Fatigue flexural behaviour of corroded RC beams strengthened with CFRP sheets

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An experimental study is carried out to investigate the fatigue flexural behaviour of corroded RC beams strengthened with carbon fiber reinforced polymer (CFRP) sheets. The specimens are 200×120×1500 mm reinforced concrete beams. The results of this study indicate that the use of CFRP sheets for strengthening corroded RC beams is an efficient technique that can maintain the structural integrity and enhance the structural behaviour of such beams. The fatigue life of the CFRP strengthened corroded beams is found to increase by 1.24-1.56 times that of a similar unstrengthened corroded beam, but less than that of the uncorroded beam. The failure mechanism, fatigue of the steel reinforcement, remains the same in both strengthened and unstrengthened beams. Thus, this study suggests the possibility of predicting the fatigue life of the corroded beam with corroded steel bars fatigue models.

Keywords: Fatigue flexural behaviour, Corrosion, Reinforced concrete beam, Sheets

Long-term performance of infrastructures is governed by structural deterioration, which is defined as the loss of capacity due to physical, chemical, and mechanical actions. Since corrosive environments and cyclic loading are among the main causes of reinforced concrete (RC) deterioration, a significant amount of research has been devoted to these two specific damage mechanisms. Corrosion can be concentrated locally to form a pit and extend across a wide area to produce general wastage. The damage to RC structures resulting from the steel reinforcement corrosion is exhibited in the form of steel cross-section reduction, loss of bond between concrete and steel, cracking, and spalling of concrete cover. On the other hand, fatigue is a kind of damage of material that occurs due to repeated loading and unloading. Fatigue has a detrimental effect on RC structures as it may significantly reduce the expected life of the structure. Although enormous effects have been made on corrosion and fatigue, the coupling effect of these two has been rarely studied. Recently, corrosion combined with cyclic loading was studied, and the results show that the loss of capacity for structures can be exaggerated.

The application of CFRP sheets in civil engineering has recently emerged as an alternative to the traditional methods for rehabilitation or reinforcement of structures. The effect of CFRP strengthening on the fatigue performance of RC beams has been addressed by many researchers, but very limited information is available on the fatigue performance of CFRP-strengthened corroded beams. Masoud et al. tested corroded beams repaired with CFRP under cyclic flexural fatigue loading and concluded that corrosion of the steel reinforcement causes a decrease of the fatigue life of a beam. Reinforcing the beam with CFRP was found to cause a reduction in the tensile stress in the steel reinforcement, and to increase the fatigue life of the beam. However, in these studies, only low and medium averaged mass loss was considered and there were insufficient data and formula to calculate the fatigue life of the beams. Aside from this, the effect of corrosion degree on the strength of steel bars after fatigue loading was not studied.

This paper presents an experimental study to examine the fatigue performance of using CFRP sheets to maintain the structural integrity of RC beams, which experiences steel reinforcement corrosion. The effect of corrosion degree on the strength of steel bars after fatigue loading is also investigated.

Experimental Procedure

A total of seven RC beams were used in this experiment. One uncorroded and strengthened specimen was loaded monotonically to obtain the static capacity of the beam. The remaining beams were tested under repeated loading. One uncorroded
and strengthened specimen was tested under fatigue loading to serve as a reference. Five specimens were corroded under different corrosion degrees (minor, medium, and severe) and then strengthened with CFRP sheets. Table 1 provides a summary of the specimens.

All specimens had the same overall dimensions. The typical geometry and reinforcement of the beams are shown in Fig. 1. The averaged compressive strength at the time of testing was 19.6 MPa. The actual yield strength and ultimate strength of the 12 mm diameter deformed bars were 382.0 and 544.3 MPa, respectively. The yield strength and ultimate strength of the 6 mm diameter plain steel bars used for the stirrups were 352.5 and 466.0 MPa, respectively. Table 2 provides a summary of material characteristics.

In order to accelerate the corrosion process, the beams were subjected to a constant density of 200 µA/cm² using DC power supply (Fig. 2). To ensure a constant current in the beams, the tension steel reinforcement bars of the beams were connected in series, and the direction of the current was carefully adjusted so that the tension steel served as the anode while the cuprum bar served as the cathode. During corrosion, the beams were inversely placed in a small tank and the bottom two-part of the specimen was immersed in 3% NaCl liquor. To achieve the desired corrosion level, the corrosion time was estimated using Faraday’s law.

The CFRP repair scheme is shown schematically in Fig. 3. One layer of flexural laminate, with 100 mm wide and 1.1 mm thickness, was bonded to the tension face of the beam with fibers oriented in the longitudinal direction to counteract the reduction in the steel area caused by corrosion. Three U-shaped CFRP sheets, each of 80 mm wide and 80 mm apart, were provided within the shear span of the beam act as end anchorages for the longitudinal CFRP laminate and to avoid any premature shear failure. The ultimate strength and elasticity modulus of CFRP sheets were 4.171 GPa and 267 GPa, respectively (Table 2). Special consideration was given to surface preparation before bonding the CFRP sheets to the concrete surface. Sandblast was employed to remove the weak layer from the surface of the beam, and then the surface was cleaned with a high-pressure air jet. Then the longitudinal cracks caused by corrosion were sealed by using an epoxy gel adhesive. The epoxy sealant was used also to seal any voids on the concrete surface to avoid having any air pockets between the CFRP sheets and the concrete. Finally, the concrete surface was ground and the beam’ corners were rounded to a radius of about 10 mm before the application of the CFRP sheets.

<table>
<thead>
<tr>
<th>Beam number</th>
<th>Type of load</th>
<th>Minimum load (kN)</th>
<th>Maximum applied load (kN)</th>
<th>Mass loss (%)</th>
<th>CFRP</th>
<th>Fatigue life (10⁴)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monotonic</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>Yes</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>Fatigue</td>
<td>10</td>
<td>35</td>
<td>0</td>
<td>Yes</td>
<td>&gt;300</td>
</tr>
<tr>
<td>3</td>
<td>Fatigue</td>
<td>10</td>
<td>35</td>
<td>8.3</td>
<td>Yes</td>
<td>134.6</td>
</tr>
<tr>
<td>4</td>
<td>Fatigue</td>
<td>10</td>
<td>35</td>
<td>13.8</td>
<td>Yes</td>
<td>45.9</td>
</tr>
<tr>
<td>5</td>
<td>Fatigue</td>
<td>10</td>
<td>35</td>
<td>15.0</td>
<td>Yes</td>
<td>61.0</td>
</tr>
<tr>
<td>6</td>
<td>Fatigue</td>
<td>10</td>
<td>35</td>
<td>16.7</td>
<td>Yes</td>
<td>30.4</td>
</tr>
<tr>
<td>7</td>
<td>Fatigue</td>
<td>10</td>
<td>35</td>
<td>22.3</td>
<td>Yes</td>
<td>8.4</td>
</tr>
</tbody>
</table>
In this experiment, the beams were subjected to four point bending. The loading system produced a constant moment region in the middle third of the beam specimen. A linear variable displacement transducer (LVDT) was used to measure the deflection at midspan, two loading points, and two pivots. Strains on the concrete and the CFRP sheets were recorded during the test to study their change under static and fatigue loading conditions. Electrical resistance strain gauges were placed on the concrete surface and CFRP sheets at the middle section of the strengthened beams.

The fatigue tests were performed under loading control. For all tests, the minimum and maximum loads in the fatigue load cycles were 10 and 35 kN, respectively. A sine wave load cycle was applied at a frequency of 3 Hz. The load was applied manually using a set point control until the desired maximum load was reached and decreased to the mean load. Figure 4 shows a test specimen under the loading test setup.

### Results and Discussion

**Observed behaviour**

All the strengthened corroded beams exhibited a similar primary mode of failure. In all cases, the failure was due to the brittle fatigue fracture of one of the tensile steel reinforcing bars (Fig. 5). Flexural cracks were initiated from the bottom of the beam after the several thousand cycles and then propagated...
to intersect with a longitudinal crack that occurred at the same height as the tension reinforcing steel bar in the middle third of the beam. Then some of these cracks proceeded vertically from the center of the longitudinal crack while the others started from the edges of the longitudinal crack and propagated towards the center of the beam as the number of applied cycles increased. The presence of CFRP sheets helped to decrease the width and propagation rate of vertical cracks and increase the space of vertical cracks. In the case of CFRP strengthened beams, fatigue failure of the reinforcing bar was accompanied by a sudden extension of the flexural cracks, a sudden increase in deflection and a significant drop in the beam stiffness, but the CFRP sheets were able to maintain the integrity of the beams in the failed position, and no failure was encountered in the tendons.

**Deflection and strain measurements**

For each beam, the deflection was recorded during periodic monotonic loading tests. Figure 6 shows the development of mid-span deflection, conducted at different stages during the fatigue load history, for the typical corroded beam 5. It can be found that there was an initial increase of the mid-span deflection, followed by a stable region where the deflection remained relatively constant throughout many cycles, and then followed by an abrupt increase of deflection just before failure. The deflection remained the same until approximately 50,000 cycles before failure occurred, making the deflection of an insipient failure very difficult. The data suggest that the increase of deflection with cycles is attributed to material fatigue damage, the bond loss between concrete and steel, and the increase in flexural cracks.
In this study, the strain on CFRP sheets and concrete was also recorded during periodic monotonic loading tests for all beams. The averaged strain in the tension steel reinforcement was determined using strain compatibility. Figure 7 shows concrete and CFRP strain, conducted at different stages during the fatigue load history, for the typical corroded beam 5. The result clearly shows an increase of the maximum strain with the number of cycles. This strain increase in concrete is attributed to cyclic creep of concrete. The strain in the steel reinforcement increases with cyclic loading as a combination result of crack propagation in concrete and fatigue damage increase in steel reinforcement. Simulation experiments were done on the corroded steel specimens machined from the reinforcement bars that were used in the RC beams.

In beams, the strain in the reinforcing bars increased suddenly before failure, indicating yielding of the reinforcement. At that point, strains in the concrete and CFRP sheet increased but remained lower than that corresponding to expect ultimate behaviour, i.e., 0.003 for concrete, and 0.01 for the CFRP composite sheet. The data indicate that the failure was due to the yielding of the corroded reinforcing steel caused by fatigue loading, which is similar to that of the uncorroded specimen. In the case of CFRP repaired beams, the CFRP reinforcement was able to continue to maintain the integrity, but became notably flexible and exhibited the debonding of CFRP sheet between two close flexural cracks.

Fatigue life

The ratio of the fatigue life versus the actual mass loss of the beams is shown in Fig. 8. The unstrengthened beams were tested at a cyclic load range of 60% of the static beam capacity. Differently, the strengthened beams were tested at a cyclic load range of 50% of the static beam capacity. A set of best fit curve to fatigue data was obtained for each set of beams and used to extrapolate the fatigue life data. Corroding of the beams to a low corrosion level decreased the fatigue life by about 26% (at 3% average mass loss). And this decreasing was found to be approximately 71% (at 10% average mass loss) while corroding of the beams to a medium corrosion level. Two factors may be subjected to the decrease of the fatigue life: Corrosion of the steel bars reduced the cross-sectional area of the bars; the formation of corrosion pits increased the severity of the stress concentrations. The scatter in the depth of the corrosion pits results in the scatter in the fatigue life.

The regression analyses show that strengthening beams with CFRP sheets increased the flexural fatigue life of the corroded beams by a factor of 1.24 at low corrosion level (at 5% average mass loss), while this factor is 1.52 at medium corrosion level (at 10% average mass loss), and 1.56 at high corrosion level (at 20% average mass loss). As expected, since failure of all beams was attributed to the fatigue of steel reinforcement, CFRP sheets increased the strength and the stiffness of RC beams. Consequently the stress on the steel reinforcement reduced, which lead to prolonging the fatigue life of the beams. It should be noted that, although CFRP
strengthening improved the fatigue behaviour of beams after corrosion and yielded a longer fatigue life, it would not completely restore the strength lost due to corrosion and would not bring the fatigue life up to the level of the virgin beam. The reason for this behaviour was related to the mode of failure, which is explained as follows.

All beams failed by rebar rupture, which indicates that the controlling factor for the fatigue strength of these beams was the fatigue strength of the tension steel reinforcement, not the fatigue strength of concrete and CFRP sheets. The reason is that both concrete and CFRP have good fatigue resistance. The presence of corrosion pits on the surface of the reinforcing bars results in the stress concentration at the root of the pit which promotes the initiation of cracks which reduce the fatigue life.

Thus, after the corrosion process, whether or not the beam was CFRP strengthened, the fatigue strength of the corroded tension steel reinforcement was smaller than that of virgin reinforcing bars. Consequently, the fatigue life was smaller. This would be true unless a sufficient number of CFRP sheets were bonded to the beam to reduce the stress in the corroded reinforcing bars to the level that would give the same life as the uncorroded reinforcing bars.

To guide the use of CFRP sheets reinforcing system on corroded RC beams under fatigue loading, an analytical procedure was developed to predict the fatigue life of the beams under any fatigue load. The experimental results show that the primary failure of strengthened RC beams is subjected to the rupturing of corroded steel bars. After steel bars ruptured, the CFRP sheets took over the load from the broken steel bars and then the CFRP sheets broke or debonded from the concrete surface under fatigue. Considering the fact of that fatigue failure of strengthened corroded RC beams depends on the fatigue properties of the corroded tension steel, the stress range on a reinforcing bar is the primary factor determining its fatigue life. The constant-stress-amplitude fatigue tests of the corroded steel bars was conducted and the stress-life \( S-N \) was obtained as:\(^{10}\):

\[
\lg N = (24.427 + 3.4\eta_s) - (7.6597 + 2.1\eta_s) \lg (\Delta\sigma) \quad (1)
\]

where \( N \) is number of cycles to failure; \( \eta_s \) is corrosion degree of steel bar; \( \Delta\sigma \) is stress range applied to the corroded steel bar in MPa.

As the fatigue loading of the beam progressed and the subsequent cracks propagated, a redistribution of stress occurred. Due to the higher strain values and hence the higher stresses in steel bar spanning, the crack was developed. This result in a shorter fatigue life for reinforcing steel embedded in the RC beam, as compared with reinforcing steel that was subjected to the same stress range in the air\(^{11}\). Further analysis of experimental results derived the following fatigue life relationship for corroded reinforcing bars embedded in CFRP sheets strengthening RC beam.

\[
\lg N = (24.427 + 3.4\eta_s) - (7.6597 + 2.1\eta_s) \lg (K\Delta\sigma) \quad (2)
\]

where \( K \) is stress coefficient. AI-Hammoud suggests that the value of \( K \) as follows: uncorroded beams \( K=1.78 - 2.15 \); medium corroded beams (7.05–9.05% average mass loss) \( K=1.78 - 2.28 \); severe corroded beams (10–14.3% average mass loss) \( K=1.87 - 2.89 \). In order to improve the applicability, this study suggests that the value of \( K \) as follows: minor corroded beams (0–5% average mass loss) \( K=1.78 - 2.15 \); medium corroded beams (5–10% average mass loss) \( K=1.78 - 2.28 \); severe corroded beams (10–25% average mass loss) \( K=1.87 - 2.89 \). The maximum nominal stress \( \sigma_{\text{max}} \) and the minimum nominal stress \( \sigma_{\text{min}} \) developed in the main reinforcing bars due to fatigue loading were calculated using a flexural analysis of the mid-span cross-section of the specimen within the constant moment zone. The nominal stress range \( \Delta\sigma \) was found to be equal to the difference between \( \sigma_{\text{max}} \) and \( \sigma_{\text{min}} \). Figure 9 shows the fatigue life analysis results for the tested specimens. The calculation results shows that stress coefficient is sensitive to assess the fatigue since a small change in the stress factor leads to a significant change in the fatigue life. Thus, quantification of an equivalent stress coefficient is an effective means of assessing the fatigue life of the corroded beams.

![Fig. 9 – Estimated fatigue life of tested beams](image-url)
Effect of corrosion degree on the strength of steel bars after fatigue loading

Fatigue failure of reinforcing steel is caused by microcrack that initiates at stress concentration on the bar surface. The crack gradually propagates as the stress continues to cycle. Sudden fracture occurs when the crack reaches a critical length where its propagation becomes unstable. Crack initiation typically occurs at the location of the largest stress concentration, usually nearby the biggish corrosion pit. Therefore, the fatigue behaviours of steel bar are significantly affected by fatigue load and corrosion, which causes the damage development and accumulation.

Corroded steel bars were obtained from tested beams after fatigue failure. After tests in tension, the typical stress-strain relationship for corroded steel bars was measured. Shown by the test results, the yield strength, the ultimate strength and the ultimate elongation of the steel bars deteriorate and the yield plateau of the steel bar almost disappeared with the development of the corrosion and the increase of the fatigue damage (Fig. 10). The above characteristic values for corroded steel bars after fatigue loading deteriorated more severely comparing to that of corroded steel bars under monotonic load.

Conclusions

This paper presents a series of fatigue tests that were conducted on corroded RC beams strengthened with CFRP sheets. The following conclusions can be drawn from this study:

(i) The beams failed primarily due to fatigue of the steel reinforcement. The failure process was sudden. Signs of severe damage appeared only a few cycles before failure. The fatigue life of the unstrengthened corrosion beam (at medium corrosion level) was only about 29% of the unstrengthened uncorrosion beam, which shows the detrimental effect of steel reinforcement corrosion on fatigue life.

(ii) Although the fatigue life of the CFRP strengthened corroded beams increased within a range of 1.24-1.56 times that of a similar unstrengthened corroded beam, it did not completely restore the strength lost or bring the fatigue life up to the level of the virgin beam due to the corrosion, unless a sufficient number of CFRP sheets are bonded to the beam to reduce the stress in corroded reinforcing bars to the level of that would give the same fatigue life as the virgin beam.

(iii) An analytical procedure was successfully obtained to predict the fatigue life of corroded RC beam strengthened with CFRP sheets.

(iv) The nominal yield strength and ultimate strength of the steel bars deteriorated with increasing of the corrosion degree. The above characteristic values for corroded steel bars after fatigue loading deteriorated more severely comparing to that of corroded steel bars under monotonic load.

Acknowledgments

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References