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Long-term behavior of wide shallow RC beams strengthened with externally bonded CFRP plates

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HIGHLIGHTS

- The addition of CFRP plates has no significant effect in reducing the long term deflections.
- Increasing the sustained load level increased immediate and long term deflections of the beams.
- Effective modulus analysis was found to reasonably predict the long term deflection of the beams.
- The Gergely and Lutz equation can be used with the EMM to predict the long term crack width of the beams.

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ABSTRACT

The use of fiber reinforced polymer (FRP) for flexural strengthening by adhesively bonding to the tension soffit of reinforced concrete (RC) beams has become a popular retrofit technique. Extensive research work is available in the literature on the short term behavior of RC beams strengthened with externally bonded FRP reinforcement. On the other hand, the long term behavior of FRP-strengthened beams has not yet been fully explored. This paper investigates the long term deflection and cracking characteristics of wide shallow RC beams strengthened with carbon FRP (CFRP) plates. Five full scale wide shallow beams were constructed: two beams were tested under static loading and three beams were tested under sustained load for a period of 600 days. Three of the beams were strengthened with CFRP plates bonded to the soffit of the beams and two beams were unstrengthened serving as control. The long term beam deflection was compared with the predictions of the effective modulus approach considering two different concrete creep models. Beams strengthened with CFRP plates showed significant improvement in the short term deflection and crack width compared to the unstrengthened beam. The strengthened beams, however, did not show that much improvement in the long term behavior. The effective modulus approach was found to reasonably predict the additional long term deflection of the beams depending on the incorporated concrete creep model. Further, an analytical procedure for predicting the long term crack width of the beams was presented.

1. Introduction

Fiber reinforced polymer (FRP) composites have been increasingly used to strengthen existing concrete structures. This is attributed to the superior properties of such materials. FRPs have high strength and stiffness to weight ratio relative to conventional construction materials such as steel and concrete. In addition, FRPs are noncorrosive materials resulting in more durable strengthening system for structural members subjected to severe environmental exposure. Externally bonded FRP, in which an FRP strip is bonded to the tension face of the flexural member using a structural adhesive, is the most popular FRP strengthening system. Extensive research has been directed to investigating the short term flexural behavior of FRP-strengthened reinforced concrete (RC) beams [1–7]. On the other hand, limited research work has been conducted on the long term performance of FRP-strengthened RC beams. More knowledge and data on the long term behav-

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ior of such beams under sustained loading is essential for the full acceptance of FRP in the strengthening and retrofit applications.

Among the few studies on the long term performance of FRP-strengthened beams, Plevris and Triantafillou [8] developed an analytical model for predicting the stresses and strains of the cross-sections of the beams as a function of time. In addition, the model was used to predict the long term deflection of the beams strengthened with FRP laminates. The model was verified against the test results of three beams tested by the investigators. Two of those beams were strengthened with CFRP laminates of different thickness, and the third was unstrengthened and used as a control specimen. The test results indicated that increasing the CFRP area fraction decreased both the immediate and the creep deflections.

The long term deflection characteristics of glass FRP (GFRP)-bonded beams under sustained loading have been investigated by Tan and Saha [9]. Nine RC beams, six of which were externally bonded with GFRP composites laminates, were subjected to sustained loads for 2 years. The test results indicated that the long term deflections of the beams were reduced by 23% and 33% with a GFRP ratio of 0.64% and 1.92%, respectively. This contribution of the GFRP composite laminates in deflection control was found, however, not to the same extent as the contribution in providing flexural strength. This finding was also confirmed by the results obtained by Kim et al. [10] and Al Chami et al. [11] from testing RC beams under sustained loading and strengthened with either CFRP or GFRP laminates. In addition and due to the relatively low modulus of elasticity of GFRP reinforcement, higher long term deflections were observed by Kim et al. [10] for the beam with GFRP than that with CFRP. Reda Taha et al. [12] indicated that the creep in the epoxy layer joining the FRP to concrete should be included in the long term analysis for the sake of obtaining more accurate predictions.

The present investigation is a part of an extensive research program [13–15] undertaken at King Saud University to examine the behavior of full-scale wide shallow beams externally strengthened for flexure with adhesively bonded CFRP reinforcement. This study provides experimental data on the long term behavior of CFRP-strengthened wide shallow beams under sustaining load for a period of 600 days. The experimental long term deflection of the beams was analyzed using the effective modulus approach. Both ACI 209 [16] and CEB-FIP [17] concrete creep models were considered in this analysis. Further, an analytical procedure for predicting the evolution of long term crack width of the beams under sustained load was presented.

2. Experimental study

In this study, five full-scale shallow beams were tested. Two of the beams were tested under static loading whereas three beams were tested under sustaining load. Three beams among the five beams were strengthened with externally bonded CFRP plates and the remaining two beams were unstrengthened.

2.1. Material properties

The CFRP reinforcement used in this study was pultruded plates having a width of 120 mm and a thickness of 1.4 mm. The tensile strength and modulus of elasticity as provided by the manufacturer were 2800 MPa and 165 GPa, respectively. The adhesive used to bond the CFRP plates to the concrete beams was a thixotropic, structural two-component adhesive, based on a combination of epoxy resins and special fillers. The bond strength and elastic modulus of the adhesive as provided by the manufacturer were 4 MPa and 12.8 GPa, respectively.

Deformed steel bars were used in reinforcing the test beams: 16 mm diameter bars were used as main tensile reinforcement while 12 mm diameter bars were used as top reinforcement. The shear reinforcements were 4-legged stirrups of 8 mm diameter and 100 mm spacing. The actual tensile properties of the 16 and 12 mm diameter bars were determined using standard tensile tests performed on three samples of each bar size. The average yield strengths of the bars were 562 and 533 MPa, respectively. The corresponding moduli of elasticity were 205 and 207 GPa.

The beams were constructed using normal weight concrete provided by a local ready-mix supplier. Concrete cylinders 150 × 300 mm, from the same concrete batch used in fabricating the beams, were prepared during casting the beams and cured under the same conditions as the beams. The average compressive strength at the time when the beams were first loaded was 30 MPa based on cylinder tests.

2.2. Test specimens

A total of five full-scale reinforced concrete beams were constructed. The beams were divided into two groups. Group I included two beams which were tested under static flexural loading to determine the ultimate capacity of the beams. One of the beams was strengthened with CFRP plates and the other beam was unstrengthened. Group II comprised three beams that were tested under sustained loading for

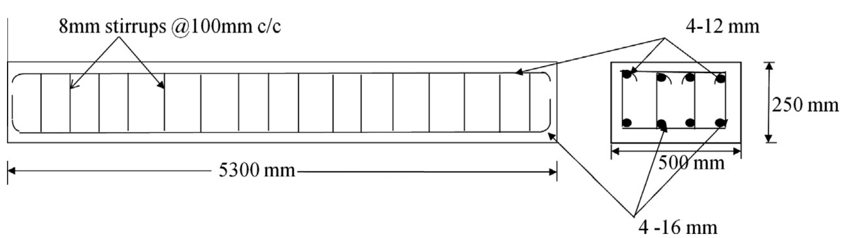

Fig. 1. Reinforcement details of the test beams.

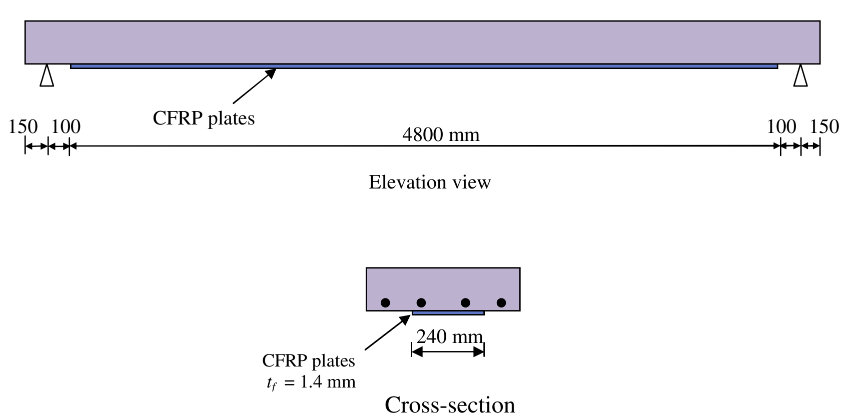

Fig. 2. Typical strengthening scheme.