the first two modes are regarded as tension failure, and the last is regarded as compression failure. Although compression failure is the preferred failure mechanism since it is more progressive and less catastrophic, in practice, where the beam and the topping slab work together in a composite action, tension failure is a common practice [15,16].

Theoretically, the flexural failure mode can be determined by comparing the reinforcement ratio with the balanced reinforcement ratio. However, available studies have shown that the actual flexural failure mode may not coincide with the predicted one [17]. That is, there is a transition region where concrete crushing and FRP rupture

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are possible. For concrete members with steel reinforcements, the definition of the transition region between tension- and compression-controlled section was proposed to achieve sufficient ductility and give adequate warning prior to failure. For concrete members with FRP reinforcement, however, a brittle flexural failure is unavoidable and this may lead to a change in the definition of the transition region. Currently, ACI 440.4R-04 [18], in accordance with ACI 318-14 [19], defines the FRP-PC sections in transition region as those that have net tensile strain in the extreme tension reinforcement at nominal strength greater than 0.002 and less than 0.005. It should be mentioned that the strain limits were originally proposed for flexural concrete members with conventional Grade 60 ($f_y = 414\,\text{MPa}$) steel bars or Grade 270 ($f_{py} = 1860\,\text{MPa}$) steel strands [20]. Considering that high-strength steel bars or strands that have different stress-strain relationships, the strain limits defining the transition region should be modified [21–24]. Since FRP is linear elastic to failure, the traditional strain limits developed for conventional steel-PC members may not be necessarily applicable to FRP-PC members.

So far, valuable design approaches have been developed for flexural capacity of PC members with boned FRP reinforcements [18,25–27]. Previous approaches mainly focused on concrete beams exclusively prestressed with FRP tendons [18,25,26]. However, very limited research was carried out to predict the flexural capacity of concrete beam with a combination of prestressed and nonprestressed FRP reinforcements, especially for the beam with T-section. Grace et al. [27] presented a design approach for concrete beams with prestressed and nonprestressed CFRP. However, the failure due to nonprestressed CFRP rupture, which was observed by Yonekura et al. [10], was not discussed in their approach. Moreover, it is important to recognize that the state of the under-reinforced section at ultimate in an FRP-PC beam is not analogous to that of a steel-PC beam. In a steel-PC beam, the failure of under-reinforced section is yielding of the tension steel, followed by eventual crushing of the concrete. This means that the concrete in compression experiences stress redistribution after the steel yields. In this case, Whitney's rectangular stress block can be used to determine the flexural capacity. In the case of an FRP-PC beam, however, the failure of the under-reinforced section is rupture of FRP. This means that there is no redistribution of stresses in the section and a catastrophic collapse will occur when the FRP fails. Consequently, an iterative procedure is required to determine the concrete stress distribution in compression. This iterative procedure is overly complex for normal calculations in design offices [28]. To avoid this iteration, ACI 440.4R-04 [18] and Grace et al. [27] approximated the concrete compressive stress distribution by using Whitney's rectangular stress block. This simplification, however, overestimates the compressive stress of concrete and consequently the lever arm, which may result in a nonconservative design.

From the above discussions, it can be concluded that there is very limited research on flexural strength design approaches of concrete beams with prestressed and nonprestressed FRP reinforcements, especially for the beams with T-sections. Besides, the brittle behavior of FRP may lead to a change in definition of the transition region, which hasn't been investigated. Moreover, an iterative procedure is required when FRP rupture governs the design. In this paper, a simplified yet rational flexural strength design approach is developed for concrete T-beams with bonded prestressed and nonprestressed FRP reinforcements. Firstly, sectional analyses under balanced failure are firstly carried out to distinguish possible flexural failure modes. Based on a statistical analysis of an experimental database of 83 beams, a new transition region is proposed. Then, rigorous sectional analyses and multiple linear regression analyses are carried out to obtain simplified design equations for predicting the flexural capacity of under-reinforced sections. Subsequently, design equations are presented to predict the flexural capacity of over-reinforced sections. Finally, the accuracy of the proposed approach is verified by experimental results of the 83 beams. It should be mentioned that the proposed design approach has been incorporated in Shanghai's Construction Standard "Design and Construction of Concrete Structures with FRP Reinforcements".

2. Distinction of flexural failure modes

2.1. Basic assumptions

Referring to ACI 440.1R-15 [29] and ACI 440.4R-04 [18], the following assumptions are made in predicting ultimate flexural strength behaviors of concrete beams with bonded prestressed and nonprestressed FRP reinforcements:

1. There is a perfect bond between the FRP reinforcement and the concrete;
2. A plane-cross section remains plane after bending deformation;
3. The maximum usable compressive strain in the concrete, ε_{cu}, is assumed to be 0.003;
4. The stress-strain curve of FRP reinforcement is idealized as linear elastic to failure;
5. The stresses in the concrete can be computed from the strains by using stress-strain curves for concrete;
6. The tensile strength of concrete is ignored; and
7. The compression contribution of the FRP reinforcements is neglected.

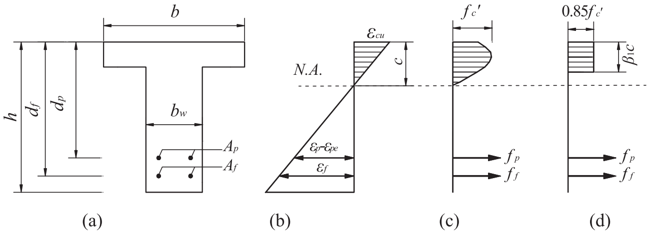
2.2. Balanced failure mode

Theoretically, the distinction among different flexural failure modes of a concrete beam can be achieved through the predicted balanced failure. Based on sectional analyses, two balanced failure conditions and three flexural failure modes are identified for concrete beams with prestressed and nonprestressed FRP reinforcements. The three failure modes include rupture of prestressed FRP (Mode I), rupture of nonprestressed FRP (Mode II) and concrete crushing (Mode III), which coincides with the observations in available experiments [10–14]. The sectional analyses indicate that the flexural failure modes depend on the arrangement of the flexural reinforcements. If the parameter χ defined by Eq. (1) is not less than 1.0, the beam will fail due to prestressed FRP rupture (Mode I) or concrete crushing (Mode III). Otherwise, the failure mode will be governed by nonprestressed FRP rupture (Mode II) or concrete crushing (Mode III).

$$\chi = \frac{(\varepsilon_{fu} + \varepsilon_{cu})}{(\varepsilon_{pu} - \varepsilon_{pe} + \varepsilon_{cu})}\frac{d_p}{d_f} \tag{1}$$

where ε_{pe} and ε_{pu} are the effective prestressing strain and ultimate tensile strain in prestressed FRP, respectively, ε_{fu} is the ultimate tensile strain in nonprestressed FRP, and d_p and d_f are the distance from extreme concrete compression fiber to centroid of prestressed and nonprestressed FRP, respectively.

Fig. 1(b) and (c) show the strain and stress distributions across the depth of a section of concrete beam, respectively. The balanced failure condition between Mode I and Mode III is obtained when the strains in the concrete and prestressed FRP simultaneously reach their maximum values. However, the stresses in nonprestressed FRP at failure, f_f,



(a) (b) (c) (d)

Fig. 1. Strain and stress conditions for $\varepsilon_{cf} = \varepsilon_{cu}$: (a) cross section (b) strain (c) stress (d) stress (equivalent).