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# Feasibility of CFRP repair for Slender RC Beams with Corroded Stirrups

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ABSTRACT: This paper presents the results of a study that investigated the feasibility of using bonded Carbon Fiber Reinforcement Polymer (CFRP) U-Jackets for shear rehabilitation of reinforced concrete slender (RC) beams with corroded web reinforcement. A total of nine rectangular RC beams (350 mm deep x 200 mm wide x 2200 mm long) were constructed. The test variables were the diameter of the stirrups, corrosion level (none, severe) and the presence of CFRP repair. The stirrups of six beams were subjected to accelerated corrosion up to 15% mass loss. Following the corrosion phase, three beams were repaired with CFRP U-wraps that were externally bonded with epoxy onto the beam cross section. All beams were tested in third point static loading. The test results showed that the achieved corrosion in the stirrups ranged from 3.68% to 17.2% mass loss. The corroded beams exhibited a reduced shear capacity up to 14% as the corrosion level increased. The CFRP repair was efficient in enhancing the shear capacity of the corroded beams.

## 1 INTRODUCTION

Corrosion of reinforcing steel bars is the number one deterioration mechanism reducing the service life of reinforced concrete (RC) infrastructures (ACI 222, 2010). The alkalinity of concrete is naturally high and thus protects the reinforcing steel bars from corrosion. However, corrosion of the steel reinforcement will initiate as a result of loss of passivity caused by chlorides ingress from de-icing chemicals in Northern climates or sea salts in coastal areas and carbonation of the concrete which leads to a reduction in the alkalinity of the concrete. As corrosion progresses, its product (rust) increases in volume and causes concrete cracking and eventually spalling of the concrete cover, and hence loss of structural bond between the reinforcement and concrete. Additionally, corrosion causes a drop in the steel cross-sectional area which leads to a reduction in its strength. The Federal Highway Administrative (FHWA) reported that 15% of bridges in the US are structurally deficient and that the annual cost of their repair is roughly 8 billion dollars (FHWA, 2002). The high costs associated with the repair of corrosion-damaged concrete promoted researchers to investigate novel repair solutions.

The recent collapse of the de la Concorde overpass in Laval, Quebec, 2006 due to shear failure highlighted the importance of shear reinforcement in concrete structures (Government du Québec, 2007). In a RC member, the stirrups are the outer-most reinforcement and their diameter is much less than that of the longitudinal reinforcement; hence corrosion of stirrups is expected to have a more detrimental effect on the serviceability and ductility of the structure.

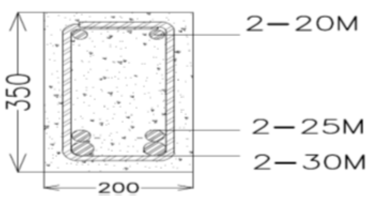
However, little research has been reported on the shear behaviour of RC beams with corroded stirrups. Most of the work simulated the effects of corrosion rather than inducing corrosion in stirrups or used small diameter stirrups (Rodriguez et al. 1997, Regan et al. 2004, Toongoenthong and Maekawa 2004, Higgins and Farrow 2006). Recently, the shear behaviour of deep beams with corroded stirrups was investigated by Suffern (2008) who reported that corrosion of the stirrups had a significant effect on the cracking and shear strength of deep beams and that FRP repair is feasible. The present study is focused on examining the effect of corrosion of shear reinforcement (stirrups) in slender RC beams and the feasibility of FRP repair.

## 2 EXPREMINTAL PROGRAM

A total of nine slender RC beams were constructed. Eight beams were subjected to accelerated corrosion and one beam was kept as control (un-corroded). All the beams were loaded to failure then the corroded beams were repaired with CFRP sheets and re-tested.The RC beams were 200 mm wide by 350 height by 2200 mm long. The beams were categorized based on three variables: 1) stirrup type [D6 (6.35 mm diameter) smooth bars, D12 (12.7 mm diameter) smooth bars and 10M (11.3 mm diameter) deformed bars]; 2) corrosion rate (0% and 15%); and 3) repair availability (un-repaired and CFRP repaired). The test matrix is presented in Table 1. The beams were divided into three group (A, B and C) based on stirrup diameter. Group A, B, and C had their web reinforcement as D6, D12 smooth bars, and 10M deformed rebars, respectively spaced at 200 mm c/c. Groups A, B and C contained three beams with different levels of corrosion in the stirrups (none 0% and severe 15% mass loss with or without CFRP repair).

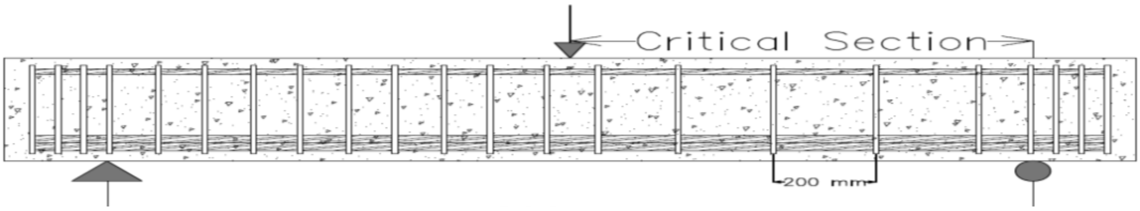
### *2.1 Test specimen*

The beams were designed to fail in shear according to the Canadian Building Code CSA A23.3-2004. All the beams were reinforced in the flexure and shear as shown in Figures 1 and Figure 2 for the control and corroded beams, respectively. . The tension reinforcement consisted of 2-30M (bottom layer) and 2-25M (top layer) reinforcing bars while the compression reinforcement was 2-20M reinforcing bars. Compression steel reinforcement was used to avoid concrete crushing in the compression zone. The web reinforcement was closed stirrups and consisted of 10M – deformed rebar and D12 or D6 smooth bars spaced at 200 mm c/c. The tension and compression reinforcements were epoxy coated bars to avoid their corrosion but the stirrups were not coated with epoxy. The clear concrete cover was 25 mm.




a) beam cross-section

Figure 1 Control beam geometry and reinforcement details




b) Reinforcement layout along the span

Figure 1 Control beam geometry and reinforcement details (cont'd)

### 2.2 Corrosion technique

The accelerated corrosion was conducted by impressing a constant current into the RC beams using an external direct current (DC) power supply. The positive terminal of the power supply was connected to the stirrup to act as anode using an electrical wire. A U-shape stainless steel tube (6.35 mm stainless steel tube) was embedded inside the concrete in between the stirrups acting as an internal cathode as shown in Figure 2. The RC beams were placed in a corrosion chamber on racks and covered by a plastic sheet to maintain high humidity. The corrosion cells (stirrup and stainless steel tube) were connected in series and the current density was kept constant at 250 µA/cm2 (or 250 micro-Ampares/ surface area) for all beams. This corresponds to an applied current based on the surface area of the stirrups of 43 µA, 77 µA and 86 µA for the 6 mm diameter, 10M, and 12 mm diameter closed stirrups, respectively.

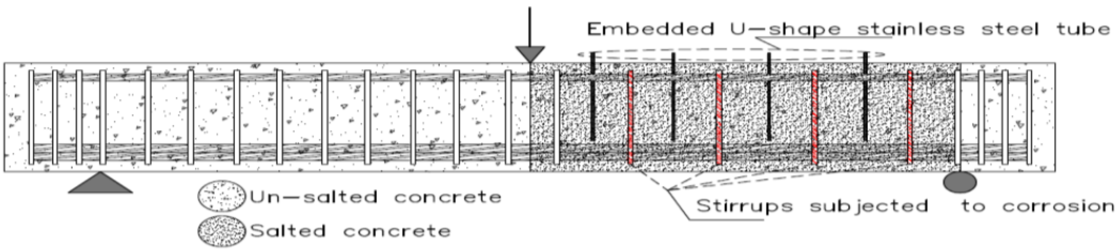



Figure 2 Corroded beam geometry and reinforcement details

### 2.3 CFRP repair

One beam from groups A, B and C that was corroded to a high corrosion level (15% mass loss) was loaded up to 80% of its ultimate load (based on the strength of the un-repaired corroded companion beam). Then, the beam was repaired in shear with U-wrapped CFRP sheets in an intermittent configuration as shown in Figure 3.

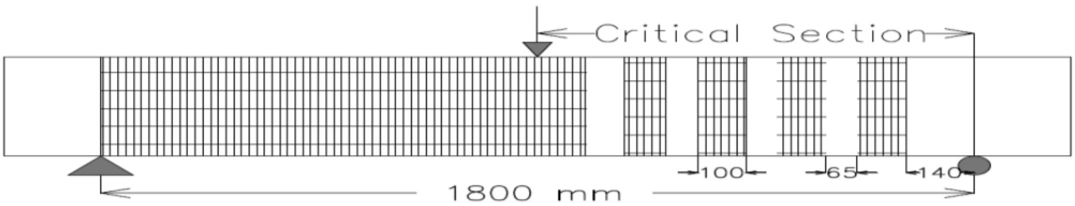



Figure 3 CFRP repair configuration

### 2.4 Load testing

All beams were tested in a three-point bending regime with a simply supported span of 1.8m. Instrumentation included strain gauges mounted on the main steel reinforcement and concrete and LVDTs were used to measure the midspan beam deflection. The beams were loaded to failure at a loading rate of 0.15mm/min. The test was stopped when the load carrying capacity dropped below 25% of the maximum measured load.

## 3 LOAD TEST RESULTS AND DISCUSSION

Table 1 presents a summary of the test results including the average mass loss (for all stirrups in the corroded shear span), concrete strength, experimental ultimate load, predicted ultimate load, and failure modes. Due to differences in concrete compressive strengths of the beams, the measured loads of the beams were normalized based on the lowest concrete compressive strength of 38 MPa by using equation 1.

$$P_{Normalized} = P_{Measured}\sqrt{\frac{38}{f_c'}} \tag{1}$$

Where: $P_{Normalized}$ = Normalized load (kN), $P_{measured}$ = Measured load (kN), $f_c'$ = Concrete compressive strength (MPa)

Table 1 Summary of test results

| Group | Beam No. | Actual mass loss % | f'c (MPa) | Ultimate Load (kN) | | Vexp./Vpred. | Failure Modes |
|---|---|---|---|---|---|---|---|
| | | | | Experimental | Predicted | | |
| A | D6-0%-UR | 0% | 38 | 253 | 252 | 1.01 | SF-DS |
| | D6-15%-UR | 3.68% | 44 | 306 | 242 | 1.24 | SF -DS |
| | D6-15%-R | 4.25% | 44 | 416 | 460 | 0.90 | SF- |
| B | D12-0%-UR | 0% | 38 | 412 | 440 | 0.94 | SF-DS |
| | D12-15%-UR | 15% | 44 | 370 | 378 | 0.98 | SF -SC |
| | D12-15%-R | 16% | 44 | 497 | 596 | 0.83 | DS-DC |
| C | 10M-0%-UR | 0% | 38 | 450 | 448 | 1.01 | SF-SC |
| | 10M-15%-UR | 15.6% | 44 | 385 | 387 | 0.99 | SF-DS |
| | 10M-15%-R | 17.2% | 44 | 443 | 605 | 0.73 | DS-DC |

*D6-0%-UR: stirrups type-theortical corrosion-Un-Repaired, R: repaired, SF: shear failure; DS: Diagonal Splitting, SC: Shear Compression, DF: Debonding of FRP, DC: Delamination of Concrete cover*

It should be noted that the beam nomenclature was revised to include the actual mass loss in brackets. For example, beam D6-15%-UR is renamed as D6-15%-UR (3.68%) to reflect that this beam had 3.68% actual mass loss.

### 3.1 Corrosion and corrosion cracking results

The measured corrosion varied depending on the stirrup diameter. Specimens with D6 stirrups had a maximum corrosion level of 4.25% while specimens with 10M stirrups had a corrosion level of 17.2% (Table 1). All the corroded beams had similar corrosion crack patterns on the concrete surface that were formed due to the expansive pressure of corrosion products from the corrosion-damaged stirrups. The cracks were mainly aligned with the stirrup locations and some cracks were also aligned with the bottom face of the cross-section. The typical crack patterns of the bottom and side faces in acorroded beam at high corrosion level are shown in Figure 4. The maximum crack widths in Group A (D6) 0.3 mm for 3.68% mass loss. In group B (D12), the maximum crack width was 1.5 mm at 15% mass loss. For group C (10M), the maximum crack width was 2.5 mm at 15.6% mass loss. It is evident that corrosion crack widths were significantly reduced for the smaller diameter stirrups possibly because of the lower mass losses achieved for these specimens during the corrosion phase.

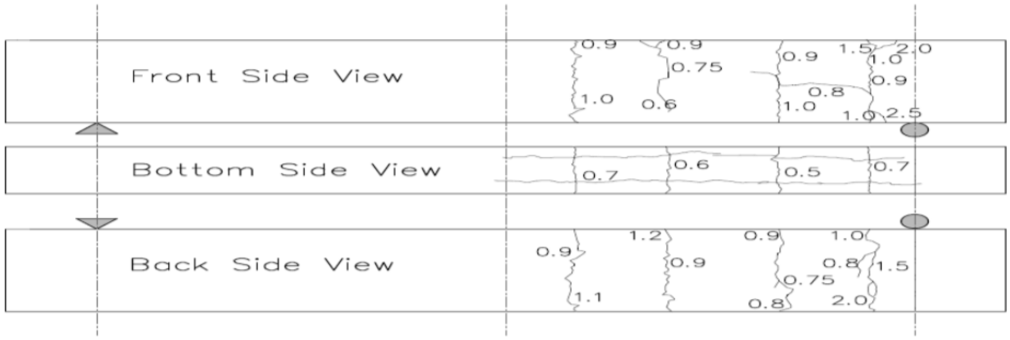
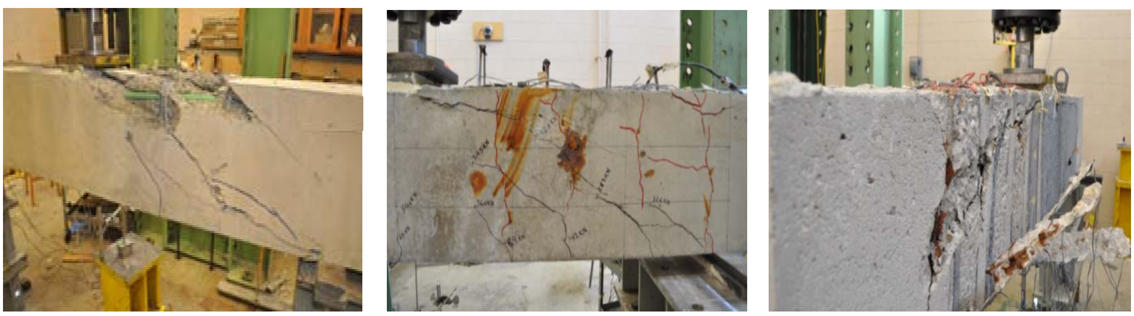



Figure 4 Typical patterns of corrosion cracking (crack width in mm)

### 3.2 *Failure modes*

All the control and corroded beams failed in shear. Initially, flexural cracks were observed at mid-span in the un-repaired beams at different loads based on the corrosion level. The diagonal cracks propagated between the support and the loading point at different loads as presented in Table 1. As the load increased, the diagonal cracks widened and the stirrups started to share in resisting the applied load and consequently the beam lost the aggregate interlock. At ultimate strength, the beams exhibited brittle shear failure. The failure mode was diagonal tension splitting failure in the control and corroded beams except for the control beam of group C which had shear compression failure as shown in Figure 5a,b. The CFRP repaired beams experienced delamination of the concrete cover with diagonal tension failure as seen in Figure 5c.

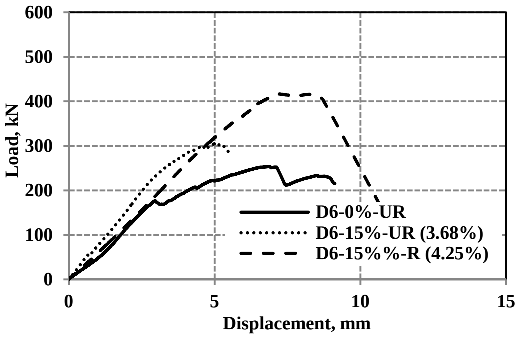


a) 10M-0%-UR　　b) 10M-15%-UR　　c) 10M-15%-R

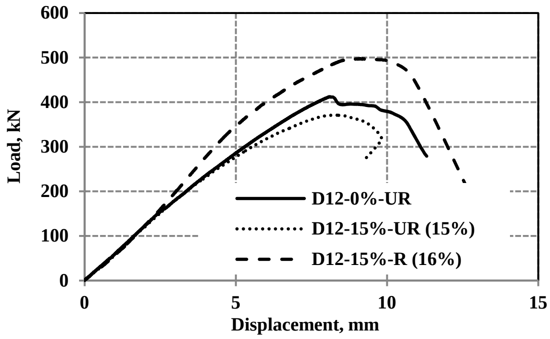
Figure 5 Failure modes of beams in group C

### 3.3 *Effect of corrosion on shear behaviour*

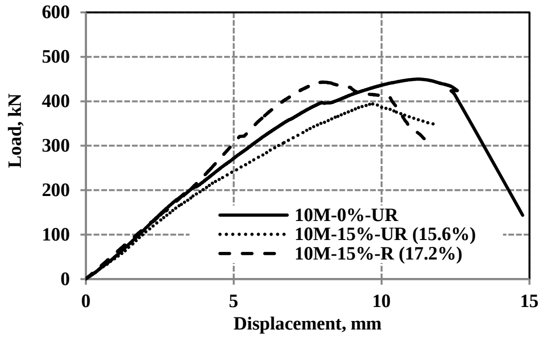
The applied load versus mid-span displacement responses of the beams in all groups are shown in Figures 6a,b,c. The load-displacement plots exhibited a bilinear behaviour and included three distinct stages: diagonal cracking, stirrups yielding and ultimate stages. The beams with smooth stirrups D6-15%-UR (3.68%) (lowest achieved corrosion level) had a 20% increase in the ultimate strength in comparison to the un-corroded beam. This is possibly due to the enchance friction between the stirrups and concrete due to corrosion products at this low corrosion level. In group B, with the highest achieved corrosion level, beam D12-15%-UR (15%) exhibited a reduction in ultimate shear strength of 11% in comparison to the control beam. The corroded beam with deformed stirrups 10M-15%-UR (15.6%) exhibited the highest reduction in ultimate strength of 14.4% in comparison to the control beam. The stiffnesses of the un-repaired and repaired corroded beams were almost identical to that of the control beam within the elastic stage prior diagonal cracking. As the diagonal crack appeared, the stiffness of the un-repaired beams started to decrease after losing the aggregate interlock; however, the CFRP repaired beam exhibited an enhancement in the stiffness up to ultimate strength. The midspan displacement at ultimate load ranged from 7.3 mm (CFRP repaired beam, 10M-15%-R) to 11.3 mm (control beam, 10M-0%-UR); this indicates the brittle nature of CFRP repaired beam in shear versus the control. The displacement at ultimate load decreased as the corrosion level increased.




a) Group A




b) Group B



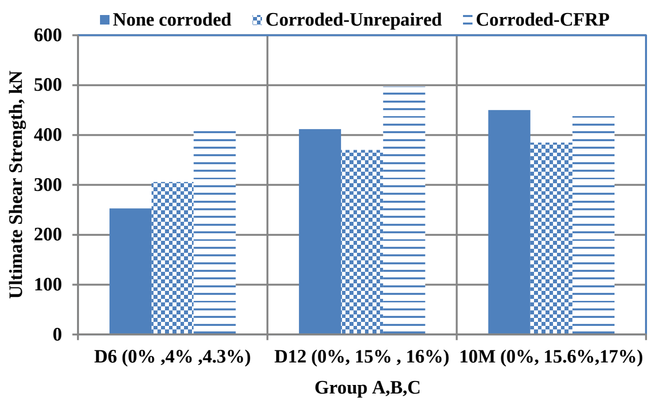

c) Group C

Figure 6 Load-displacement responses of beams in group A, B, C

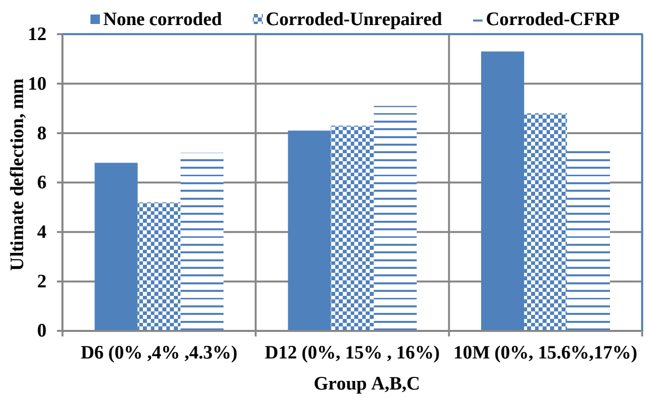
### 3.4 *Effect of CFRP repair*

Figure 7a shows a comparison of shear strengths for the control, unrepaired corroded and CFRP repaired corroded beams in each group. The actual mass loss for each group is shown in between bracket following the stirrups diameter. In group A (6 mm diameter), the CFRP repair restored the ultimate strength of the corroded beam (4.25% actual mass loss) up to 164% and 121% in comparison to the control beam (uncorroded) and corroded beam (3.68% actual mass loss). In group B (D12), the CFRP repaired corroded beam (16% actual mass loss) exhibited a 21% improvement in ultimate shear strength in comparison to the control beam (un-corroded) and a 34% increase in strength in comparison to the unrepaired corroded beam (15% achieved mass loss). In group C (10M), the CFRP repair restored the ultimate strength of the corroded beam (17.2% actual mass loss) up to 98% and 115% in comparison to the control beam (uncorroded) and corroded beam (15.6% actual mass loss).

Figure 7b shows the ultimate deflection for all groups. The CFRP repaired corroded beams with smooth stirrups in group A (D6) and B (D12) exhibited increases in the ultimate deflection in comparison to both the unrepaired control and corroded beams. The deflection increase ranged from 106% to 136%. However, the CFRP repaired corroded beam with deformed stirrups in group C exhibited a reduction of 35% in ultimate deflection in comparison to the unrepaired control beam (Figure 6b). The CFRP repair in group C led to a 17% reduction in the deflection in comparison to the unrepaired corroded beam. This was consistent with the fact that the unrepaired corroded beam exhibited a 22% reduction in deflection in comparison to the control.




a) Ultimate shear strengths of all groups




b) Ultimate deflections of all groups

Figure 7 Effect of CFRP repair on shear strength and deflection

### 3.5 *Predicted Shear Strength*

Table 1 compares the predicted to the measured ultimate loads. The predicted ultimate loads of were calculated using CSA a23.3-04 for the unrepaired beams and ISIS manual no. 4 for the repaired beams. The ratio of experimental to predicted strength ranged from 0.73 to 1.24. The unconservative results, ratio less than 1.0 is possibly due to the assumptions used in accounting for the effects of stirrups corrosion in the equation. These results demonstrate the need for a more refined analysis to account for shear strength of beams with corroded stirrups.

# 4 CONCLUSION

This study investigated the effects of corroded stirrups on the shear strength of RC beams and the feasibility of CFRP repair to restore the shear strength of RC beams due to corroded web reinforcement. Based on the test results, it was shown that corrosion has a moderate effect on the shear strength of beams with corroded stirrups. The reduction in ultimate strength was up to 14% versus the control uncorroded beam. Repair with CFRP sheets was effective to restore the shear strength (and the stiffness) of the corroded beam; the increase in ultimate shear strength ranged between 15% to 64% in comparison to the unrepaired corroded beam.

# 5 ACKNOWLEDGMENT

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