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Fatigue performance of prestressed concrete beams using BFRP bars

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HIGHLIGHTS

- Basalt bars were used in prestressing concrete beams subjected to fatigue loading.
- There was little effect of prestressing on fatigue strength for low fatigue lives.
- Enough prestress was retained to close cracks for fatigue lives above 100,000 cycles.
- Prestressed beams failed by bar rupture after concrete crushing in monotonic tests.

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ABSTRACT

Basalt fibers have recently been introduced as a promising addition to the existing fiber reinforced polymer (FRP) family. A limited amount of information is available on basalt FRP (BFRP) bars and their structural concrete applications. This paper presents the flexural behaviour of sixteen prestressed concrete beams using BFRP bars under monotonic and fatigue loading. The investigated parameters were the level of prestress of the bars (0%, 20% and 40% of their static tension capacity) and the fatigue load ranges. The experimental findings showed that beams with the bars prestressed to 40% of the bar strength had a higher fatigue strength than those prestressed to 0% and 20%. For 40% and 20% prestressed beams, there is no improvement in fatigue performance for load ranges above 20% and 13% of the ultimate capacity of the beams a level at which calculations showed that the remaining prestress did not close cracks at the minimum load in the fatigue load cycle. When compared on the basis of load range versus cycles to failure, the data for the three beam types fell onto a single curve at load levels where the remaining prestress after fatigue creep relaxation no longer closed the crack at the minimum load.

1. Introduction

Structural elements can fail under either static or fatigue loading. Since concrete structures such as marine structures, parking garages and bridges are subjected to fatigue loading during their lives, it is important to understand their creep and fatigue behaviour. In addition, the limit states (ultimate and serviceability) governed by fatigue behaviour must be taken into account by designers. The primary variable in causing fatigue failure of both steel and composites is the range of applied stress. When a concrete beam is prestressed, the range of stress in the reinforcement is small up to the load at which the concrete cracks. This is because the area of the uncracked concrete in the region of the reinforcement is much greater than that of the reinforcement, and most of the change in force required to balance an applied moment is supplied by a reduction in the compressive stress in the concrete. After cracking, however, the tensile forces required to balance additional moment are supplied by the reinforcement and the stress in the reinforcement increases rapidly and the beam stiffness is reduced.

Glass and carbon fibers have a good resistance to creep; on the other hand, polymeric resins are more susceptible to creep; as a result, fiber type, volume fraction and fiber orientation and temperatures which lead to a decrease in resin strength play an important role in the creep performance of FRP reinforcing rebar.

A study by Noël and Soudki [5] was conducted to investigate fatigue behaviour of GFRP, the results showed that GFRP bars embedded in concrete have shorter fatigue lives than similar bars tested in air by approximately a full order of magnitude.

Preliminary fatigue test results carried out by El Refai [3] showed that the fatigue limit of BFRP bars was about 4% of their ultimate capacity. However, the fatigue limit of GFRP bars was about 3% of their ultimate capacity. Furthermore, the results

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showed that BFRP has a low sensitivity to water moisture and is a durable material. Therefore, BFRP would be suitable for use as prestressing or non-prestressing.

Compared to steel, the BFRP materials possess a considerable higher strength-to-weight and modulus-to-weight ratios. These properties can be very useful and advantageous for different applications Chemical and mechanical properties of the BFRP material can serve both structural and functional issues pertinent to the particular structure [1]. Therefore, BFRP materials are good candidate for prestress and non-prestress applications. However, a lack of studies on basalt bar reinforced concrete beams in fatigue applications has limited the use of this type of bars in the construction industry. The aim of this study is to investigate the performance of prestressed concrete beams using BFRP bars under monotonic and fatigue loading. Different presetressing levels of bars and fatigue load ranges were investigated.

2. Experimental program

Sixteen concrete beams were reinforced with sand coated BFRP bars. The beams that were tested under monotonic and fatigue loading were divided into three groups. The first group had six non-prestressed beams. The second group had six beams that were prestressed to a bar stress of 40% (582 MPa, 71 kN) of the material's static tension capacity as listed in Table 1 and the third group had four beams that were prestressed to a bar stress of 20% (291 MPa, 35.5 kN) of the materials tension capacity. Two beams, one from the first group and the other one from the second group were monotonically loaded to failure under deflection control at a rate of 1 mm per minute and served as a control for all groups, because the expected ultimate load capacity for the third group under monotonic loading is the same as the other two groups. The expected mode of failure for both prestressed and non-prestressed beams was by the bar rupture.

2.1. Test specimens

Six beams were non-prestressed and ten beams were pretensioned (six prestressed to 40% and four to 20%). The beam dimensions were 2400 mm in length and 300 mm in height and 150 mm in width, as shown in Fig. 1. All of the beams were simply supported over a length of 2200 mm center to center and subjected to two equal central loads, spaced 300 mm apart, to produce a constant moment region in the middle of the beam. This configuration which creates two equal shear regions with lengths of 950 mm each was designed to avoid bond failure and ensure flexural failure through bar rupture. All of the beams were reinforced with one basalt bar in the tension region with a diameter of 12.45 mm. Two 10 M Grade 400 deformed steel bars were provided in the compression zone. The clear concrete cover of 35 mm was kept constant for all the beams. In order to avoid shear failure and ensure a flexural failure, adequate shear reinforcement was provided in the form of 10 M stirrups spaced at 100 mm center to center.

2.2. Instrumentation and prestressing procedure

Sixteen concrete beams were cast and tested. The control beam was loaded monotonically to failure; the load was applied by a hydraulic jack through a load cell, and a steel spreader beam that transferred the load to the test beam. All the beams were loaded in four- point bending as shown in Fig. 2. Nine strain gauges were used in one of the prestressed beams (40% prestressing), which was tested under monotonic loading. The gauges were fixed on the tension reinforcement, three of which were in the constant moment region and three in each of the two shear spans at distances of 100 mm, 250 mm, and 500 mm from the support to measure the strain in the tension reinforcement during prestressing and flexural loading. For the other nine beams a total of 5 strain gauges used. Three strain gauges were placed on the tension reinforcement in the moment constant region only, two of which were placed under the point loads on each side and one was mounted in the middle of the moment constant region. In order to fix the strain gauges, the sand coating of the rebar was removed and the surface of rebar was flattened and cleaned. Then the strain gauges were coated with wax in order to protect them from any damage during casting. The other two strain gauges were mounted on the concrete, one at the top of the concrete at the center of the moment constant region and the other one in the middle of the concrete compression region at the center line of the beam. A linear variable differential transducer (LVDT) was placed at the mid span of the beam to measure the deflection. Ten basalt rebars were prestressed. Six of them were prestressed to 40% of their ultimate capacity and four basalt rebars were prestressed to 20% of their ultimate capacity. Anchorage components used for prestressing are shown in Fig. 3.

To eliminate a stress concentration that can lead to premature failure in the anchor zone, at the interface between the grip and the prestressed bars, the BFRP bars were stressed using a prestressing system having an anchor designed to eliminate this problem developed at the University of Waterloo [2]. The surface at the end of each BFRP bar was cleaned using acetone before anchoring. In order to distribute the stress on the surface of the bar and prevent the wedges from notching the bar, copper sleeves were placed on the bar and then three steel wedges were pushed firmly into the barrel of the grip after they had been assembled around the sleeve. To reduce the friction between the barrel and the wedges, the outer surface of the steel wedges was lubricated with G-n Metal Assembly Paste, and then the wedges were seated into the barrel that was fitted into a steel plate using a hydraulic jack as shown in Fig. 4.

Table 1
Mechanical properties of BFRP bars [6].

Specification	Sand coated Bars
Diameter (mm)	12.45
Ultimate tensile capacity (MPa)	1456
Modulus of elasticity (GPa)	53.3
Actual area (mm^2)	121.7

2.3. Material properties

The mechanical properties of the sand coated BFRP rebars, were determined from a tensile test conducted at the University of Waterloo [6] as reported in Younes et al. [7]. The tested beams were cast from two batches of concrete. All of the 20% and 40% prestressed beams, were cast from one batch; however, the non-prestressed beams were cast from the other batch. The concrete used for the beams was designed to achieve a target compressive strength of (55 MPa) after 28 days. For each of the sixteen beams, cylinders with dimensions of 100 mm in diameter and 200 mm in height were cast and tested to determine the compressive strength of the concrete. Five cylinders were tested at the time of releasing the prestressed bars, and another five were tested 28 days after the pouring of the beams. For the prestressed beams, the average compressive strength after 28-days for five cylinders of the concrete was 50 MPa. For the non-prestressed beams, the average after 28 days was found to be 55 MPa. The mechanical properties of the basalt bars are shown in Table 1.

2.4. Loading scheme

In order to study the effect of prestressing level (0%, 20% and 40% of the bar failure load) on the fatigue life of BFRP reinforced beams, five beams of the first group, five beams of the second group, and four beams of the third group were subjected to fatigue loads under load-control.

The minimum load in the load cycle for the fatigue beam specimens was kept equal to 10% of the 85 kN ultimate strength of the control beams and the maximum load was varied for all the tested beams from 11.5% to 80% of the ultimate strength of the control beam (85 kN). The test frequency for all tests was 3.5 Hz. One beam from each of groups two and three was tested again at a higher load range after it had reached the run out limit (1,000,000 cycles).

3. Experimental results

3.1. Static results

3.1.1. Non-prestressed concrete beam

The first specimen tested under monotonic load was a non-prestressed beam which served as a control beam for the non-prestressed beams. Its load versus deflection curve is shown in Fig. 3. The concrete cracked at a load of 10 kN. The first hairline cracks appeared in the form of flexural cracks in the constant moment region. Four cracks occurred at the same time, two in the middle of the constant moment region and the other two just outside of the constant moment region. At this point, the slope of the load deflection curve decreased indicating that the flexural stiffness of the beam had decreased.

As the load increased, more flexural cracks appeared in the two shear spans of the beam. Then a longitudinal crack occurred on the bottom of the mid-span of the beam at a load of 38 kN. The cracks in the constant moment region grew vertically as the load increased. When the load reached 85 kN, which was slightly lower than the expected ultimate load 90 kN, the basalt rebar ruptured, as expected, followed immediately by crushing of the concrete at the top of the beam.