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Abstract

This paper presents experimental data and results on the shear behavior and strength of slender reinforced concrete (RC) beams with corroded steel stirrups. A total of nine RC beams were constructed and tested up to failure. The test beams were 200 mm wide, 350 mm deep, and 2800 mm long. The beams were tested in four-point bending under a simply supported span of 2400 mm. The shear span to depth ratio was kept constant at 3.0 for all beams. Six beams had the embedded stirrups subjected to accelerated corrosion prior to structural testing. The test variables were the corrosion damage level and the stirrup spacing. The test results indicated that the corroded beams exhibited reduced shear strength in comparison to the uncorroded control specimens. The reduction in shear strength was found to increase with the decrease of stirrup spacing.

Keywords: Shear strength, Corrosion, Steel stirrups, Concrete beams.

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Introduction

The deterioration of concrete structures due to corrosion of their steel reinforcement is a serious and pressing problem that requires immediate attention considering its socioeconomic implications. At the time of corrosion cracking, the reduction in the steel cross-sectional area is insignificant (Andrade et al. 1993). Nevertheless, if repairs are not taken at this early stage, the corrosion will continue, leading to concrete delamination and spalling rendering exposed steel reinforcement. This would accelerate the corrosion rate; further reduce the steel cross-sectional area to a level that might cause sudden rupture of the reinforcing steel.

Considerable research has been conducted on the effects of corrosion on the flexural strength of beams and the bond strength between the reinforcing steel and the surrounding concrete. The behavior of reinforced concrete beams with corroded steel in the longitudinal direction indicated that both load-carrying capacity and ductility were decreased (Azad et al. 2007, Du et al. 2007, Almusallam et al. 1996, Cabrera et al. 1996). Bond tests indicated loss of bonding between concrete and steel with increasing section loss of steel bars owing to corrosion (Amleh and Mirza 1999, Stanish et al. 1999). However, limited research has been carried out on the corrosion effects on the shear behavior of reinforced concrete beams (Higgins and Farrow 2006, Suffern et al. 2010). The research work described in this paper is directed to explore the behavior of reinforced concrete slender beams with corroded stirrups. The study focuses on accelerated corrosion damage to stirrups within reinforced concrete beams, visual distress characterization, and shear strength.

Experimental Investigation

The experimental program consisted of shear tests on a total of 9 full-scale reinforced concrete beams. Six beams were subjected to accelerated corrosion and the remaining three beams were not corroded. All beams were provided with adequate longitudinal reinforcement to promote the shear failure before reaching the flexural capacities of the beams. The test variables included the level of corrosion damage of the steel stirrups and the stirrup spacing.

Materials

The beams were constructed using concrete provided by a local ready-mix supplier. The concrete was batched at a water-cement ratio of 0.45 and the maximum coarse aggregate size was 20 mm. During casting the beams with corrosion stirrups, a measured volume of concrete was removed from the concrete transit mixer truck and salted water was mixed into this concrete in an on-site mixer. The amount of salt added was based on requiring 2 % chlorides by mass of cement. The chloride ions have two purposes: to depassivate the steel so that the corrosion process can occur, and to lower the resistivity of the concrete. The salted concrete was placed only within the region around the corroded stirrups in the test span using dividers. The specimens were wet cured for a period of 7 days, and then allowed to dry cure for a period of at least 21 days. After curing, the accelerated corrosion process was started. The 28-day minimum curing time allowed the concrete to achieve the design strength, so that the corrosion-induced cracking would not be influenced by the time varying concrete strength. Deformed steel bars were used in reinforcing the test beams. Steel bars with diameter of 10 and 25 mm were used as top and main tensile reinforcement respectively, while steel bars with diameter of 8 mm were used as stirrups. The yield tensile strength of the reinforcing bars was 480, 530, and 495 MPa for 25, 10, and 8 mm diameter bars, respectively.

Test Specimens

The test specimens were 200 mm wide, 350 mm deep, and 2800 mm long. All beams were reinforced with four 25 mm-diameter deformed steel bars as main tensile reinforcement and two 10 mm-diameter deformed steel bars as top reinforcement. The tensile bars were anchored in the test span using a standard hook to prevent anchorage failure. The steel stirrups were deformed bars having a diameter of 8 mm. One of the shear spans of the beams was allowed to include corroded stirrups while the other shear span included uncorroded stirrups. The stirrup spacing in the test span was variable (100, 150, and 200 mm) whereas the spacing of stirrups in the uncorroded span was kept constant at 100 mm for all beams. The test matrix is given in Table 1 and the reinforcement details and dimensions are shown in Figure 1. The beams were tested under shear span to depth ratio, a/d = 3. The beams included 6 beams with corroded stirrups and 3 beams with uncorroded stirrups. The corroded beams included two levels of corrosion damage with target section losses of 10 and 20%.

Table 1. *Test Matrix*

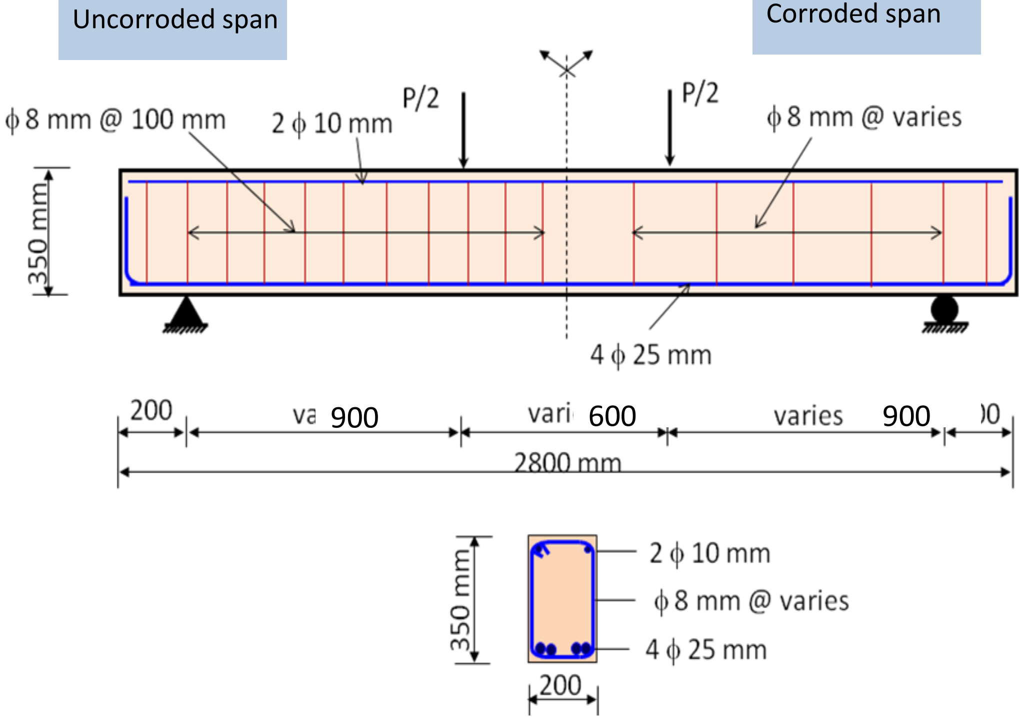
Beam	**Shear span to depth ratio, a/d**	**Stirrup spacing (mm)**	**Target mass loss (%)**
0-200	3	200	0
10-200		200	10
20-200		200	20
0-150		150	0
10-150		150	10
20-150		150	20
0-100		100	0
10-100		100	10
20-100		100	20

Accelerated Corrosion of Stirrups

For the corroded stirrups, an electrical connection had to be made between the stirrups and power supply. A steel bar was welded to the stirrup and extended outside the specimen to complete the electrical connection, as shown in Figure 2. The ties used to attach the corrosion stirrups were wrapped in electrical tape to prevent an electrical connection with the longitudinal reinforcement. Also, the longitudinal reinforcement was covered with electrical tape at the stirrups location. The longitudinal steel bars were epoxy-coated to preclude corrosion of these elements. A 10 mm diameter stainless steel tube was bent into a U shape and embedded within the concrete around the corroded stirrup to serve as a cathode.

After curing, specimens were subjected to accelerated corrosion. The accelerated corrosion was conducted by impressing a constant current into the concrete beam specimens using an external direct current (DC) power supply. The DC power supply can apply a maximum current of 500 mA with an accuracy of 1%. The steel stirrups were connected to the positive terminal of the power supply to act as an anode. This occurred through the steel bar welded to the stirrup and extended outside the specimen. The U shape stainless steel tube was connected to the negative terminal of the power supply to act as a cathode. For the purpose of an accelerated corrosion, a current density of 0.4 mA/cm^2 was applied through the stirrups using the DC power supply. Faraday’s Law was taken as guidance for determining the amount of time to produce the corrosion damage. A compressed air mist nozzle was used to spray mist over the test specimens to facilitate the corrosion reaction. Figure 3 shows the wiring schematic and Figure 4 illustrates the corrosion setup.

Figure 1. *Typical Beam Reinforcement and Dimensions*



Test Setup

After completion of the accelerated corrosion process, the beams were tested up to failure. The beams were tested in four-point bending over a simply-supported clear span of 2400 mm, as shown in Figure 1. Each tested beam was loaded directly on the top compressive face with two concentrated loads and supported at the bottom. The beams were tested using Instron Machine with a capacity of 500 kN.

During testing, load was monotonically applied at a stroke-controlled rate of 1.0 mm/min and the formation of the cracks on the sides of the beams were also marked and recorded. The applied load, displacements, and strain readings were electronically recorded during the test using a data acquisition system.

Figure 2. *Stirrup Electrical Connection*

Figure 3. *Wiring System*

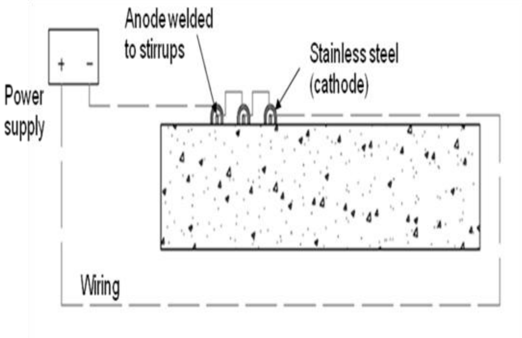


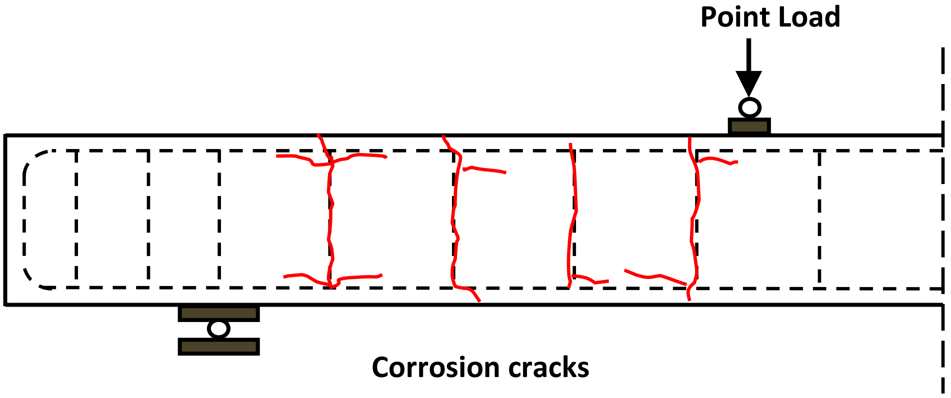
Figure 4. *Accelerated Corrosion Setup*

Test Results and Discussion

Accelerated Corrosion Results

During the accelerated corrosion process, all corroded beams showed corrosion cracks and rust staining. The cracks produced from corrosion were traced and recorded. The cracks were primarily vertical at the locations of the vertical stirrups. Secondary longitudinal cracks propagated at or near the location of the longitudinal steel, even though the longitudinal steel was not corroding. A typical corrosion crack pattern is schematically shown in Figure 5.

Figure 5. *Typical Corrosion Crack Pattern*



The crack widths were measured manually using a hand-held 50X microscope with a sensitivity of 0.02 mm. The measurements were taken after the accelerated corrosion phase was completed and prior to structural testing. Table 2 summarizes the maximum and average crack width for each beam. It can be noticed that the cracks became wider in beams with higher mass loss. For beams with target mass loss of 10%, the maximum crack width ranged between 0.1 and 0.2 mm compared to 0.24 and 0.42 mm for beams with target mass loss of 20%. Similar observation can be noted when the average crack width in Table 2 are compared. This correlation between width of corrosion crack and section mass loss of stirrups reflects the possibility of the corrosion cracks to serve as a measure of the damage extent caused by corrosion. For corrosion-damaged members in real structures, the corrosion crack width is easier to be measured in comparison to mass loss determination.

In addition to the visual inspection of corrosion damage and crack width measurements, the actual mass loss of the corroded stirrups was determined. After structural testing, corroded stirrups were removed from the beam to determine the amount of section mass loss. The mass loss for each beam was determined based on the average mass loss for the shear reinforcement in the failure region. Table 2 gives the average mass loss for each beam. It can be noted that beams of target mass loss of 10% showed actual mass loss in the range of 7.2 to 10.3% while actual mass loss in the range of 16.8 to 18% was showed for beams of 20% target mass loss.

Table 2. *Corrosion Crack Width and Mass Loss*

Beam	Maximum crack width (mm)	Average crack width (mm)	Average mass loss (%)
10-200	0.10	0.08	7.2
20-200	0.24	0.13	17.0
10-150	0.20	0.10	10.3
20-150	0.40	0.30	16.8
10-100	0.14	0.08	9.0
20-100	0.42	0.28	18.0

Shear Strength

A summary of the beam test results is presented in Table 3. The table gives the actual compressive concrete strength, the measured load at ultimate, the ultimate strength reduction due to corrosion of stirrups, and the failure mode.

The failure modes of the nine beams are given in the last column of Table 3. Two failure modes were obtained: shear-compression failure or rupture of stirrups. The shear-compression failure is characterized by crushing of the concrete above the upper end of the inclined crack. The control beams with uncorroded stirrups in addition to beam 10-100 with closely spaced corroded stirrups (100 mm spacing) failed in shear compression. All other corroded beams failed by rupture of stirrups. Rupture of stirrups occurred due to the reduction in cross-sectional area of the bars caused by corrosion.

Table 3. *Summary of Beam Test Results*

Beam	f_c' (MPa)	Ultimate load (kN)	Ultimate shear strength $V_{u,\,exp}$ (kN)	Normalized shear strength $\frac{V_{u,exp}}{bd\sqrt{f_c'}}$	Reduction in normalized shear strength (%)	Failure mode*
0-200	35.1	284	142	0.39	--	SC
10-200	34.9	314	157	0.43	--	SR
20-200	40.7	272	136	0.35	11	SR
0-150	28.4	332	166	0.51	--	SC
10-150	34.6	332	166	0.46	9	SR
20-150	40.9	346	173	0.44	13	SR
0-100	36.9	388	194	0.52	--	SC
10-100	44.4	408	204	0.50	4	SC
20-100	44.0	345	172.5	0.42	19	SR

* SC = shear compression; SR = stirrup rupture.

Due to the variation in concrete strength, the shear strength of the beams was normalized with respect to the square root of compressive concrete strength and the width (b) and depth of the beams (d). The corroded beams showed degradation in ultimate shear strength when compared with that of uncorroded control beams. Table 3 provides a measure of this degradation in terms of the reduction in normalized shear strength of the corroded beams. The reduction in shear capacity of the corroded beams ranged from 4 to 19%. In slender members, a substantial part of the shear strength is provided by the stirrups. Corrosion of stirrups leads to reduction in the cross sectional area of the stirrups reducing their contribution to the shear strength of the beams. In addition, corrosion of stirrups results in cracking and delamination of the side concrete cover reducing the effective width of the beam. The reduction in the effective width of the beam results in reduction in the concrete contribution to the shear strength of the beams. All of these effects resulted from corrosion contributed to reduce the overall shear capacity of the beams with corroded stirrups.

The variation of the reduction in normalized shear capacity was plotted against the degree of corrosion in terms of average mass loss as presented in Figure 6. The figure indicates that more corrosion damage in the stirrups causes more reduction in shear capacity of the beams. The effect of the stirrup spacing on the reduction in shear capacity is presented in Figure 7. The general trend in the figure indicates that the reduction in shear strength became larger for beams with closely spaced stirrups. This result may be expected because more corrosion cracks were developed in such beams in comparison with beams of wider stirrup spacing.

Figure 6. *Variation of Reduction in Shear Capacity with Average Mass Loss*

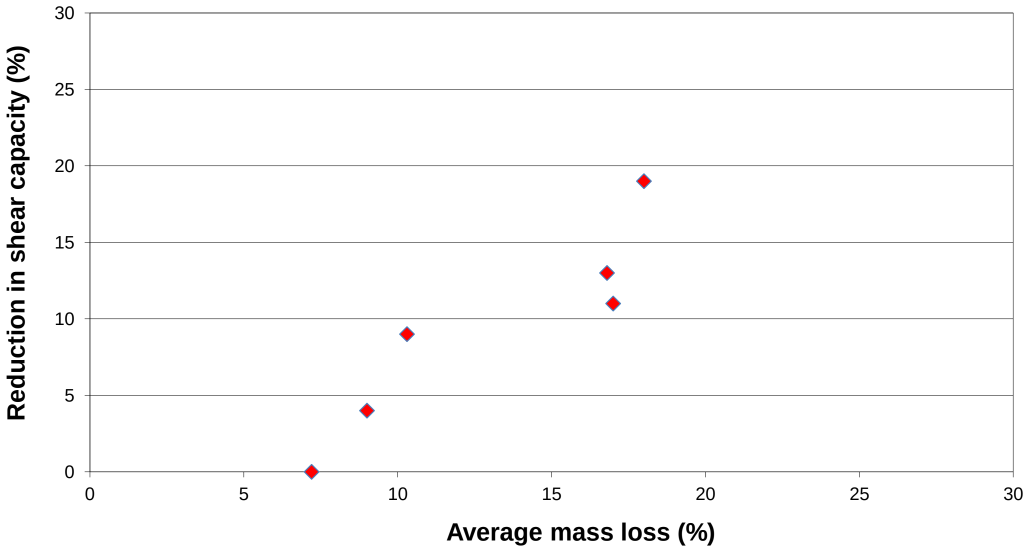
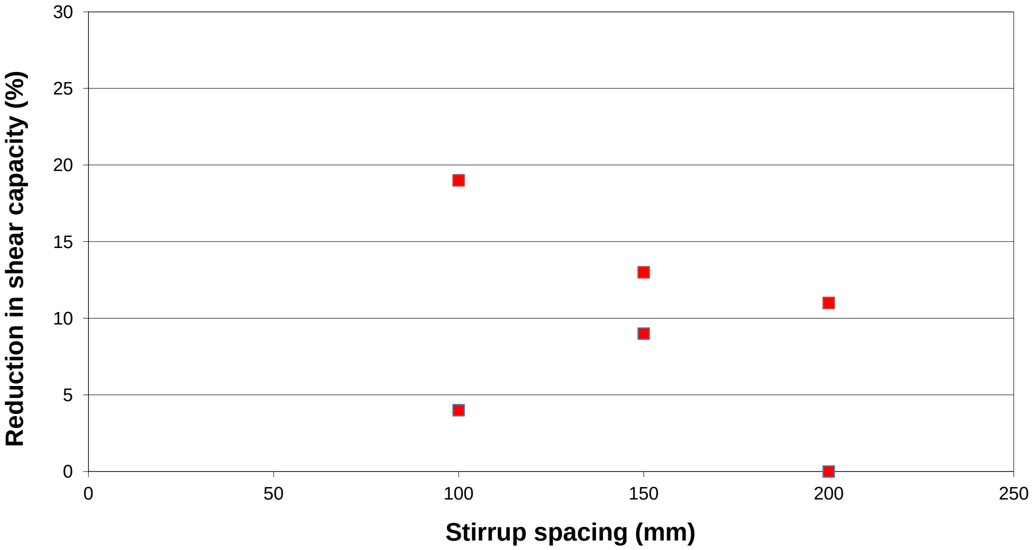


Figure 7. *Variation of Reduction in Shear Capacity with Stirrup Spacing*



Conclusions

A total of 9 full-scale reinforced concrete beams were constructed and tested up to failure. Six beams included embedded steel stirrups subjected to accelerated corrosion prior to structural testing, while three beams were uncorroded serving as a reference. All beams were tested in four-point bending under shear span to depth ratio of 3. The test variables were the corrosion level and the stirrup spacing. Based on the obtained test results, the following conclusions can be drawn:

- Corroded beams showed degradation and reduction in shear strength compared to uncorroded beams. This degradation increased as the corrosion level increased.
- Unlike the control beams, all corroded beams failed by rupture of stirrups due to corrosion except the beam with closely spaced stirrups.
- The reduction in shear strength due to corrosion of stirrups appeared to increase with the decrease in stirrup spacing.

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