FRP REPAIR OF CORROSION-DAMAGED CONCRETE BEAMS – WATERLOO EXPERIENCE

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Abstract: Corrosion of steel reinforcement is one of the main durability problems facing reinforced concrete infrastructures worldwide. This paper gives an overview on a seven year research program conducted at the University of Waterloo, sponsored by ISIS (Intelligent Sensing for Innovative Structures) Canada, to examine the viability of using fibre reinforced polymer (FRP) composites as a repair and strengthening method for corroded reinforced concrete structures. The majority of the research was carried out in the laboratory utilizing large-scale members. The results revealed that FRP repair successfully confined the corrosion cracking and improved the structural performance of corroded beams. Analytical models were developed to validate the experimental data. The FRP repair system was implemented in Fall 2005 to address corrosion damage in a bridge in the Region of Waterloo.

Introduction

Corrosion of reinforcing steel causes many structures in adverse environments to experience unacceptable loss in serviceability or safety far earlier than anticipated and thus need replacement, rehabilitation, or strengthening. As steel corrodes, there is a corresponding drop in the cross-sectional area. The corrosion products occupy a larger volume than the original steel which exert substantial tensile forces on the surrounding concrete and causes it to crack and spall off. If corrosion cracking can be prevented or delayed, a certain degree of structural strength may be maintained in a corroding RC beam.

Fibre reinforced polymer (FRP) systems are promising alternatives for the rehabilitation of deteriorated and deficient concrete members. In addition to their high strength to weight ratio, durability in adverse environments and high fatigue strength, FRP sheets can be easily externally bonded to reinforced concrete slabs, beams, and columns (ACI Committee 440 1996).

A multi-phase research program was undertaken at the University of Waterloo (see Table 1) to investigate the viability of using externally bonded fiber reinforced polymer (FRP) laminates to rehabilitate corrosion-damaged reinforced concrete beams (Soudki, et al. 2006, Badawi and Soudki 2004a and 2004b; Craig and Soudki 2005, 2002; El Maaddawy et al 2004, 2005a and 2005b; Masoud et al 2005 and 2001, 2000; Soudki and Sherwood 2003 and 2001, 1998). Several reinforced concrete beams (20 small-scale, 24 medium-scale and 50 large-scale beams) with variable chloride levels (0 to 3%) were constructed. The test variables were: level of corrosion damage at the time of FRP repair, location of corrosion damage, effect of short-term static, long-term sustained loading and fatigue loads. The beams were repaired by externally epoxy bonding FRP laminates to the concrete surface bonded to the tension face, with the fibre orientation in the longitudinal direction followed by transverse laminates bonded to the tension face and up each side of the beam, with the fibre orientation in the transverse direction. Two types of FRPs were used: Glass (GFRP) sheets had an ultimate strength of 600 MPa, an elasticity modulus of 26 GPa, and an ultimate elongation of 2.24%. The Carbon (CFRP) sheets had an ultimate strength of 960 MPa, an elasticity modulus of 73 GPa, and an ultimate elongation of 1.33%. The tensile reinforcement of the specimens was subjected to accelerated corrosion by means of impressed current up to 15% mass loss. Strain gauges were used on the FRP laminates to quantify tensile strains induced by the corrosion process. Accelerated corrosion was applied using a constant impressed current of 150 $\mu A/cm^2$. The current was impressed through the main longitudinal rebars, which act as the anode while the stainless steel bar in each specimen acts as the cathode. Following the corrosion phase, the specimens were tested in flexure in a four-point bending regime. Details of the test program, test methods, and test results are found elsewhere.

M. Pandey et al. (eds), Advances in Engineering Structures, Mechanics & Construction, 165–173.

Table 1. Overall experimental program

Researcher	Loading	Member	Dimensions (mm)	Number
Sherwood	Static	Flexural beams	102x154x1200	16
Craig	Static	Bond-beams	152x254x2000	37
	Static	Pull-out	150x150x150	24
Masoud	Static/Fatigue	Flexural beams	152x254x3200	20
	Fatigue	Flexural beams	120x175x2000	8
El Maaddawy	Sustained	Flexural beams	152x254x3200	29
Badawi	Static	Shear critical	152x254x3200	15
Rteil	Fatigue	Flexural beams	152x254x2000	60
Al Hammoud	Fatigue	Bond-beams	152x254x2000	29

In the following, key findings from FRP repair for reinforced concrete beams subjected to corrosion damage, are given.

Effects of FRP Repair on Serviceability

Corrosion Cracking

Figure 1 shows typical average crack width versus mass loss for corroded specimens. The width of the longitudinal cracks was measured at discrete time periods throughout the accelerated corrosion process for all the corroded specimens. It is evident that the FRP repair process reduced the crack opening by about 88% at the end of corrosion process. This implies a significant enhancement in appearance of FRP repaired corroded specimens by reducing crack opening due to further corrosion.

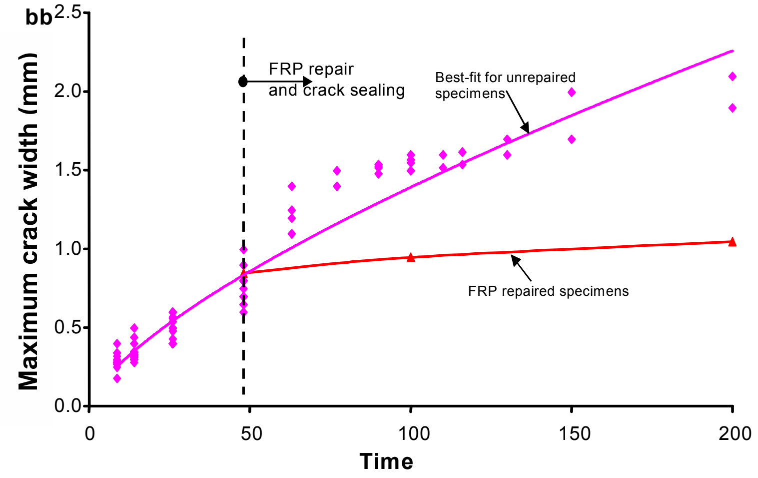


Figure 1. Crack width vs. time

Steel Mass Loss

Fig. 2 shows the average steel mass loss versus time relationship for various test specimens. A linear regression analysis for the steel mass loss results after repair showed that during the post-repair corrosion phase the steel mass loss rate in the specimens having the continuous-wrapping was on average about 32% lower than the level for the beams having the intermittent-wrapping. The presence of the sustained load during the post-repair corrosion phase increased the steel mass loss rate by about 9% and 12.5% for the specimens repaired with continuous and intermittent wrapping schemes, respectively. The specimens corroded under a sustained load had connected internal microcracks and external flexural cracks which increased the penetration of oxygen and moisture into the concrete and reduced the concrete resistivity and thus increased the steel mass loss rate to a level higher than that for the specimens corroded without load.

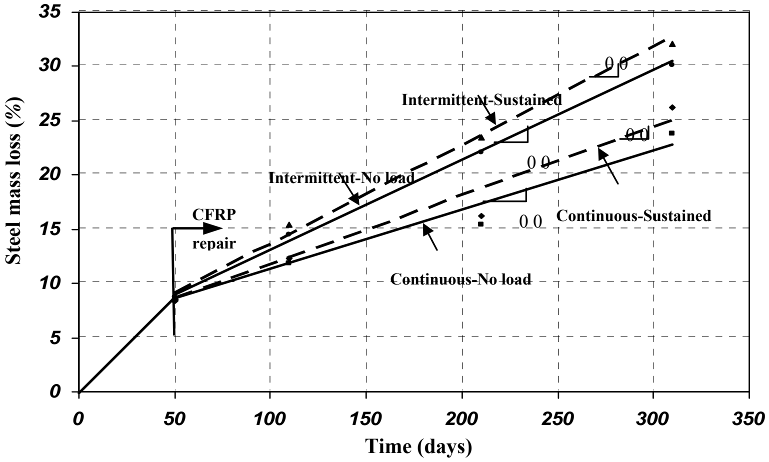


Figure 2. Steel mass loss versus time relationship

Bond Strength

Corrosion plays a devastating role in reducing the structural capacity of unconfined flexural members. CFRP confinement of the bond zone in bond-beam specimens serves to maintain steel-concrete bond interaction. The effect of CFRP on the confinement of corrosion-damaged members varies depending on whether the member has adequate bond or is bond deficient. For those members with inadequate bond length, the added CFRP confinement improved the performance of bond-deficient corroded members allowing them to outperform the unconfined specimen (Figure 3). It is important to understand the nature of failure of the CFRP confined specimens. Since no cracks were visible with the CFRP wrap in place, there are no indications of failures. Even under conditions of high ultimate bond stresses, the presence of low slip initiation bond stresses indicates that failure could potentially occur prematurely by bond pullout in the case of sustained loading or creep. Confinement was found to be more effective when applied prior to excessive corrosion of the specimens. Typically, small amounts of post-repair corrosion were found to have no effect or in some instances helped increase bond strength as a result of increased confining pressures. However, as the post-repair corrosion levels increased, the bond strength deteriorated. The overall structural performance of beams wrapped with CFRP was enhanced. However, caution and engineering judgement must be used in the application of this repair method since abrupt failure of the member due to bond pullout failure could occur without warning if repair is performed at high corrosion levels or if members were initially designed with inadequate bond. The confining wrap may increase the bond strength, but as with all repairs, this should not be used as a band-aid solution, and the cause of deterioration must be addressed to prevent further corrosion and deterioration.

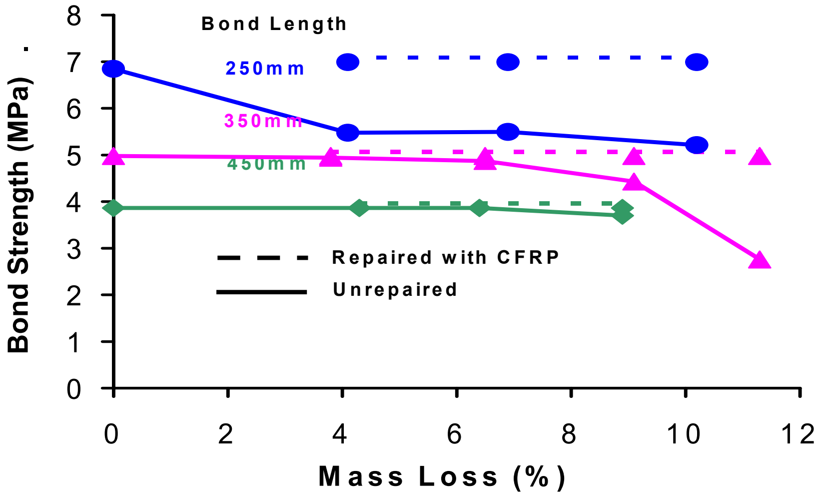
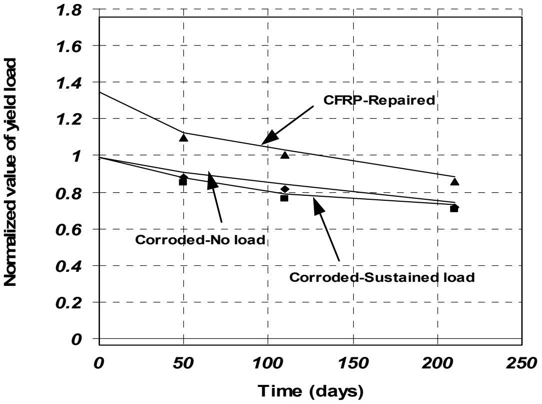


Figure 3. Bond strength vs. mass loss

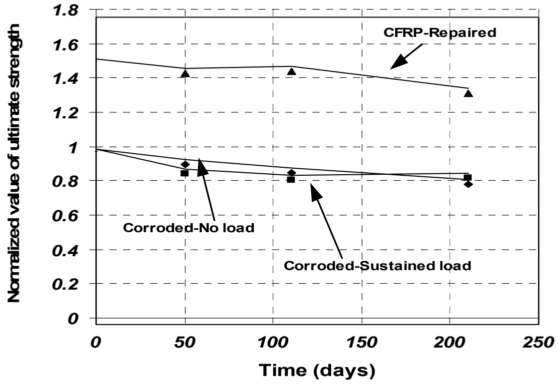
Effects of FRP Repair on Static Strength

Figure 4 (a) and (b) show the normalized yield load vs. mass loss and normalized ultimate load vs. mass loss for the corroded-no load, corroded under load and CFRP repaired specimens. The normalized load is taken relative to the control specimen (at 0% mass loss). Corrosion of the steel reinforcement up to a 5.5% theoretical mass loss while the beam is unloaded resulted in a 10% and 9% reduction in the yield and the ultimate loads, respectively compared to those of the virgin uncorroded beam. The reduction in the yield and the ultimate capacity increased to 13% and 13.2%, respectively when the corrosion occurred under sustained load. A 12% theoretical mass loss of the steel reinforcement caused 16% and 11% reductions in the yield and the ultimate loads, respectively when corrosion occurred without load. Loading the beam with a 12% mass loss increased the reductions in yield and ultimate load to 22% and 17%, respectively compared to the virgin uncorroded specimen.

When CFRP external reinforcement was added there was an increase in the load carrying capacity. Compared with the uncorroded virgin beam, the uncorroded-strengthened beam exhibited a 30% and a 49% increase in the yield and the ultimate load, respectively. When a beam is corroded before the application of the CFRP laminates it doesn’t reach the same strength as a strengthened uncorroded beam. The yield and the ultimate loads of the corroded-repaired beam at a 5.5% theoretical mass loss were 85% and 97%, respectively of that of the uncorroded-strengthened beam but they were higher than those of the virgin control beam by 11% and 43%, respectively. Increasing the level of corrosion damage to a 12% theoretical mass loss before repair reduced the yield strength to 77% of that of the uncorroded-strengthened beam while the ultimate strength remained at 97% of that of the uncorroded-strengthened beam. The yield load of the beam repaired after corrosion to a 12% theoretical mass loss was almost the same as that of the virgin control beam while the ultimate strength was still higher than that of the virgin beam by 43%. It is interesting to note that the ultimate strengths of the corroded-repaired beams were very close to that of the uncorroded-strengthened beam. This means that while corrosion of the steel reinforcement reduces the ability of the CFRP repair to increase the yield load its effect on the ultimate strength gained by repairing the beam with CFRP laminate is minimal.



a) yield strength



b) ultimate strength

Figure 4. Plots of normalized load vs. time

Effects of FRP Repair on Fatigue Strength

Figure 5 shows the fatigue life vs. load range for flexural and bond specimens. The life-load range variation of bond-beams is presented in Figure 5a. In set B-CD (with a 5% mass loss due to corrosion) the fatigue bond strength decreased by 23% and 15% compared to the control (uncorroded) beams at 3,000 cycles and 50,000 cycles respectively. The decrease was less at low load ranges (high fatigue lives) than at higher load ranges (lower fatigue lives). When CFRP sheets were added to strengthen the beams an increase of 15 % in fatigue bond strength compared to the fatigue strength of the corroded unstrengthened beams was achieved. This increase was about the same at all fatigue lives. It should be noted that CFRP sheets at long fatigue lives were able to restore the original uncorroded fatigue strength of the beams.

The variation of the fatigue life with the load range applied on flexure-beams in Figure 5b. The fatigue strength in set F-CD flexural beams was reduced by approximately 10% compared to those of set F-C. Repairing the 5% corroded beams with CFRP (set F-CR) increased the fatigue strength of the beams by 10% at 100,000 cycles and by 18% at 750,000 cycles compared to the corroded unrepaired beams (set F-CD). It should be noted that repairing with CFRP sheets restored the fatigue flexural strength of the corroded beams to a level equal to that of the original uncorroded beams.

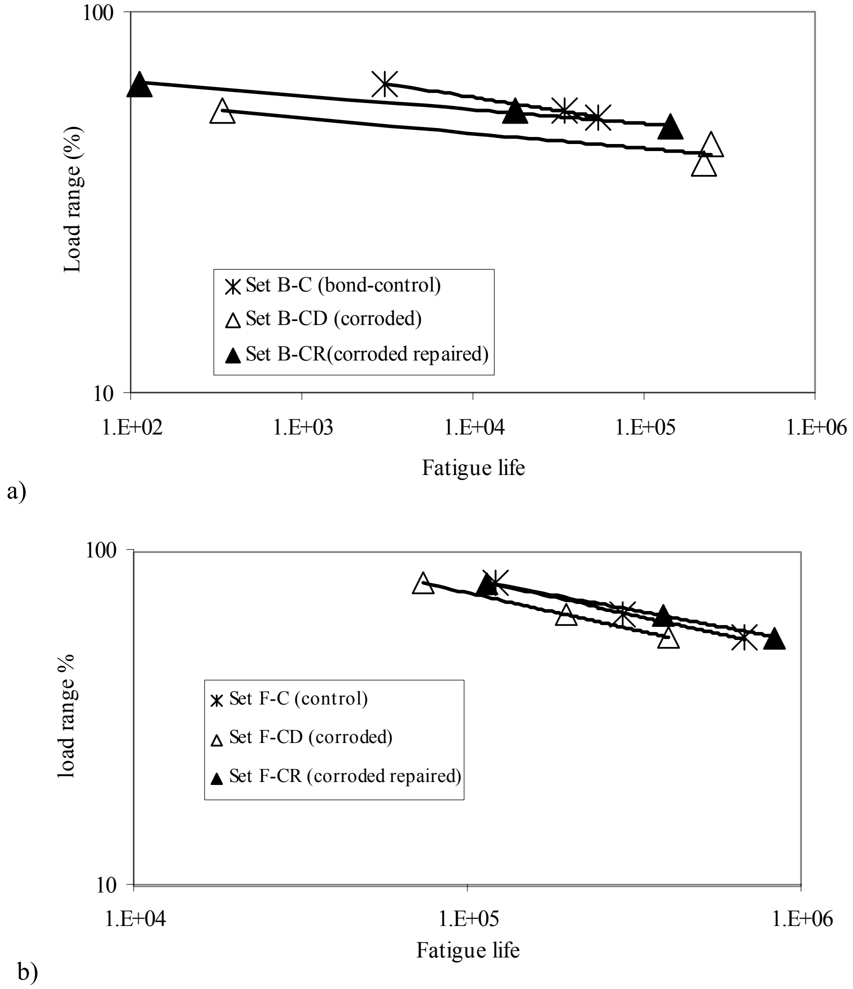


Figure 5. Variation of the fatigue life with load ranges: a) bond beams, b) flexure beams

Analytical Modeling

A unified model that predicts the non-linear flexural response of corroded RC beams repaired with fibre reinforced polymer (FRP) sheets was developed. The model accounts for the effects of corrosion and FRP-wrapping on the transfer of load from the steel to the concrete between flexural cracks. The effects of the additional FRP reinforcement and the reduction in the steel area due to corrosion on the beam strength are predicted by the model. The beam cross section is discretized into finite layers while the beam span is modelled as a series of elements based on the mean crack spacing. The model was implemented into a new computer program. A comparison of the model's predictions with experimental results showed that the model accurately predicted response of both corroded and FRP-repaired beams. (Fig. 6).

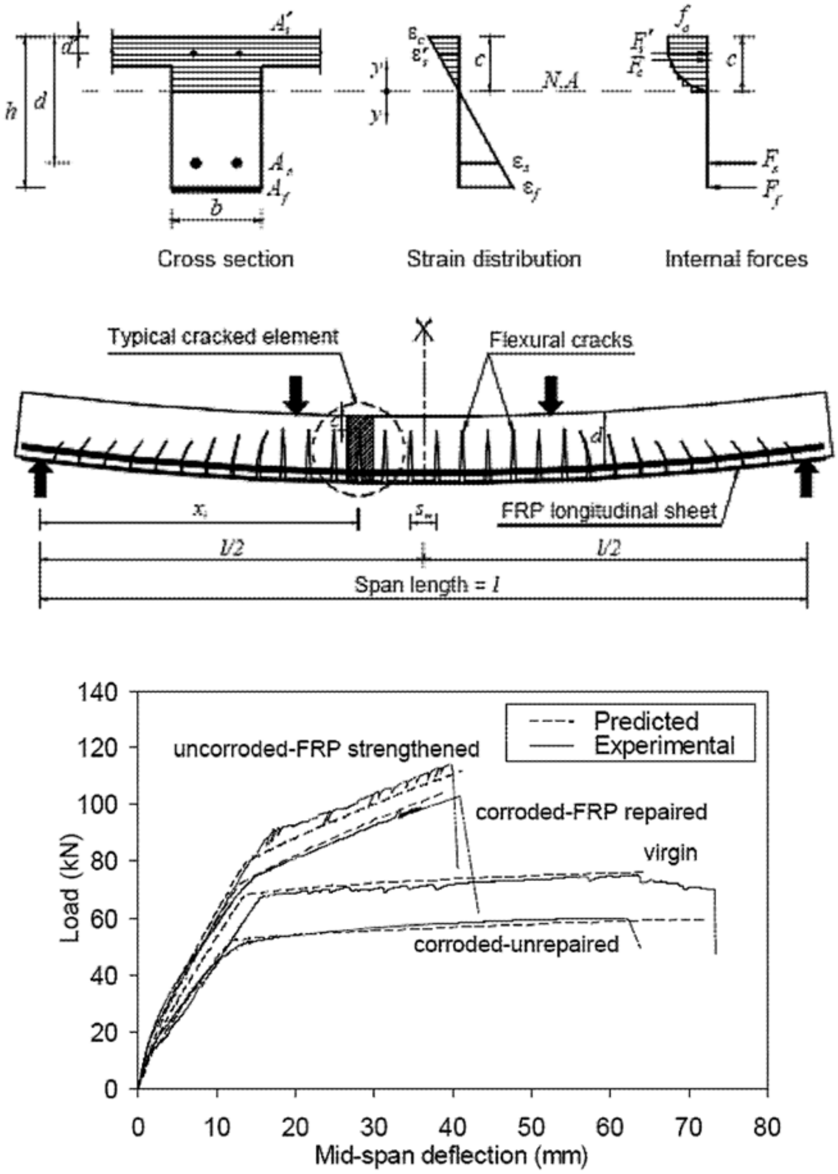


Figure 6. Analytical model and results

Field Implementation

In Fall 2005, the ISIS Waterloo group in collaboration with the C3 group successfully implemented the FRP repair onto a bridge girder in the region of Waterloo along with sensors to monitor the performance of the repair system. The FRP repair will be monitored over time to assess its effectiveness in the field. Figure 7 shows a photo of the FRP sheets on the girder.

Figure 7. Photo of CFRP repair on the bridge girder

Concluding Remarks

FRP composites are viable for the strengthening or repair of reinforced concrete beams that are experiencing steel reinforcement corrosion capable to maintain the structural integrity, serviceability and ultimate monotonic strength. The results in this paper provided important benchmark data, analytical modeling as well as field implementation of the FRP repair.

Acknowledgements

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