DURABILITY AND FATIGUE BEHAVIOR OF HIGH-STRENGTH CONCRETE BEAMS PRESTRESSED WITH CFRP BARS

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ABSTRACT

The need for sustainable structures has motivated an international interest in the use of fiber reinforced polymer (FRP) materials as internal reinforcement for concrete infrastructure applications. One of the contributing factors affecting the widespread use of FRP materials is the limited information regarding their long-term performance. In particular, knowledge of the long-term durability of FRPs is of prime importance.

The research work presented in this paper is the result of a research collaboration between North Carolina State University (NCSU) and the University of Cambridge (UC). The research investigates the durability of concrete beams prestressed with carbon FRP (CFRP) bars and compares the results with those of companion beams prestressed with steel wires. A total of fifteen beams have been constructed and tested under different mechanical and environmental conditions. The parameters included in the program were the level of sustained stress in the bars and wires (55 and 70 percent of the ultimate bar or wire strength), the environmental exposure condition (air exposure and continuous exposure to 15 percent by mass salt water spray at 54 °C temperature), the length of time under sustained load (9 and 18 months) and the method of testing (with or without application of cyclical loading prior to static testing to failure). Test results show that the beams prestressed with steel wires did not survive the environmental exposure over 12 months whereas the beams prestressed with CFRP bars survived up to the end of the 18 month long extreme environmental exposure.

1. INTRODUCTION

The need for sustainable structures has motivated an international interest in the use of fiber reinforced polymer (FRP) materials as internal reinforcement in concrete infrastructure applications. To date, FRPs have not realized their full potential within the construction industry. One of the contributing factors is limited information regarding their long-term performance. In particular, since the service life of a civil engineering structure is typically 50 to 100 years, knowledge of the long-term durability of FRPs is of prime importance.

This research work, performed at NCSU and conducted in collaboration with the UC, investigated the durability of concrete beams prestressed with CFRP bars. The research findings provide a unique evaluation of the durability and estimation of the service life of concrete structures prestressed with CFRP bars when compared with equivalent structures prestressed with steel wires. The experimental program investigated concrete beams prestressed with CFRP bars or steel wires which were subjected to sustained loading and environmental exposure prior to testing under realistic static and fatigue loading conditions.

2. EXPERIMENTAL PROGRAM

The test series consisted of fifteen concrete beams prestressed with either CFRP bars or steel wires. The beams were precracked prior to being subjected to various combinations of sustained loading and exposure conditions. The pre-cracking generated a path for moisture to propagate directly to the prestressing bars and wires, thus representing the most severe exposure conditions in the field. Under sustained loading, the stress in the bars and wires was either 55 or 70 percent of the ultimate bar or wire strength, f_{pu}. The environmental exposure conditions consisted of either air exposure or continuous exposure to 15 percent by mass salt water spray at 54 °C. Further parameters were the length of time under sustained load (9 or 18 months) and the test method (with or without application of cyclical loading prior to static testing to failure). A summary of the testing scheme is given in Table 1.

The aggressiveness of the environment to which the prestressing materials were exposed will have accelerated their degradation compared to real time behavior. The chloride concentration in the solution used was approximately four times higher than that of seawater. Scott and Lees (2006) suggest that this elevated concentration is not likely to have a significant effect on the rate of solution uptake, and hence rate of degradation, in the CFRP bars. Elevating the temperature from 20 ^{o}C to 54 ^{o}C may accelerate the rate of uptake in epoxy matrix FRPs by an order of magnitude (Chin *et. al.* (1999) and Vanlandingham *et. al.* (1999)). Further work is underway to assess the temperature effects on uptake in this specific CFRP material along with further aspects such as bond strength. The elevated temperature will increase the corrosive effect of the salt water on the steel prestressing wires (Silverman and Puyear, 1987). It has not, however, been possible at this stage to assess the effects of elevated temperature and chloride concentration acting in synergy to corrode the steel.

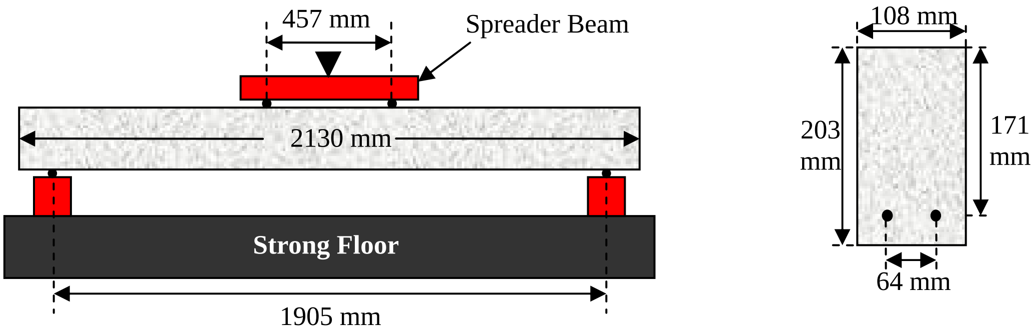
2.1 Test Specimens

The beam design was based on the fatigue study completed by Agyei (2002) at the UC. The beams tested at NCSU had 108 × 203 mm rectangular cross-section with an overall length of 2130 mm as shown in Figure 1. Each beam contained two prestressing bars or wires with a spacing of 64 mm and a clear cover of approximately 20 mm from the side of the beam. The distance from the bottom surface of the beam to the center of the bars or wires was

32 mm. The size of the specimens were similar in three key aspects used for typical applications of CFRP prestressed concrete wind turbine masts; the bar diameters (4 – 4.5 mm), concrete cover (32 mm) and crack widths under sustained loading (typically 0.2 – 0.3 mm). It is these geometry parameters that govern the rate of solution ingress to the FRP bars and corrosion of the steel, hence any consequent degradation that may occur.

Table 1 – Summary of the experimental program

Beam No	**Reinforcing Material**	**Sustained Stress Level in Bars and Wires**	**Environmental Exposure**	**Duration of Combined Sustained Load and Exposure Program**	**Cyclic Loading**
B1	CFRP Bar	0.55 f_{pu}	15 Percent Salt Water Spray 54 ºC Temperature	9 Months	No
B2					Yes
B3		0.70 f_{pu}			No
B4					Yes
B5				18 Months	No
B6					Yes
B11	Steel Wire				No
B12					Yes
B7	CFRP Bar	0.55 f_{pu}	Air	9 Months	Yes
B8		0.70 f_{pu}		18 Months	No
B9					Yes
B10	Steel Wire	0.55 f_{pu}		9 Months	No
B13					Yes
B14		0.70 f_{pu}		18 Months	No
B15					Yes



(a) (b)

Fig. 1 – General view of the test specimens (a) elevation and (b) cross-section

2.2 Material Properties

Details of the concrete mixture design are given in Table 2. Ten 102×203 mm companion cylinders were cast for each test specimen to determine the compressive concrete strengths (f'_c) on the day of bar or wire detensioning, 28 days after casting, at the commencement of the sustained loading, when the beam was tested to failure and the tensile strength after 28 days.

Details of the CFRP prestressing bar and steel wire material properties are given in Table 2. A single wire from a seven-wire 12.7 mm low relaxation prestressing steel strand was used. The diameter was comparable to that of the CFRP bar. The initially applied prestressing level was 0.55 f_{pu} for both the CFRP bars and steel wires. The test specimens prestressed with CFRP bars were designed to fail by bar rupture and the stresses in the concrete would be fairly low. The test specimens prestressed with steel wires were designed to fail by the yielding of the wire followed by concrete crushing.

Table 2 – Concrete mixture design and properties of the prestressing bars and wires

Concrete Mixture Design	
Material	**Amount**
SPC Type Cement (kg/m^3)	571.3
Dry Densified Silica Fume (kg/m^3)	49.8
Lillington Sand (kg/m^3)	1568.6
Superplasticizer (kg/m^3)	10.29
Polypropylene Fibers (kg/m^3)	1.03
Water (kg/m^3)	205.9
water/cementitious material	0.33
f'_c at 28 days (MPa)	61.5

Properties of Bars and Wires		
Property	**CFRP Bar (SACAC Ltd.)**	**Steel Wire (VSL Inc.)**
Nominal Diameter	4.0 mm	4.3 mm
Area	12.57 mm^2	14.52 mm^2
Tensile Strength	2200 MPa	1940 MPa
Modulus of Elasticity	161000 MPa	200000 MPa
Max. Elongation	1.37% (rupture)	5.21% (yield)

2.3 Specimen Preparation

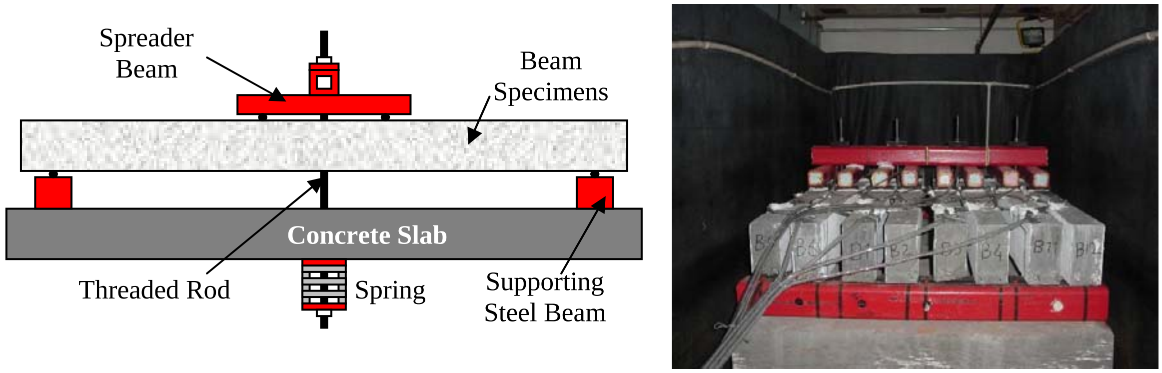
Expansive cement anchors were used to prestress the CFRP bars to avoid premature bar failure due to stress concentrations within the anchorage zone. To stress the steel wires, 4 mm multiple use chucks and 4 mm reusable anchor chucks were used for the dead and live ends respectively. The applied prestressing forces were 14.7 and 15.1 kN for the CFRP bar and steel wire respectively. The beams were typically detensioned three days after casting.

2.4 Test Set-Up and Method

All the beams were precracked under a two point simply supported loading configuration between 28 and 30 days after casting using the test set-up shown in Figure 1(a). The sustained loading was then applied to the precracked beams using a two point simply-supported loading configuration. Threaded rods were used to load the beams against a supporting slab as shown in Figure 2(a). The specimens were loaded so that the stress levels in the bars or wires were 55 percent or 70 percent of f_{pu}. Seven specimens under sustained load were then exposed to air as control specimens, and eight beam specimens were placed under sustained load in the environmental chamber as shown in Figure 2(b). The tank of the environmental chamber was filled with 15 percent by mass salt water solution at 54 ºC. A heater-thermostat combination was used to maintain a constant water temperature. A pump-pipe system was used to spray water on the specimens continuously. The duration of the combined sustained load and environmental exposure program was either 9 or 18 months.

After completion of the combined sustained loading and environmental exposure program, the beams were tested to failure using a two point simply supported loading configuration (Figure 1a). Seven of the beams were tested under static loading whilst eight of the beams were subjected to cyclic loading prior to static loading to failure. The static load was applied at a rate of 668 N per minute. The procedure for the cyclic loading included the application of a load level corresponding to bar or wire stress ranges varying from 65 to 75 percent of f_{pu}

at a frequency of 3 Hz for two million cycles. The specimens that survived the cyclic loading were then tested to failure under static loading.



(a) (b)

Fig. 2 – Test set-up for sustained loading (a) elevation and (b) in environmental chamber

3. TEST RESULTS AND DISCUSSIONS

The experimental program details are given in Table 3. All beams subjected to cyclic loading survived two million cycles except beam B7 due to an experimental problem related to the testing equipment which was corrected for the rest of the testing program. The load versus midspan deflection behavior of all the beams tested to failure is shown in Figures 3 to 5.

Table 3 – Experimental program details

Beam No	**Type**	**f'_c at 28 days (MPa)**	**f'_c at Static Test (MPa)**	**Exposure Condition/Time**	**Bar/ Wire Stress Level (f_{pu})**	**Cyclic Loading**		**At Failure**	
						Load Range (kN)	**Bar/Wire Stress Range (f_{pu})**	**Max. Load (kN)**	**Max. Defl. (mm)**
B1	C	81.1	95.2	Salt/9 months	0.55	Static Testing Only		23.6	10.7
B2	C	67.0	84.6	Salt/9 months	0.55	16.0-18.7	0.65-0.75	30.8	12.0
B3	C	66.9	93.1	Salt/9 months	0.70	Static Testing Only		31.0	10.9
B4	C	82.5	100.1	Salt/9 months	0.70	16.0-18.7	0.65-0.75	30.1	12.2
B5	C	76.2	103.9	Salt/18 months	0.70	Static Testing Only		31.0	11.2
B6	C	65.9	82.3	Salt/18 months	0.70	16.0-18.7	0.65-0.75	29.0	10.0
B7	C	63.5	66.3	Air/9 months	0.55	16.0-18.7	0.65-0.75	*	
B8	C	78.0	83.2	Air/18 months	0.70	Static Testing Only		29.3	8.8
B9	C	70.3	77.1	Air/18 months	0.70	16.0-18.7	0.65-0.75	27.7	4.0
B10	S	63.1	70.3	Air/9 months	0.55	Static Testing Only		26.1	42.8
B11	S	62.9	-	Salt/18 months	0.70	Failed under Environmental Exposure			
B12	S	70.8	-	Salt/18 months	0.70				
B13	S	65.8	67.5	Air/9 months	0.55	16.0-18.7	0.65-0.75	23.1	33.4
B14	S	47.0	55.2	Air/18 months	0.70	Static Testing Only		22.4	52.1
B15	S	46.2	52.9	Air/18 months	0.70	16.0-18.7	0.65-0.75	23.9	46.1

* Failed due to short of electric circuit of the actuator after 300000 cycles
- No Specimens were tested
S = Prestressed with steel wire, C = Prestressed with CFRP bar

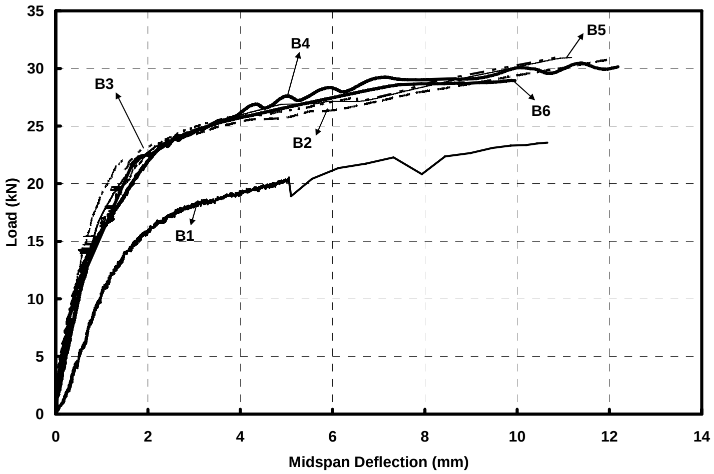


Fig. 3 – Load vs. midspan deflection of beams prestressed with CFRP bars (exposed to environmental conditions)

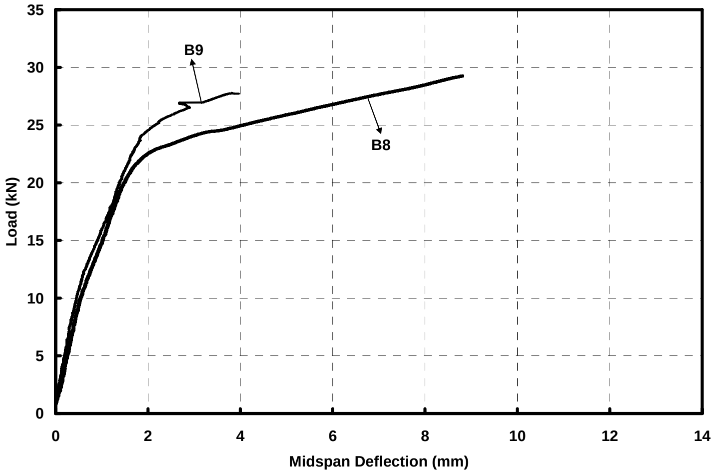


Fig. 4 – Load vs. midspan deflection of beams prestressed with CFRP bars (exposed to air)

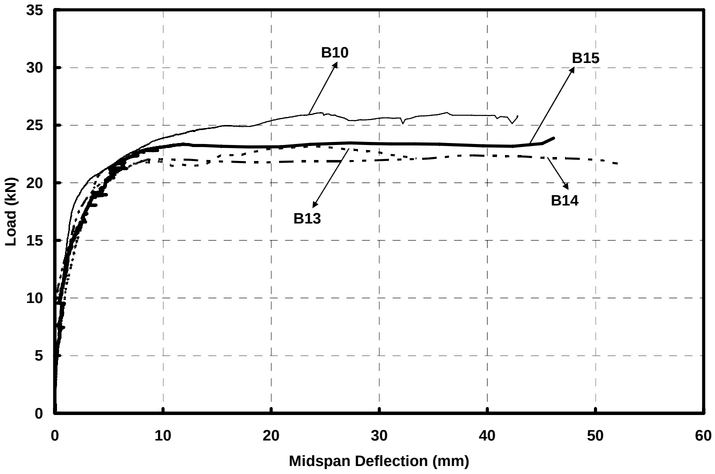


Fig. 5 – Load vs. midspan deflection of beams prestressed with steel wires (exposed to air)

All the CFRP-prestressed beams subjected to salt spray and increased temperatures showed a similar type of behavior except beam B1 which failed under a relatively low load (see Figure 3). Reasons for this discrepancy are being investigated. B6 which was exposed to the most severe loading (0.70 f_{pu} bar stress, 18 months salt water exposure, cyclic loading) showed a slight reduction in ultimate load and deflection at failure when compared with a salt water exposed CFRP beam subjected to a lower sustained stress level tested statically after 9 months (B3). However, this reduction was not significant. The length of exposure also did not seem to influence the behavior greatly in that the behavior of B3 was similar to B5 and that of B4 was similar to B6. Interestingly, the beams with CFRP bars that were exposed to air (B8 and B9 as shown in Fig. 4) had lower ultimate load capacities and deflections at failure than the broadly equivalent beams left in the environmental chamber (B5 and B6, see Fig. 3). The maximum load capacity of CFRP-prestressed beams subjected to static testing after cycling had slightly lower capacities than those tested without cycling

The beams prestressed with steel wires were affected more significantly than the beams prestressed with CFRP bars under exposure to salt water spray. Under identical conditions, CFRP prestressed beams B5 and B6 survived the environmental exposure program for 18 months whereas steel prestressed beams B11 and B12 failed after 12 months. On inspection of the steel wires in beams B11 and B12 post failure, significant levels of corrosion were observed, which caused the wire rupture. This illustrates the benefit of using CFRP to prestress concrete in aggressive environments, in comparison with structures prestressed with steel.

The load-deflection behavior of the surviving steel-prestressed beams was broadly similar (see Fig. 5). B10 was subjected to the least severe conditions (0.55 f_{pu} sustained bar stress, air exposure for 9 months and tested statically) and had the highest ultimate load capacity. B14 which had a higher stress level and longer exposure time had a lower capacity than that of B10. However, the influence of the cyclic versus static testing after the exposure period seemed to be inconclusive since B14 and B15 (18 months exposure) had similar load-deflection profiles whereas B13 failed at a lower load than B10 (9 months exposure).

The maximum deflections at failure of the beams prestressed with steel wires were all much greater than those of the beams prestressed with CFRP bars; an expected result given the ductility of the steel compared with the brittle CFRP. In all of the beams, a degradation in stiffness was observed as the number of cycles of fatigue loading increased.

4. CONCLUSIONS

Test results indicate that:

1. Generally, the CFRP prestressed beams retained greater strength compared to the steel prestressed beams across the range of tests undertaken.
2. The beams prestressed with steel wires did not survive the environmental exposure over 12 months whereas the beams prestressed with CFRP bars survived 18 months up to the end of the environmental exposure.

3. When precracked, the beams prestressed with steel bars could sustain induced stresses of 0.7 f_{pu}, when exposed to air, but not when exposed to a heated salt water spray over a period of 12 months.
4. Cyclic loading did not have a major effect on beams prestressed with CFRP bars and steel wires.
5. A higher sustained bar stress in the beams prestressed with CFRP bars resulted in a slight reduction in beam strength. Beams prestressed with steel wires subjected to higher sustained stress levels become more vulnerable to environmental effects.
6. Exposing the beams prestressed with CFRP bars to 15 percent by mass salt water spray and 54 ºC temperature did not affect their behavior or cause any deterioration.
7. Increasing the salt water environmental exposure period for beams prestressed with CFRP bars affected neither the overall durability nor the strength.

5. ACKNOWLEDGEMENTS

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