Composite Structures 92 (2010) 612–622

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Flexural response predictions of reinforced concrete beams strengthened with prestressed CFRP plates

Weichen Xue *, Yuan Tan, Lei Zeng

Department of Building Engineering, Tongji University, Shanghai 200092, PR China

ARTICLE INFO

Article history:
Available online 20 September 2009

Keywords:
Prestressed CFRP plate
Flexural strengthening
RC beam
Theoretical formula

ABSTRACT

Existing experimental studies showed that the reinforced concrete (RC) beams strengthened with prestressed carbon fiber-reinforced polymer (CFRP) plates had three possible flexural failure modes (including the compression failure, tension failure and debonding failure) according to the CFRP reinforcement ratio. Theoretical formulas based on the compatibility of strains and equilibrium of forces were presented to predict the nominal flexural strength of strengthened beams under the three failure modes, respectively, and a limitation on the tensile strain level developed in the prestressed CFRP plate was proposed as the debonding failure occurred. In addition, the calculation methods for cracking moment, crack width and deflection of strengthened beams were provided with taking into account the contribution of prestressed CFRP plates. Experimental studies on five RC beams strengthened with prestressed CFRP plates and a nonlinear finite element parametric analysis were carried out to verify the proposed theoretical formulas. The available test results conducted by other researchers were also compared with the predicted values.

1. Introduction

The application of bonded fiber-reinforced polymer (FRP) laminates to the exposed faces of concrete members provides an efficient, light-weight, non-corrosive alternative to the other rehabilitative methods [1]. Common FRP laminate forms suitable for the strengthening of structural members are sheets and plates. FRP sheets with small nominal thickness could be employed to strengthen the members with irregular surfaces, like seismic strengthening of concrete columns. However, multiple plies of FRP sheets are usually needed to meet the requirements of flexural strengthening of the concrete beams or slabs, which should correspondingly consume extensive labors, and a reduction factor would be introduced for evaluating the effective thickness of multiple FRP plies. Compared with the FRP sheets, FRP plates with relatively large cross-sectional areas could achieve the more effective strengthening effects. And the FRP plate has some stiffness itself which is convenient to the construction in field applications [2].

It was found that premature debonding of FRP laminate was the most popular brittle failure mode observed in flexure tests of strengthened beams, and the tensile stresses in FRP laminates were only 10–20% of their ultimate tensile strength as the beams failed [3]. So the FRP laminates usually could not be utilized efficiently in non-prestressed strengthening applications. In the 1990s, some researchers claimed that prestressing the CFRP laminates prior to bonding could be an innovative way to use a higher percentage of the material's tensile strength [4–6]. Several prestressing/anchor systems were developed [5–9], and a series of experimental studies on RC beams strengthened with prestressed CFRP sheets or glass fiber-reinforced polymer (GFRP) plates were conducted during the past two decades [4,5,7,10–14]. While studies on RC beams strengthened with prestressed CFRP plates are relatively limited. Garden and Hollaway's research work found that the possible failure modes of RC beams strengthened with prestressed CFRP plates included the compression failure, tension failure, debonding failure and concrete shear failure [15]. And the prestressing technique could efficiently utilize the high strength of CFRP plates by delaying or avoiding the premature debonding, but bring a reduction in ductility simultaneously. Quantrill and Hollaway conducted tests on four RC beams strengthened with CFRP plates that were prestressed to the levels between 17.5% and 41.7% of their tensile strength, which indicated that the technique of prestressing the CFRP plates prior to bonding provided a more efficient solution to improve the serviceability and increase the flexural capacity of strengthened beams [6].

Theoretical studies on flexural strengthening of RC beams with prestressed FRP laminates have been carried out by some researchers since the early 1990s. Triantafillou et al. addressed that the proper design of a singly reinforced section of strengthened beam would require that steel reinforcements yield precede concrete crushing, while the prestressed CFRP sheets do not rupture or

* Corresponding author. Tel.: +86 21 65980418; fax: +86 21 65986345.
E-mail addresses: xuewc@tongji.edu.cn (W. Xue), yuantan_tj@163.com (Y. Tan).

0263-8223/$ - see front matter © 2009 Elsevier Ltd. All rights reserved.
doi:10.1016/j.compstruct.2009.09.036

debond from concrete at ultimate [4]. Under the mentioned precondition, the calculation formulas for nominal flexural strength of FRP prestressed section was provided. Wang and Zhou also discussed the calculation method for nominal flexural strength of singly reinforced concrete beams strengthened with prestressed FRP laminates based on the traditional flexural theory, but the influence of FRP debonding was not taken into account in their analytical work [16]. Yu et al. developed an innovative mechanical device for prestressing CFRP sheets and studied the strain distributions in sections of strengthened beams at the prestressing transfer process, decompression and ultimate stage, respectively. It should be noted that the iterative method was applied in the calculation of nominal flexural strength under the FRP rupture failure [13]. Although a comprehensive set of recommendations or guidelines for concrete structures externally bonded with FRP laminates have been developed by several organizations, including ACI, CSA, *fib*, ISIS, JSCE, CECS, etc. [17–21], no specific regulations for flexural strengthening with prestressed FRP laminates are involved in the current codes.

In summary, calculation method for the nominal flexural strength of strengthened beams prestressed with FRP laminates under debonding failure was not proposed in the existing analytical studies. In addition, studies on the calculation of cracking moment, crack width and deflection of strengthened beams have not been reported by researchers. This paper presents the investigations for predicting the nominal flexural strength, cracking moment, crack width and deflection of RC beams with prestressed CFRP plates. An experimental program and a finite element (FE) parametric analysis are conducted to verify the theoretical formulas.

2. Calculation of nominal flexural strength

2.1. Basic assumptions

The following assumptions are made in calculating the nominal flexural strength of RC beams strengthened with prestressed CFRP plates:

- The strains in the reinforcement and concrete are directly proportional to the distance from the neutral axis, that is, a plane section before loading remains plane after loading.
- Compressive stresses in concrete, f_c, are given by [22]

$$f_c = \begin{cases} f'_c\left[\frac{2\varepsilon_c}{\varepsilon_0} - \left(\frac{\varepsilon_c}{\varepsilon_0}\right)^2\right] & \text{if } 0 \leqslant \varepsilon_c \leqslant \varepsilon_0 \\ f'_c\left[1 - \frac{0.15}{0.004-\varepsilon_0}(\varepsilon_c - \varepsilon_0)\right] & \text{if } \varepsilon_0 < \varepsilon_c \leqslant 0.003 \end{cases} \tag{1}$$

where f'_c is the cylinder compressive strength of concrete; ε_c the compressive concrete strain and ε_0 the compressive strain in concrete at the peak stress. As the ultimate compressive strain in concrete reaches 0.003, concrete stress of 0.85 f'_c shall be assumed uniformly distributed over an equivalent compression zone bounded by edges of the cross section and a straight line located parallel to the neutral axis at a distance $a = \beta_1 c$ from the fiber of maximum compressive strain, where c is the actual depth of the compression zone, and the parameter β_1 can be determined according to ACI 318-08 [23].

- Reinforcing steel is assumed to behave elastic-perfectly plastic response, and the FRP plate has a linear elastic stress–strain relationship up to failure.
- The shear deformation within the adhesive layer is neglected since the adhesive layer is very thin with slight variations in its thickness.
- The tensile strength of concrete is ignored.

2.2. Observed failure modes

Several flexural failure modes controlling the ultimate strength in RC beams strengthened with prestressed CFRP plates have been reported in the literatures by researchers [6,15]. It was observed that the possible flexural failure modes of strengthened beams included the compression failure (i.e. crushing of concrete in compression prior to the rupture or debonding of CFRP plate), tension failure (i.e. rupture of CFRP plate prior to the crushing of concrete in compression) and debonding failure (i.e. force in the prestressed CFRP plate could not be sustained by the concrete substrate, which results in the CFRP plate debonding prior to the concrete crushing).

2.3. Tensile strain limitation for prestressed CFRP plate under debonding failure

For strengthened beams prestressed with CFRP plates, the debonding failure was mainly caused by the difference of strain increase between the bonded concrete surface and CFRP plates. Similar to the tensile strains developed in the steel tendons at ultimate for a prestressed concrete beam, the total strain capacity of the prestressed CFRP plates for strengthened beams under debonding failure can be expressed as:

$$\varepsilon_{pf} = \varepsilon_{pe} + \varepsilon_d + \Delta\varepsilon_{pf} \tag{2}$$

where ε_{pe} is the effective strain in the CFRP plate after all losses; ε_d the additional strain in the prestressed CFRP plate that causes the extreme precompressed fiber to reach zero strain, which refers to the state of decompression and $\Delta\varepsilon_{pf}$ the ultimate strain increase beyond ($\varepsilon_{pe} + \varepsilon_d$) under debonding failure.

It is known that after the decompression state, a prestressed concrete beam could be treaded as the corresponding nonprestressed beam in the analytical work [24]. Thus, the ultimate strain increase in the prestressed CFRP plate after decompression was comparable to the tensile strain limitation for the nonprestressed CFRP plate. Herein, a tensile strain limitation $[\varepsilon_{pfu}]$ could be proposed for predicting the maximum tensile strain level in the prestressed CFRP plate under the debonding failure or tension failure.

$$[\varepsilon_{pfu}] = \begin{cases} \varepsilon_{pe} + \varepsilon_d + \kappa_m\varepsilon_{pfu} & \text{if } \varepsilon_{pe} + \varepsilon_d + \kappa_m\varepsilon_{pfu} < \varepsilon_{pfu} \\ & \quad \text{(debonding failure)} \\ \varepsilon_{pfu} & \text{if } \varepsilon_{pe} + \varepsilon_d + \kappa_m\varepsilon_{pfu} \geqslant \varepsilon_{pfu} \\ & \quad \text{(tension failure)} \end{cases} \tag{3}$$

In Eq. (3), the item of $\kappa_m\varepsilon_{pfu}$ represents the strain increase limitation for the prestressed CFRP plate, which can be determined by Eq. (4) proposed for preventing the debonding failure of nonprestressed CFRP plate in ACI 440.2R-02 [17].

$$\kappa_m\varepsilon_{pfu} = \begin{cases} \frac{1}{60}\left(1 - \frac{nE_f t_f}{360{,}000}\right) \leqslant 0.90\varepsilon_{pfu} & \text{for } nE_f t_f \leqslant 180{,}000 \\ \frac{1}{60}\left(\frac{90{,}000}{nE_f t_f}\right) \leqslant 0.90\varepsilon_{pfu} & \text{for } nE_f t_f > 180{,}000 \end{cases} \tag{4}$$

where ε_{pfu} is the nominal ultimate tensile strain of the prestressed CFRP plate; κ_m the reduction factor; n the number of plies of CFRP plate at the location along the length of the member where the moment strength is being computed; E_f the tensile modulus of elasticity of CFRP plate (MPa) and t_f the thickness of CFRP plate (mm).

In addition, seen from Eq. (3), the tensile strain limitation $[\varepsilon_{pfu}]$ is related the jacking stress applied to the CFRP plate. FRP materials subjected to a constant load over time can suddenly fail after a time period referred to as the endurance time. This type of failure is known as creep-rupture. To avoid the creep-rupture of the FRP reinforcement under sustained loads, the stress level limit for nonprestressed CFRP reinforcement was proposed as 0.55 times of its