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Fatigue of reinforced concrete beams strengthened with externally post-tensioned CFRP tendons

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ABSTRACT

The fatigue performance of reinforced concrete beams strengthened with externally post-tensioned carbon fiber-reinforced polymer (CFRP) tendons was examined in an experimental and analytical study. Five unstrengthened and 13 strengthened reinforced concrete beams were tested under various fatigue load ranges until failure. The strengthened beams were post-tensioned with two external CFRP tendons on a double-harped profile. The results demonstrated that external post-tensioning significantly decreased the stresses in the internal reinforcement at all stages of loading, and hence extended the fatigue life of the strengthened beams. All beams failed due to the fatigue fracture of the internal steel reinforcing bars. The CFRP tendons demonstrated excellent fatigue performance, with no indication of distress at the deviated points or at the anchors. A fatigue model based on a strain-life approach was proposed to predict the fatigue life of the strengthened beams. The model allows the effect of strengthening on the fatigue life of the beams to be explicitly evaluated during the strengthening design process.

1. Introduction and background

Strengthening of existing concrete structures is generally required to enhance the load-carrying capacity of the structure or to reduce excessive structural deflections to specified service limits. Some structural elements, such as bridge girders and slabs in parking garages, are subjected to cyclic loads during their service lifetime. This type of loading may cause failure due to fatigue even when the nominal peak loads are less than the ultimate capacity of the structure. While fatigue failures are not common in concrete structures, the application of strengthening measures to increase the load-carrying capacity of existing structures may result in increased stresses in the concrete and original steel reinforcement. If the applied loading is cyclic, the risk of a fatigue failure may increase in the strengthened structure. For some strengthening applications, external post-tensioning offers the ability to strengthen the structure and actively reduce deflections, while also improving fatigue behavior by altering the stress ranges in the concrete and steel reinforcement.

In the last few decades, the use of fiber-reinforced polymer (FRP) tendons to strengthen concrete structures has increased considerably, primarily due to the non-corroding nature of the FRP materials. Experimental and analytical investigations reported that there is no significant difference in the flexural performance between the FRP and steel externally post-tensioned beams [5,10,27]. Gallab and Beeby [17] reported on the factors affecting the ultimate monotonic response of prestressed concrete beams externally post-tensioned with Parafil ropes draped at two points along the beam sides. The factors include the initial prestressing stress, the effective depth of the external tendons, the location of deviators and the distance between deviators, the area and prestress in internal bonded tendons, the span/depth ratio, and the concrete strength. It was reported that increasing the prestressing level in the tendons and the depth of the external tendons reduced the amount of deflection at any stage of loading. The cracks completely closed and the full cross section was used in the deflection calculations whenever the bottom concrete stress is still in compression due to prestressing. All beams were reported to have failed by yielding of steel reinforcement followed by crushing of the concrete.

FRP prestressing tendons may represent an attractive solution for some external post-tensioning applications where strengthening of damaged structures is required or where design loading

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conditions have increased. Shahrooz et al. [24] investigated several FRP strengthening techniques to retrofit four 76-year-old T-beams. Unlike the FRP bonded techniques, it was reported that external post-tensioning with CFRP tendons was the best option, particularly for members with extensive deterioration, because it did not rely on the quality of bond between the poor concrete and the FRP material. The stiffness, capacity, and ductility of the retrofitted beams were significantly enhanced.

Reinforced concrete elements are generally expected to crack under service loads. When reinforced concrete elements are strengthened with external post-tensioning tendons, closure of cracks depends on the degree of damage of the element at the time of the post-tensioning, the amount of prestressing, and the post-tensioning tendon profile and tendon eccentricities. The service loads applied to the strengthened element, usually higher than the original design loads of the initial structure, may cause the cracks to reopen under load application. Peak stresses are consequently induced in the reinforcement and in the concrete at the location of these cracks. If the strengthened post-tensioned element is subjected to repeated loads, the oscillating action of opening and closure of cracks induces high local stress variations in the embedded bars. In this case, failure due to fatigue fracture of the bars may be a concern particularly if the cracks are not fully closed after post-tensioning. While a number of parameters associated with the fatigue behavior of the partially prestressed bonded beams have been investigated, research on the fatigue behavior of concrete structures strengthened with external post-tensioned tendons is comparatively limited, particularly when FRP tendons are used.

Taniguchi et al. [26] conducted fatigue tests on three T-beams internally prestressed with CFRP tendons and post-tensioned with external AFRP tendons. The internal and external tendons were initially prestressed at 22% and 40% of the tendon's ultimate capacity, respectively. All of the beams survived two millions cycles without failure, although a 12–15% decrease in the prestressing force was recorded during fatigue loading, attributed to either relaxation of the tendons or slippage of the anchors.

Grace and Abdel-Sayed [18] used a combination of bonded internal CFRP tendons with unbonded external double-draped carbon fiber cables in the construction of four bridge models having double-tee cross sections. The post-tensioning forces in the external tendons varied between 57% and 78% of their ultimate capacity. The four models were tested under fatigue loading at different load ranges within the working load limit (less than the cracking loads), and infinite fatigue lives were reported for all models. Insignificant losses in the prestressing forces were encountered in the externally draped tendons (approximately 3% of the initial force).

Braimah et al. [9] tested three beams post-tensioned with internally unbonded CFRP tendons under fatigue loading. The CFRP tendons were post-tensioned to 60% of their ultimate capacity. Only one CFRP post-tensioned beam survived two million cycles of fatigue loading. Failure of the other post-tensioned beams was initiated by the fracture of the tendons at the tendon-anchor junction after surviving a few thousand cycles.

The available literature reveals only limited information on the fatigue performance of CFRP post-tensioned reinforced concrete beams. Additionally, an analytical model to predict the fatigue life of the strengthened beams could not be found.

2. Research significance

Research has shown that the use of external post-tensioning as a strengthening measure for reinforced concrete elements can increase ultimate capacity while reducing deflections. Additionally, it is anticipated that external post-tensioning can improve the fatigue performance of strengthened concrete elements. The current study tested unstrengthened reinforced concrete beams and beams strengthened with external CFRP post-tensioning tendons under fatigue loading, and demonstrated the enhancement of fatigue behavior provided by external post-tensioning. An analytical modeling approach using strain-life fatigue procedures developed for metal structures was used to predict the fatigue life of the beams. The model provides a rational approach that can be used to explicitly assess the effectiveness of the strengthening measures to extend the fatigue life of a reinforced concrete structure.

3. Experimental program

The experimental program consisted of 18 unstrengthened and strengthened reinforced concrete beams tested under fatigue loading. The beams were divided into three groups as listed in Table 1. Group 1 consisted of five unstrengthened beams to serve as controls. Groups 2 and 3 consisted of strengthened beams internally reinforced with two 15 M (0.63 in. dia.) and two 20 M (0.78 in. dia.) bars, respectively. The strengthened beams were externally post-tensioned with two CFRP tendons located along the sides of the beams.

All beam specimens were 3500 mm (138 in.) long, with a depth of 254 mm (10 in.), and a width of 152 mm (6 in.), as shown in Fig. 1. The specimen represented a concrete girder with a span-to-depth ratio of 15.4. The internal tensile reinforcement consisted of Grade 400 (58 ksi) deformed reinforcing bars. Two reinforcement amounts were considered: groups 1 and 2 beams with two 15 M (0.63 in. dia.) bars, and group 3 beams with two 20 M (0.78 in. dia.) bars. Two 8 mm (0.31 in.) diameter plain steel bars were used for compression reinforcement. These reinforcement configurations represented a typical under-reinforced (tension-controlled) concrete beam. The shear reinforcement consisted of 8 mm (0.31 in.) diameter stirrups spaced at 75 mm (3 in.) over the full length of the beam. The steel reinforcement and the concrete in compression were instrumented in the constant moment region of the beams using strain gages (Fig. 1). All beams were tested under four-point bending with a clear span of 3300 mm (130 in.) and loads applied at the one-third points of the span.

The 28-day average compressive strength of concrete was 35 MPa (5.08 ksi). The tested yield and ultimate strength of the steel reinforcing bars were 450 MPa (65.3 ksi) and 550 MPa (79.8 ksi), respectively. The CFRP tendons used were Aslan200™, 9.5 mm (0.37 in.) diameter, with an average measured ultimate strength of 2162 MPa (313.6 ksi) and a modulus of elasticity of 144 GPa (20,885 ksi).

The external CFRP tendons were harped under the two loading points by means of steel deviators having a 500 mm (19.7 in.) radius of curvature, as shown in Fig. 2. Thin Teflon™ sheets were used as cushioning to minimize the friction between the CFRP tendon and the deviators. The tendons had an eccentricity of 87 mm (3.43 in.) from the longitudinal axis of the beam in the constant moment region with no eccentricity at the beam-ends. The tendons were post-tensioned to 40% of their ultimate capacity ($0.4f_{pu}$ or approximately 60 kN (13.5 kips) in each tendon). This prestress level is less than the maximum value of 60% of f_{pu} typically recommended for CFRP post-tensioned tendons after release [2,11,12] since the maximum tension stress in the tendons at the deviator locations is greater than the net tension in the tendon due to bending [18,23]. Using the approach recommended by Quayle et al. [23], the peak stress at the deviator was computed to be 66% of f_{pu}, slightly exceeding the recommended limit. The post-tensioning force was applied using two hollow hydraulic jacks mounted on a structural steel stressing chair at one end of the beam (Fig. 2). The force in the tendons was monitored using four hollow load cells seated at the ends of each tendon. The CFRP tendons were anchored by the wedge-type steel anchors developed at the University of Waterloo [4]. Tension fatigue tests on the tendon-anchor assembly were conducted under various stress ranges before using them to anchor the external tendons in the beams. The results of these tests showed that failure of the tendon-anchor assembly would occur in the CFRP tendons rather than in or near the anchor. An endurance limit of a stress range of approximately 216 MPa (31.3 ksi) was determined for the assembly [15].

The strengthened beams of groups 2 and 3, having two different reinforcement ratios, were intended to model typical in-service reinforced concrete beams that needed strengthening. In order to simulate this condition, the tests on the beams were conducted in stages, as illustrated in Fig. 3. The virgin beam was first preloaded up to 50% of its yield load (point A; 30 kN (6.74 kips) for group 2, and 42 kN (9.44 kips) for group 3). The load level was then reduced to 25% of the yield load (point B) and maintained constant during the post-tensioning process. This load level simulated the effect of the superimposed load that would be subjected to an in-service beam during strengthening. The post-tensioning force of 60 kN (13.5 kips) or 40% of the ultimate tendon capacity was then applied gradually in each tendon until the desired force in the tendons was achieved (point C). The beams were loaded to their maximum peak load (point D) and then unloaded to the mean load (E) prior to applying fatigue cycles. All beams were cycled between the fatigue peak loads (C and D) until failure occurred or the number of the recorded cycles exceeded one million cycles. Beams lasting for more than one million cycles were intentionally halted and were considered as run-outs. These specimens were then subjected to a higher load range until a finite fatigue life was achieved. Data were recorded continuously for the first one-thousand cycles, and then at intervals of time depending on the anticipated life of the beam.