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CFRP Repair of Corrosion-Damaged Bond Region

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ABSTRACT: Structures such as bridges and marine structures are subjected to repeated loading. At the same time those structures are prone to corrosion. Corrosion of reinforced concrete (RC) structures is a multi-billion dollar problem that affects structures worldwide. One of the main consequences of corrosion in RC is the deterioration of the bond between the concrete and the steel. A recent study reported by the authors showed that a corrosion level of only 5% mass loss decreased the fatigue bond strength by about 12%. Research conducted over the past few years has shown that reinforcement with fiber reinforced polymer (FRP) sheets can provide a viable solution to the corrosion-bond problem. This paper examines the effect of strengthening with FRP sheets on the bond strength of corroded steel bars in concrete beams subjected to repeated loading. Twenty anchorage-beams were tested. The beam dimensions were 152 x 254 x 2000 mm. The variables were the level of corrosion (5% and 9% measured mass loss) and the load range applied. The repeated loading caused bond fatigue failure in unwrapped uncorroded beams, but some wrapped corroded beams failed by fatigue of the steel at a corrosion pit. The slip versus number of cycles curves for the wrapped corroded beams differed from that of the uncorroded unwrapped beams. Repairing with CFRP sheets increased the fatigue bond strength of wrapped beams corroded to 5% and 9% mass loss by 11% and 4% respectively above that of the uncorroded unwrapped beams.

1 INTRODUCTION

Corrosion of steel is a major problem that affects structures worldwide. In reinforced concrete (RC) structures, the corrosion of steel reinforcement results in reducing its cross-sectional area and produces rust that has a volume several times larger than the parent steel. This expansive volume cracks the concrete cover and reduces the bond between the steel and concrete. The weakening of the bond interaction leads to increased deflection and crack width and a decrease in the load carrying capacity of the RC structure. Several research studies have shown that corrosion decreases the bond strength and increases the slip of the steel bars relative to concrete (FIB 2000). Recently, the repair of corroded structures using fiber reinforced polymers (FRP) sheets has been studied at the University of Waterloo. FRP sheets are attractive because of their light weight, high strength, ease of application and non-corrosive nature. They have been shown to reduce corrosion activity and increase the yield and ultimate static strengths of corroded structures as well as to increase the bond strength (Craig and Soudki 2005, El Maaddawy and Soudki 2005). However, many structures, such as bridges, that are prone to corrosion are subjected to repeated loading. Repeated loading causes damage that affects the serviceability of RC structures and in extreme cases causes fatigue failures. A recent study reported by the authors examined the effect of corrosion on the fatigue of bond. Results showed that a corrosion level of a 5% mass loss resulted in a decrease of 12% in fatigue strength (Rteil et al. 2007).

This paper examines the benefits of using FRP to repair the bond of corroded structures under a repeated loading regime.

2 EXPERIMENTAL PROGRAM

The experimental program consisted of testing twenty RC specimens under repeated loading. The variables in the tests were the level of corrosion (0%, 5% and 9% measured mass loss), the load range applied and whether the beams were wrapped with FRP sheets or not. Table 1 identifies the test matrix.

Table 1. Test matrix and results

Group	Specimen notation*	Min. load (kN)	Max. load (kN)	Load range (%)*	CFRP	Corrosion level (%)	Fatigue life (N_f)	Failure mode
UW0	F45-UW0	10	55	45	No	0	442,134	Bond splitting
	F47-UW0		57	47			31,423	Bond splitting
	F50-UW0		60	50			2,041	Bond splitting
	F53-UW0		63	53			25,052	Bond splitting
	F55-UW0		65	55			1,714	Bond splitting
W5	F50-W5	14	83	50	Yes	5	142,208	Bond splitting
	F52-W5a		86	52			523,270	Bond splitting
	F52-W5b		86	52			1,950	Steel rupture
	F55-W5		90	55			17,731	Bond splitting
	F65-W5		104	65			113	Bond splitting
W9	F45-W9	14	76	45	Yes	9	510,313	Steel rupture
	F47-W9		79	47			452,836	Steel rupture
	F48-W9		80	48			9,027	Bond splitting
	F50-W9a		83	50			51,319	Bond splitting
	F50-W9b		83	50			14,145	Bond splitting
	F50-W9c		83	50			293,023	Bond splitting
	F52-W9a		86	52			2,529	Bond splitting
	F52-W9b		86	52			8,742	Bond splitting
	F55-W9a		90	55			1,523	Bond splitting
	F55-W9b		90	55			127,973	Steel rupture

* Fx-Yz: x is the load range applied given as a percentage of the static bond capacity; Y = UW for unwrapped beams and W for CFRP wrapped beams; z = corrosion level given as percentage of the measured mass loss (0, 5 or 9%). The letters a, b and c that appear after the last part of the notation are to differentiate between beams in the same group tested at the same load range.

2.1 *Specimens*

Anchorage-beam specimens were used in this study in order to get realistic bond stress behavior (bond stress values and distribution). In an anchorage-beam, the tension steel bars are unbonded in the middle of the beam, thus limiting the force transfer between the steel and concrete to the bonded length (anchorage length) which was chosen so that the specimen fails by bond splitting before the steel yields. The specimens were 2000 mm long and had a rectangular cross-section (150 x 250 mm). Each specimen was reinforced in tension with two deformed steel bars, 20 mm in diameter, and in shear with 8 mm smooth hoop stirrups spaced at 125 mm (Fig. 1). The anchorage length was 250 mm. The unbounded length was created by covering the steel bars with low-density polyethylene (LDP) tubes. In addition, two pockets were created at the end of the bonded region to allow for easy instrumentation of the steel bars (Fig. 1).

2.2 *Accelerated corrosion*

In order to achieve a significant amount of corrosion in a reasonable amount of time, the beams were subjected to accelerated corrosion. Salt was added to the concrete mix to help initiate the corrosion activity. The steel bars were connected to the positive terminal of a power supply to force them to act as anodes, and a stainless steel tube, 9.5 mm in diameter (Fig. 1), was connected to the negative terminal of the power supply to act as a cathode. The power supply provided a constant current density of 150 $\mu A/cm^2$. The exposure corrosion time of the specimens varied in order to achieve the chosen corrosion levels. After the beams were tested, the steel bars were extracted and cleaned and the mass loss was measured in accordance with ASTM standard G1-03 (ASTM 2003).

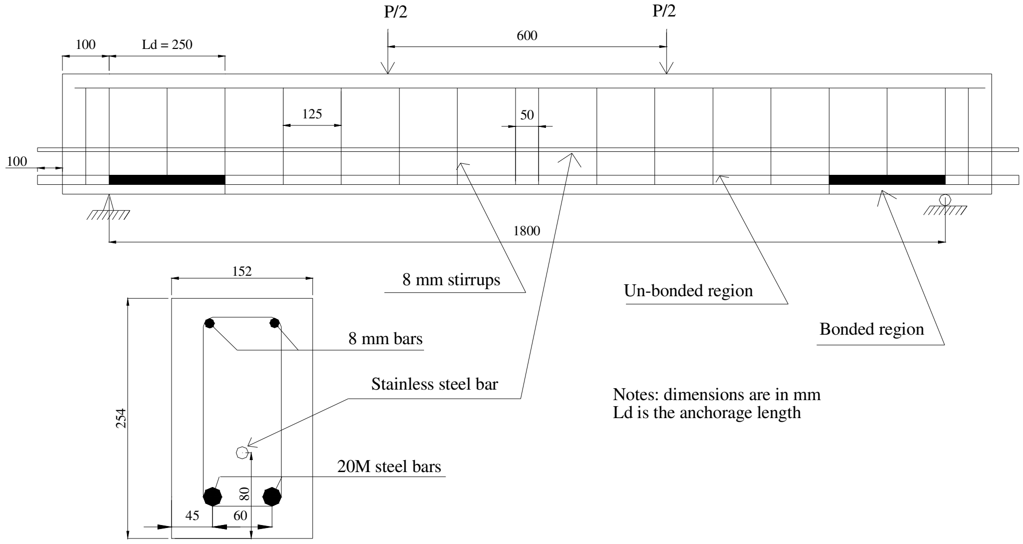

Figure 1. Anchorage-beam specimen details

2.3 *FRP repair*

The repair scheme consisted of wrapping the anchorage zone (at both ends of the beam) with a single U-shaped carbon fiber reinforced polymer (CFRP) sheet. The fibers orientation was perpendicular to the longitudinal steel in order to provide the required confinement for concrete against corrosion and bond stresses. The CFRP sheets were applied in accordance with the manufacturer procedure. It should be noted that the corrosion cracks were sealed by an epoxy before the beams were wrapped.

2.4 *Materials properties*

The concrete was supplied by a local ready mix plant. The concrete had a water-cement ratio of 0.6 and a compressive strength of 42 MPa at the time of beam testing.

All the reinforcing steel was grade 400 with a yield strength of 440 MPa. The stainless steel tubes were type 304L.

The CFRP sheets were manufactured and provided by SIKA. The tensile strength, tensile modulus, elongation and thickness of the CFRP system (sheets and epoxy), as provided by the manufacturer, were 715 MPa, 61 GPa, 1.09% and 0.38 mm respectively.

2.5 *Instrumentations and test setup*

Several linear variable displacement transducers (LVDT) were used to measure the free (at the extended bars) and loaded (at the pocket) ends slip of the steel bar relative to the concrete. In addition, strain gauges were mounted on the CFRP sheets (at the level of the steel bars) to monitor the strain variation in the CFRP sheets. The sensors were connected to a computerized data acquisition system that stored the data at a frequency of 30 Hz.

The beams were tested in four-point bending with a span of 1800 mm and a constant moment region of 600 mm. The load applied to each specimen ranged from a minimum that corresponded to 10% of the specimen static capacity to a maximum that varied to give fatigue lives between 1,000 and 1,000,000 cycles. The static capacity of the uncorroded beams was determined experimentally (Rteil et al. 2007). The load was applied manually until the desired maximum load was reached, then decreased to the mean load. Subsequently, the controller was used to automatically apply a sinusoidal wave between the maximum and minimum loads. The tests were performed under load control at a frequency of 1.5 Hz. The tests were stopped either when the beams failed by fatigue, or when a test reached 10^6 cycles which was considered to be a run-out.

The failure of a specimen was defined as the cycle during which the specimens could no longer carry its maximum load.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 *Mode of failure*

In the unwrapped uncorroded beams (group UW0), longitudinal cracks initiated at the pocket and ran along the reinforcing bars during the first few cycles. As the number of cycles increased, the number and width of these cracks increased. This behavior took place at both ends of the beams (where the bonded zones are) and continued until about 20% to 25% of the beams' life after which the cracks ceased to grow. At about 80% to 90% of the beams' life the longitudinal cracks in the bonded area started to widen again at one end of the beam and continued to widen at an ever increasing rate until failure. The failure of all the unwrapped beams was by bond splitting (Table 1) of the concrete cover at the side and bottom faces of the beams (Fig. 2a). After the tests were stopped the failure plane of the concrete was examined. It was noticed that the concrete keys (concrete between the steel lugs) in the bottom concrete cover were intact (Fig. 2b) while the concrete layer above the steel bar in the vicinity of the steel lugs was crushed. This implies that the bond forces pushed the bottom concrete cover away by wedge action and only the upper concrete layer above the bars that was held against the bars by the stirrups provided resistance to the bond forces.

The corroded beams had longitudinal cracks due to corrosion before the beams were tested. These cracks were sealed with an epoxy before the CFRP wrapping was applied. During the testing of these beams, the presence of the CFRP sheets prevented a visual inspection of the crack behavior. It was realized that the majority of the beams failed when the CFRP sheets ruptured at both sides of one of the beams' anchorage areas while it remained intact at the other end (Fig. 3). After the tests were halted, the CFRP sheets were removed and the concrete surface was inspected. The concrete surface of these beams had longitudinal splitting cracks signifying a bond failure (Fig. 3). Also in these beams both the concrete cover and the layer above the steel showed evidence of crushing indicating that the confinement provided by the CFRP sheets resulted in forcing the concrete to remain in contact with the steel. The concrete surface at the other end had little or no longitudinal cracks. A few of the beams (Table 1) failed when the steel bars ruptured before concrete splitting. This is due to the lack of corrosion protection for the steel at the pocket, which resulted in severe corrosion pits that initiated the fatigue failures. It should be noted that beams failing in steel rupture are excluded from the following discussion.

a) Concrete splitting b) Failure plane for unwrapped beams (bottom cover)

Figure 2. Failure of the uncorroded unwrapped beams (group UW0).

3.2 *Fatigue behavior*

The fatigue lives of the specimens reported in this paper are presented in Table 1 and shown in Figure 4. Also shown in Figure 4 are previously reported results of tests on unwrapped beams corroded to a 5% mass loss (Rteil et al. 2007). As the applied load range increases, the bond fatigue life of the specimens decreases linearly on a log-log scale (Fig. 4). The fatigue strength of Group W5 (wrapped and corroded to 5%) increased by 26% compared to their unwrapped counterparts (unwrapped and corroded to a 5% mass loss). The fatigue strength of the wrapped specimens corroded to a 5% and a 9% mass loss increased on average by 11% and 4% respectively compared to that of the unwrapped uncorroded specimens. Comparing groups W5 and W9 it is shown that increasing the corrosion rate from 5% to 9% decreased the fatigue life of the specimens by about 6%. The CFRP sheets increased the fatigue strength of the corroded specimens at a low corrosion rate to a level above that of the uncorroded unwrapped specimens. Even at the higher corrosion rate the strength was restored to its original level.

a) CFRP failure
b) Splitting concrete cracks

Figure 3. Bond failure of the wrapped corroded beams (Groups W5 and W9).

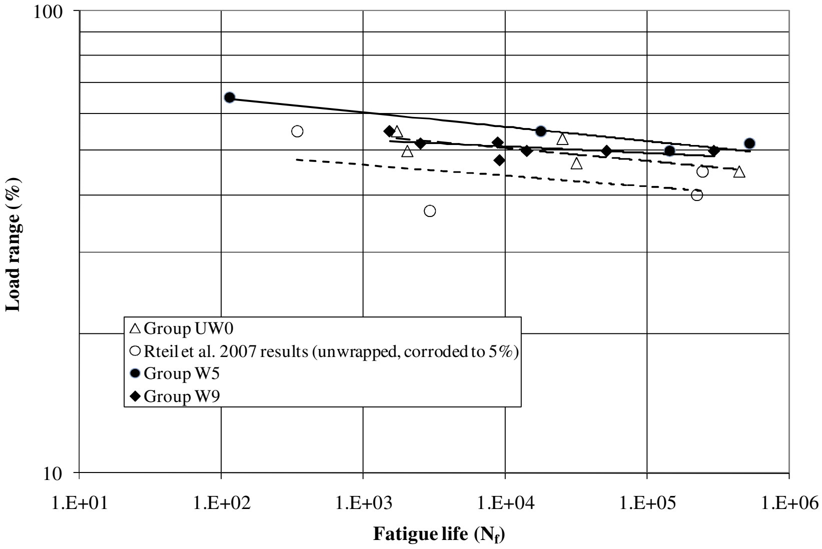

Figure 4. Variation of the load range with life.

3.3 *Slip Behavior*

The slip of the uncorroded unwrapped beams (Group UW0) shown in Figure 5 can be divided into two parts. In the first part the slip does not increase much, however, in the second part, the slip increases exponentially. The duration of the first part depended on the load range applied. As the load range increased the duration of the first part decreased from 90% of the beams' life to 30% of the beams' life.

For the corroded wrapped beams, the slip behavior was different. In the first 5 to 10% of the wrapped beams' life, the slip increased rapidly to about 1.5 to 2.0 mm (Fig. 5). After that, the slip continued to increase but at a much slower rate. The rate of slip increase for both corrosion levels (5% and 9% mass loss) was 0.033 mm per 1% of the cycle to life ratio. Between about 90% of the cycles to failure and failure the slip increased exponentially (Fig. 5). It is interesting to note that a similar behavior was also recorded for the variation of the CFRP strain. The strain in the CFRP sheets increased rapidly during the first 4 to 8% of the beams' life. After that, the

CFRP strain continued to increase but at a much lower and constant rate until failure. This behavior was the same for all wrapped beams irrespective of their corrosion levels.

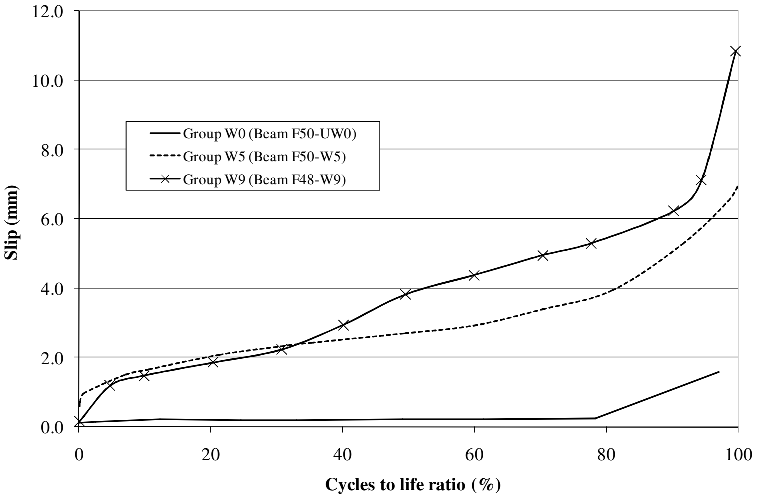

Figure 5. Typical slip behavior of the wrapped and unwrapped beams.

4 CONCLUSIONS

Based on the above discussion the following conclusions are drawn.

- All unwrapped beams and most of the wrapped beams failed by bond fatigue. Some wrapped beams failed by fatigue of the steel bars initiated at a severe corrosion pit.
- Even for the beams corroded to a 9% mass loss, the CFRP sheets increased the fatigue strength to the level of the uncorroded unwrapped beams. At a 5% mass loss the repaired corroded beams had a greater strength than the uncorroded unwrapped beams.
- The CFRP sheets changed the initial slip behavior of the wrapped beams from the slow increase shown by the unwrapped beams to a rapid initial slip. This period of high initial slip corresponded to a period during which a rapid increase in FRP strain showed that the forces in the FRP opposing splitting of the concrete cover were being mobilized.

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