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Experimental performance of RC beams strengthened with FRP materials under monotonic and fatigue loads

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HIGHLIGHTS

- Beams strengthened with (EBR) plates and near-surface mounted (NSM) bars have been tested under monotonic and fatigue load.
- The influence of the strengthening material's properties and prior cracking of the member are investigated.
- The relief of local stress in the member's reinforcing steel bars before they rupture together with the fatigue life of the reinforcing steel, after its initial fracturing, determined the efficiency of strengthening.

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ABSTRACT

Carbon fiber-reinforced polymers (CFRPs) are increasingly being used to repair and strengthen reinforced concrete (RC) structural members. CFRP strengthening may be applied by bonding polymeric plates to the exterior of the member's tension surface or by placing CFRP bars inside the concrete member cover to provide near-surface mounted reinforcement. It is not clear which of these approaches is most effective at resisting fatigue loads. To compare their efficacy, four-point bending tests with reinforced concrete beams were conducted under monotonic and fatigue loading using both strengthened and unstrengthened RC beams. The influence of the strengthening material's properties and prior cracking of the member are investigated and discussed by analyzing failure mechanisms, load-deflection curves, and strain measurements for steel bars and CFRP materials observed during loading experiments. The results obtained indicate that the efficiency of strengthening is primarily determined by the relief of local stress in the member's reinforcing steel bars before they rupture, and the fatigue life of the reinforcing steel after its initial fracturing.

1. Introduction

The use of carbon fiber reinforced polymer (CFRP) materials to strengthen reinforced concrete (RC) members in highway bridges is becoming increasingly common around the world because CFRP exhibits excellent corrosion resistance and tolerance of environmental agents while also offering a high stiffness to weight ratio together with easy transportation and handling, limited thermal expansion, and good fatigue performance. The most common techniques for strengthening concrete members in bridges involve the insertion of strengthening CFRP rods into grooves carved into the concrete of the soffit girder or the application of bonded sheets or plates to the member's soffit surface [5]. The former approach is referred to as near-surface mounted (NSM) reinforcement.

Several recent studies have investigated the effect of FRP plates on the fatigue strength of reinforced concrete beams [2,4,6,10,11,13,16,20,25] and some have examined the effect of strengthening with NSM bars [2,3,19,21,22,26,27]. In addition, the authors of this paper have presented an extensive investigation into the behavior of CFRP-strengthened RC beams in which the behavior of the strengthening material and the strengthened reinforced concrete members was examined under fatigue loading [14].

Despite these works, there have only been a few comparative studies examining beams strengthened with NSM bars and plates under fatigue loading. Aidoo et al. [2] studied the performance of full-scale interstate bridge girders strengthened with CFRP materials under fatigue loading. Three strengthening methods were investigated: the bonding of CFRP strips to the soffit surface, strengthening with NSM CFRP strips, and strengthening with hybrid strips using powder actuated fasteners. Under monotonic loads, all three methods increased the girders' load-carrying capacity. However, it was not clear whether plate or NSM strengthening

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offered the best performance under fatigue loading because a certain degree of relative slippage or debonding occurred with the CFRP strips.

A similar study was conducted by Quattlebaum et al. [21] using small-scale specimens strengthened with CFRP in three different ways. Their results contradicted the findings of Meier et al. [16] and suggested that CFRP strips were unable to bridge cracks resulting from failure of the primary reinforcing steel. Consequently, they found that NSM CFRP strips performed better than either CFRP strips or powder actuated fasteners.

Sena-Cruz et al. [23] conducted a similar comparison to those reported by Quattlebaum et al. [21] and Aidoo et al. [2], testing reinforced concrete beams strengthened in the same three ways under monotonic and fatigue loads. The greatest decrease in stiffness due to fatigue loading occurred in beams strengthened with NSM strips.

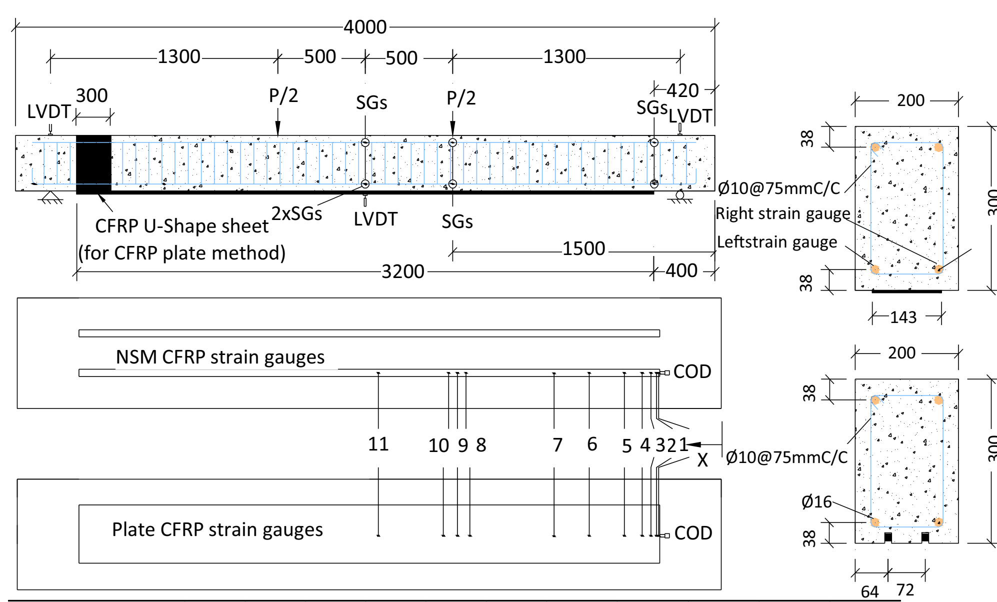
In keeping with earlier studies, it was not clear whether NSM bars or surface-mounted plates offered better overall strengthening performance, and many aspects of CFRP strengthening remain unclear. To shed further light on these issues, this manuscript describes a study on the response of the CFRP plate and NSM bar strengthening methods under monotonic and fatigue loading in reinforced concrete beams constructed with steel reinforcements having identical steel stress levels. The influence of the properties of the strengthening CFRP material is also investigated, along with that of pre-existing cracks in the beams. The results obtained provide new insights into the behavior of FRP-strengthened RC beams under fatigue loading conditions, and illustrate some important advantages and disadvantages of the plate and NSM bar approaches.

2. Specimen details

The beams used in this study were 4000 mm long with rectangular cross sections of 200 × 300 mm as shown in Fig. 1. The size of the beams were selected to complete the series of tests of the previous full-scale tests with the same size [7,18]. Their longitudinal steel reinforcements in tension and compression were two rods with nominal diameters of Ø16 mm. The shear reinforcement, which was designed to ensure flexural failure in the strengthened beams, consisted of Ø 10 mm stirrups at a spacing of 75 mm. Three beam types were tested – beams strengthened with NSM bars, beams strengthened with traditional laminate plate bonding, and beams without FRP strengthening. The plate- and NSM-bar strengthened beams were further subdivided into two classes depending on the Young's modulus of the CFRP used, which was either 150 GPa or 200 GPa. The length of the strengthening laminates and rods (3200 mm) was chosen to match the beams' critical anchorage length [24], which produced laminates and rods that ended between the supports and would therefore not be significantly affected by the bearings.

Plate strengthening was performed with two strips of 1.4 mm thick CFRP material, one with a width of 100 mm and another with a width of 43 mm. For beams strengthened with 200 GPa CFRP, the strengthening materials used were StoFRP Plate IM 100C and StoFRP Plate IM 60C, respectively. For beams strengthened with 150 GPa CFRP, the materials used were StoFRP Plate 100E and StoFRP Plate 50E, respectively. In both cases, the 43 mm wide strengthening strips were prepared by cutting narrow strips supplied by the CFRP manufacturer. The laminate strips were bonded to the surface of the beam soffit using StoPox SK41 epoxy after surface grinding to expose the gravel and primer application; the thickness of the adhesive epoxy layer after plate bonding was 2 mm. After the strengthening plates had been applied, two layers of CFRP sheeting were wrapped around one end of the plate-strengthened beam to form a 300 mm wide U-jacket (with the fiber direction being perpendicular to the longitudinal axis of the beam) in order to ensure that any debonding of the strengthening plates would occur at the other end of the beam's span. The jacket was formed using the wet lay-up technique and bonded to the beam using StoPox LH epoxy.

NSM strengthening for beams strengthened using 200 GPa CFRP was performed using two 10 × 10 mm quadratic rods (StoFRP BAR IM 10C), each having a modulus of elasticity of 200 GPa. The rods were fitted to the beam by cutting two parallel grooves along the beam's length using a concrete saw with two parallel saw blades. After chipping away the cut concrete, two grooves with widths of



FRP Gauge	1	2	3	4	5	6	7	8	9	10	11
Location, X(mm)	405	420	450	500	600	800	1000	1470	1500	1530	2000

Fig. 1. Beam setup (all dimensions in mm).