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Load carrying capacity of RC beams with locally corroded shear reinforcement

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Abstract: Much research has been carried out on the effect of corrosion of longitudinal reinforcement on structural performance of reinforced concrete beams. However, transverse reinforcement (stirrups) has not been given much consideration, and there is not much literature available on the effects of corrosion of stirrups. In this study, detailed research has been conducted to observe the behavior of reinforced concrete beams with corroded stirrups only. Seven beams of 1,800-mm length, 100-mm width, and 150-mm height were prepared, and corrosion of stirrups was accelerated by applying direct current. The stirrups were corroded in the shear span, the middle span, or the full span at two levels, i.e., mild and severe corrosion. After the target corrosion level was achieved, corrosion cracks were marked and measured, and then a four-point load was applied to investigate the flexural behavior of the beams. After the test, the distribution and width of flexural cracks were also measured and marked. Finally, the stirrups were taken out to quantify the weight loss. Reduction in flexural capacity was observed in all the beams, but the maximum deflection varied for each beam. The failure mode did not change, and all the beams failed in flexure, both before and after corrosion.

Keywords: corrosion, stirrups, corrosion cracks, flexural cracks, flexural capacity, ductility.

1. Introduction

Numerous studies in the past have shown that corrosion of reinforcing steel adversely affects the mechanical behavior of RC structural members [1, 2]. According to these studies, structural performance of the RC beam decreases with an increase in corrosion level. Corrosion causes expansion of the reinforcing steel, which exerts pressure on the surrounding concrete, and cracks start occurring on the concrete surface. This cracking results in delamination and subsequent spalling of cover concrete. This phenomenon increases with higher levels of corrosion. Research on these cracks is very important to assess the durability and service life of RC structures [3-5]. As the corrosion process continues, the steel cross-sectional area begins to decrease resulting in loss of nominal strength and elongation. The bond strength between concrete and steel also decreases due to corrosion, which has a considerable contribution to the reduction of ultimate strength and maximum deflection [4].

Many previous research examined the behavior of RC beams when the main longitudinal reinforcement and transverse (shear) reinforcement are corroded simultaneously. There are considerable losses of ultimate strength and maximum deflection when both reinforcement types are corroded at the same time [5]. The failure mode may also change because of corrosion and ductility loss [5]. However, there is not much literature available that focuses only on the corrosion of shear reinforcement. When the shear reinforcement (stirrup) is corroded, there will be a reduction in cross section, along with some volumetric changes and spalling of concrete cover. These losses can lead to diagonal tension failure or shear failure, which may cause brittleness and sudden failure in the beam [6]. Although stirrups in the middle span do not have much contribution towards the flexural strength, the corrosion of stirrups will affect the flexural strength and ductility of the RC beams. Corrosion of stirrups will produce corrosion cracks, which may then act as the predefined failure paths for the flexural cracks to follow in the loading test. However, the effect of stirrups corrosion only in the shear span is also important, as the failure mode can be changed from flexural to shear failure. The ductility of RC beams

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relies on longitudinal reinforcement elongation and good flexure control design, but, with the corrosion of shear reinforcement, it can be changed to undesirable diagonal tension and sudden failure. The corrosion of shear reinforcement aggravates localized failure, which is more dangerous, as it is difficult to predict and control.

In this paper, a detailed research program is undertaken to study the effect of corrosion of stirrups on the structural capacity of RC beams. The main longitudinal bars were epoxy coated to avoid corrosion. Seven beams of 1,800 mm length, 100 mm width, and 150 mm height were prepared using normal concrete, and corrosion of only stirrups was accelerated by applying direct current. The stirrups were corroded in the shear span, the middle span, or the full span, and at two corrosion levels, such as mild corrosion (approximately 10% weight loss on average) and severe corrosion (approximately 20% weight loss). The corrosion cracks formation after the stirrup corrosion, and the flexural behavior of the corroded RC beams were then investigated and compared with the control beam.

2. Experimental procedure

2.1 Materials

Seven beams were cast using concrete with a compressive strength of 32 MPa and a water-to-cement ratio (*w/c*) of 0.52. Deformed steel bar of 13 mm in diameter, with a yield strength (f_y) of 395 MPa, was used as longitudinal reinforcement after coating with epoxy to avoid corrosion. For stirrups, deformed steel bar of 6 mm in diameter with f_y = 395 MPa was used.

2.2 Specimen preparation

A wire was connected at the top of the stirrups using soldering to facilitate current for corrosion. All the stirrups were weighed after attaching wire with soldering. Steel cage was prepared with 120 mm spacing of stirrups and 30 mm concrete cover. A sponge was placed at the bottom of beam and then wrapped with three towels all around after curing for the purpose of keeping the target area of the beam wet. Figure 1 shows the beam layout and cross sectional view.

2.3 Corrosion process

After 14 days of curing, the beams were subjected to direct current to induce corrosion. After preparing the beams, they were placed in a pool with 3% NaCl solution. The height of solution was up to the sponge level. Accelerated current technique was applied for corrosion. A current of 2.6 mA/cm^2 was passed for 7 days and 14 days for mild and severe corrosion, respectively [7].

Corrosion was done in two series (referring to mild and severe corrosion) with each series comprising three beams. Each series consists of corrosion of stirrups only in the shear span, the middle span, or the full span. The stirrups corrosion in shear span was allowed in only one shear span, whereas middle span is defined as the central span between the two point loads where the shear force is zero and the bending moment is the maximum value. Table 1 lists the test variables and Fig. 2 shows the corrosion process. The beams are named as B Number-corrosion level (MC/SC) -location of corrosion (FS/MS/SS): for example, B9-MC-MS is the beam no. 9, which is mildly corroded in the middle span.

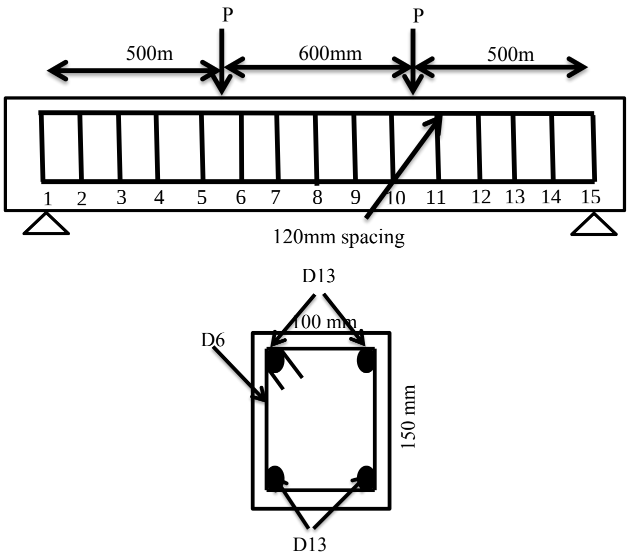


Fig. 1 – Beam layout and cross sectional view

Table 1 – Beam test variables

Beam index	Corrosion level	Corrosion location
B2-STD	Standard beam	No corrosion
B3-MC-FS	Mild corrosion (10%)	Full span
B4-SC-FS	Severe corrosion (20%)	Full span
B7-MC-SS	Mild corrosion (10%)	Shear span
B8-SC-SS	Severe corrosion (20%)	Shear span
B9-MC-MS	Mild corrosion (10%)	Middle span
B10-SC-MS	Severe corrosion (20%)	Middle span

2.4 Beam testing

Corrosion cracks distribution and their widths were marked and measured after corrosion, and then a four-point load was applied to observe the ultimate load carrying capacity of the beams. After the beams failed, the flexural cracks distribution and their widths were also checked and compared. Finally, the stirrups were taken out to measure

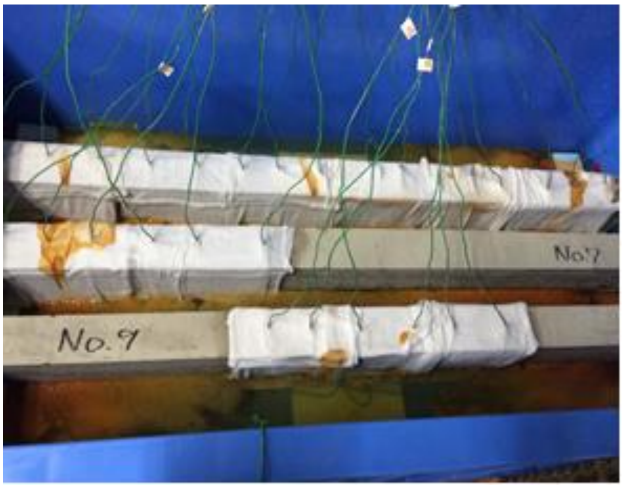


Fig. 2 – Corrosion process for beams

weight loss. All the stirrups were weighed after cleaning with acid solution to ensure that all corrosion products were washed away.

3. Results and discussions

3.1 Weight loss

Figure 3 shows the weight loss of mild corrosion case for B3-MC-FS, B7-MC-SS, and B9-MC-MS with respect to the location of the corroded stirrups. For the mild corrosion, the maximum weight loss was 30.5% and observed in B7-MC-SS (stirrups corroded in the shear span only). The minimum weight loss of 3.2% was also observed in this beam, and the average weight loss for all the stirrups of B7-MC-SS was 10.5%. B9-MC-MS (stirrups corroded in the middle span) had a slightly higher weight loss, with an average of 11.6% for all the stirrups. The maximum and minimum weight losses for B9-MC-MS were 14.7% and 9.4%, respectively. The average weight loss for the 15 stirrups of B3-MC-FS was 7.2%, with the maximum and minimum values as 10.4% and 3.7%, respectively with little variation in weight loss among the stirrups.

Figure 4 shows the weight loss of stirrups and location for B4-SC-FS, B8-SC-SS, and B10-SC-MS. For the severely corroded beams, the expected weight loss was 20%, but actually slightly less corrosion was observed for most of the stirrups. The maximum and minimum weight losses measured in B4-SC-FS (stirrups corroded in the full span) were 42.2% and 4%, respectively, with the average weight loss of 16.7%. This wide range of the differences shows the change in resistance of concrete. As in the case of the mild corrosion, the stirrups corroded in the middle span had the maximum average weight loss for the severe corrosion. B10-SC-MS (stirrups corroded in the middle span) had average weight loss of 17.6%, with extreme values of 29.7% and 13.7%. For B8-SC-SS (stirrups corroded in the shear span), the average percentage of weight loss was 14.4%, with extremes of 23.5% and 8.8%.

The weight loss of a stirrup depends on the amount of current passed through it. Different amounts of current passed through all the stirrups, as the resistance was different for each of them. The resistance depends on the pore size distribution and non-homogeneity of concrete, so different amounts of current resulted in different percentages of weight loss, which also more or less resembles the natural conditions because corrosion is not uniform throughout a member.

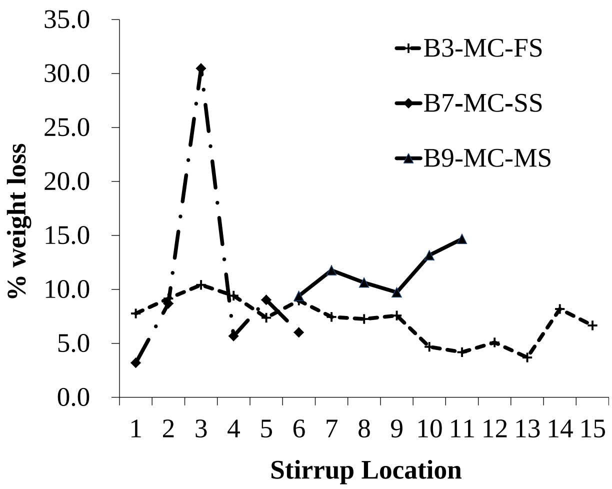


Fig. 3 – Weight loss of stirrups for mild corrosion

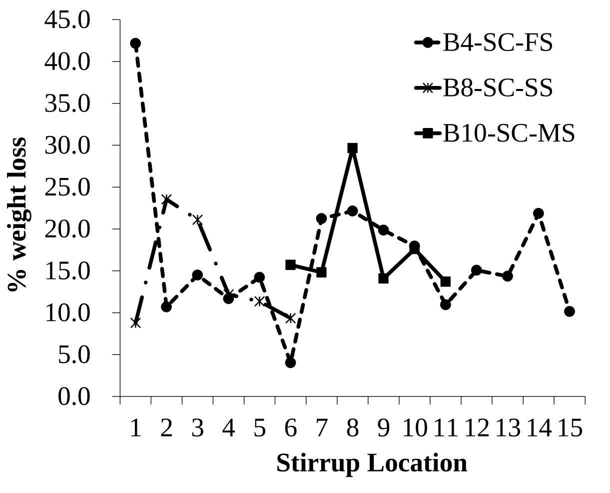


Fig. 4 – Weight loss of stirrups for severe corrosion

3.2 Corrosion cracks

It was found that the number of corrosion cracks was almost the same despite having different levels of corrosions (mild and severe). Table 2 summarizes the frequency of corrosion crack width ranges for all the beams. For example, 55 cracks appeared in B3-MC-FS, which was corroded in the full span with 10% weight loss (mild level), as compared to 62 cracks for B4-SC-FS, which was also corroded in the full span, but with 20% weight loss (severe corrosion). Similarly B7-MC-SS

Table 2 – Frequency of corrosion crack widths for mild and severe corrosion

Crack widths (mm)	B3-MC-FS	B4-SC-FS	B7-MC-SS	B8-SC-SS	B9-MC-MS	B10-SC-MS
0.03 ≤ crack width < 0.06	8	26	4	12	3	12
0.06 ≤ crack width < 0.1	7	20	5	11	0	12
0.1 ≤ crack width < 0.3	37	9	20	8	23	3
0.3 ≤ crack width < 0.6	3	5	3	2	7	0
0.6 ≤ crack width < 1.0	0	2	1	0	0	0
Total	55	62	33	33	33	27

(mildly corroded in the shear span) and B8-SC-SS (severely corroded in the shear span) were both observed to have 33 cracks each.

Figure 5 shows the frequency of corrosion cracks for the mild corrosion. For 10% weight loss (mild corrosion), the maximum number of cracks remained was in the range of 0.1-0.29 mm width. B3-MC-FS had the maximum number of cracks (37) in the range of 0.1-0.29 mm. This is because the stirrups were corroded in the full span, so the length across which corrosion cracks appeared was greater. For B7-MC-SS (shear span corrosion) and B9-MC-MS (middle span corrosion), the number of cracks was the same (33) with a slight change in the frequency of crack widths. Only B7-MC-SS had one crack in the range of 0.6-0.99 mm width, and there were no cracks smaller than 0.03 mm.

sion (10% weight loss). In all the beams with severe corrosion, the maximum cracks were in the range of 0.03-0.059 mm width. For the crack range of 0.06-0.099 mm, B8-SC-SS (shear span corrosion) and B10-SC-MS (middle span corrosion) had almost the same number of cracks, 11 and 12, respectively, but for B4-SC-FS, the corrosion cracks decreased for the wider crack width ranges starting from 0.06-0.99 mm. The cracks were spread across all the crack width ranges, but as the crack width increased, the number of cracks decreased. Cracks were found on all four sides of beams where the stirrups are corroded. Figure 7 shows the corrosion crack widths and distributions on the front and back side surfaces of the corroded beams.

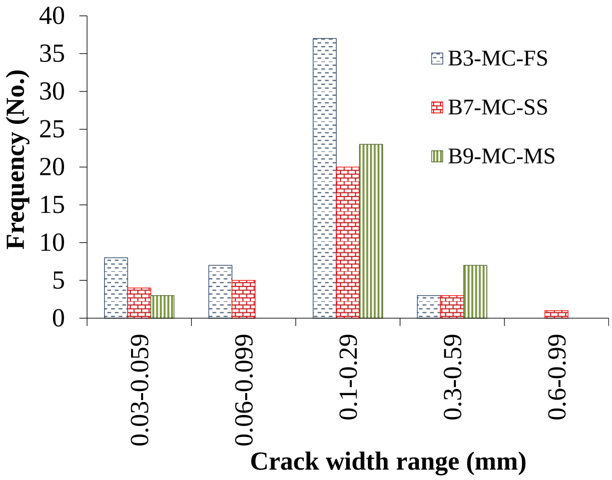


Fig. 5 – Corrosion crack width frequencies for mild corrosion

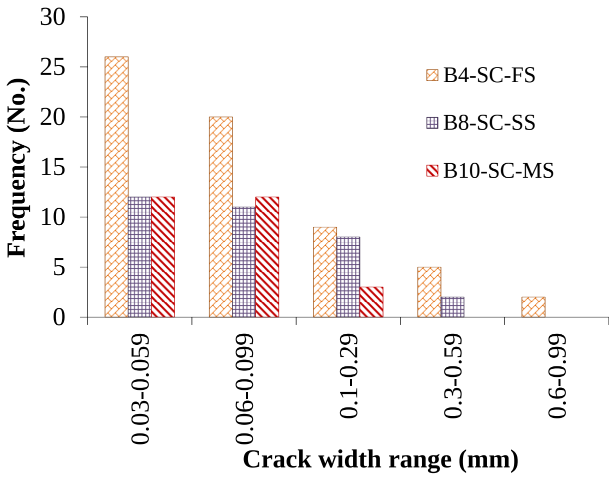


Fig. 6 – Corrosion crack width frequencies for severe corrosion

Figure 6 shows the frequency of corrosion cracks for severe corrosion. For the severe corrosion (20% weight loss) micro cracking formation was observed. The number of cracks was more for smaller crack widths, unlike the case of mild corro

As discussed previously, the amount of current passed from each stirrup was not the same and it was also inconsistent. This resulted in weight loss variations, as well as corrosion cracks formation. The current was inconsistent because the resistance

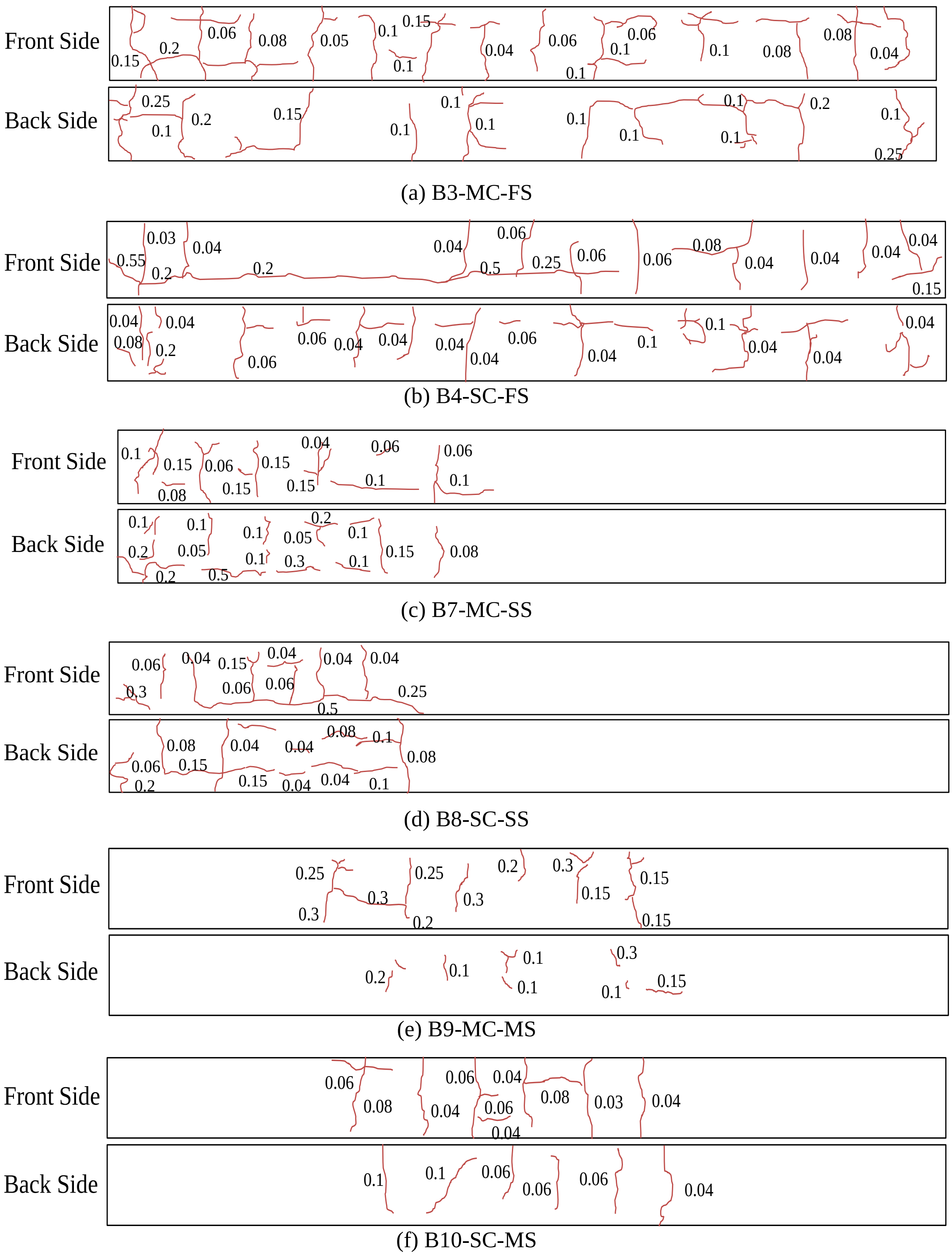


Fig. 7 – Corrosion crack widths and distributions of corroded beams

of concrete and electrolyte composition changes with the application of current with time. The resistance of concrete depends on the quality of concrete such as porosity, pore size distribution, corrosion crack width and distribution. However, the total amount of current supplied was constant as it was a controlled supply from DC convertor.

3.3 Flexural cracks

The number of flexural cracks was greater for the mild corrosion, and fell across almost all crack width ranges. Table 3 lists the frequency of flexural crack width ranges for all the cases. In the full span (B3-MC-FS) and the shear span (B7-MC-SS) with mild corrosion, the maximum number of cracks was in the range of 0.3-0.59 mm wide, with 14 and 18, respectively.

Table 3 – Frequency of flexural crack widths for mild and severe corrosion

Crack widths (mm)	B3-MC-FS	B4-SC-FS	B7-MC-SS	B8-SC-SS	B9-MC-MS	B10-SC-MS
0.03 ≤ crack width < 0.06	0	4	3	4	0	0
0.06 ≤ crack width < 0.1	0	5	4	4	3	2
0.1 ≤ crack width < 0.3	10	12	15	13	21	9
0.3 ≤ crack width < 0.6	14	6	18	9	19	7
0.6 ≤ crack width < 1.0	9	4	10	7	11	3
1.0 ≤ crack width < 3.0	9	2	3	9	6	4
3.0 ≤ crack width < 6.0	7	0	1	3	2	3
6.0 ≤ crack width < 9.0	1	0	0	2	3	0
9.0 ≤ crack width	1	0	1	2	4	0
Total	51	33	55	53	69	28

For the middle span mild corrosion B9-MC-MS, the maximum number of cracks was in the range of 0.1-0.29 mm width with 21 cracks. The beams were designed to fail in flexure before corrosion. After corrosion, the beams also failed in flexure because the degree of corrosion in the stirrups was not too high, and the concrete shear capacity was not reduced much. In case of B9-MC-MS, corrosion occurred in the middle span, and the failure mode was also flexure. The corrosion cracks started to widen up in the four-point loading test. After the application of further load, new cracks also started to occur and, because of this cracking, the maximum cracks fell in the range of 0.1-0.29 mm width. The maximum number of cracks (69) was also found in B9-MC-MS. Figure 8 explains the frequency of flexural cracks for mild corrosion.

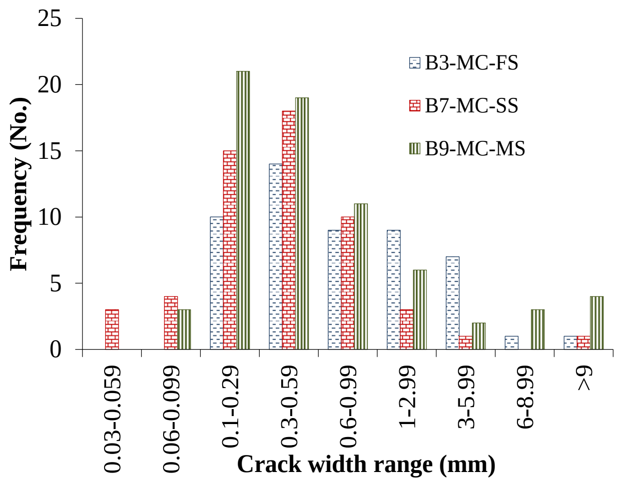


Fig. 8 – Flexural crack width frequencies for mild corrosion

The number of cracks for the severe corrosion cases was much less than those of the mild corrosion for the full span and middle span corrosion. However, the beam with severely corroded stirrups in the shear span had almost the same number of cracks as the mild corrosion. This is because the corrosion cracks were initiated in the shear span, but failure occurred in the middle span. The corrosion cracks in the shear span had no contribution to the flexural cracks because the locations of these cracks were different.

The maximum number of cracks for B4-SC-FS and B10-SC-MS were 33 and 28, respectively. When compared with the number of cracks for B3-MC-FS (51) and B9-MC-MS (69), it was observed that, with a greater degree of degradation, the number of flexural cracks became less. In case of corrosion cracks, the crack width for the maximum number of cracks was less than for the higher degree of degradation. The maximum number of cracks for the severe corrosion was in the range of 0.1-0.29 mm width for all three cases. The maximum number of cracks in the range of 0.1-0.29 mm width for B4-SC-FS was 12, as compared to 13 for B8-SC-SS and 9 for B10-SC-MS. In B10-SC-MS, the cracks already existed because of corrosion, which could be the cause for smaller number of cracks. For B4-SC-FS, there was no crack wider than 3 mm, and, for B10-SC-MS, no crack wider than 6 mm, as compared with beams with mild corrosion B3-MC-FS and B9-MC-MS. However, B8-SC-SS (shear span severe corrosion) did not follow the pattern of B4-SC-FS and B10-SC-MS, which was also severely corroded. This was because the cracks, or degradation, were in the shear span, but the loading cracks were in the middle span. The loading cracks had no relation with the corrosion cracks in this case. Figure 9 shows the frequency of flexural cracks for mild corrosion, while Fig. 10 shows the flexural cracks width and distribution on both side surfaces of the corroded beams.

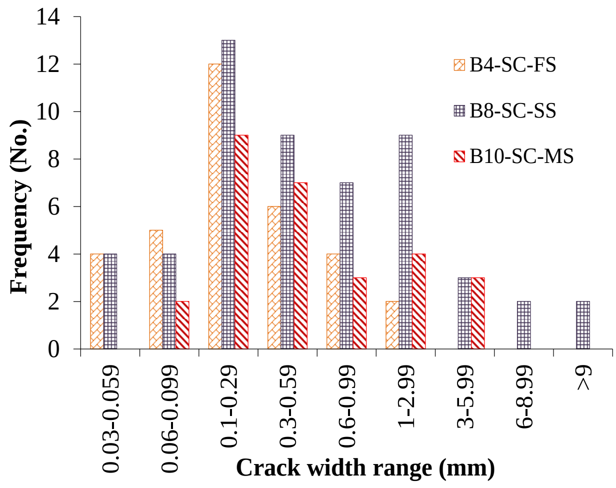


Fig. 9 – Flexural crack width frequencies for severe corrosion

3.4 Measured flexural strength and deflection

Figures 11 and 12 show the results of the loading test and deflections for the mild and severe corrosion, respectively. B2-STD had no corrosion as it was the control beam. It followed typical behavior of the reinforced concrete beam with an ultimate load of 39.53 kN and maximum deflection of 21.96 mm. All the other beams with corrosion had less flexural capacity, and the maximum deflections of all beams were different. The design failure mode of all the beams was flexure, and after corrosion, they still had flexural failure. The expected corrosion did not affect the failure type, although it was likely to be shear failure as the stirrups were corroded.

For mild corrosion (10% weight loss) the least flexural capacity was observed in B9-MC-MS, in which corrosion of stirrups were done in the middle span. The flexural capacity was 32.37 kN, with a 18.11% reduction from the control beam, and the maximum deflection was 14.90 mm, with a 32.14% reduction. The corrosion cracks and failure cracks occurred in the middle span of the beam. B7-MC-SS (stirrups corroded in the shear span) somewhat followed the same behavior as the control beam B2-STD, with the least reduction in load carrying capacity. The ultimate load capacity was 37.03 kN, with just a 6.32% reduction, and the maximum deflection of 21.89 mm was almost the same as that of the control beam B2-STD. B3-MC-FS also followed the same behavior in the beginning but, after the peak load of 36.49 kN, the behavior changed. The reduction in flexural capacity was 7.69%; however, instead of decreased maximum deflection, it increased. The maximum deflection was 31.21 mm, with an increase of 42.12% compared to the control beam B2-STD. This increase in maximum deflection was not expected, and the maximum deflection was considered to be less than the control beam as the stirrups were corroded in the full span.

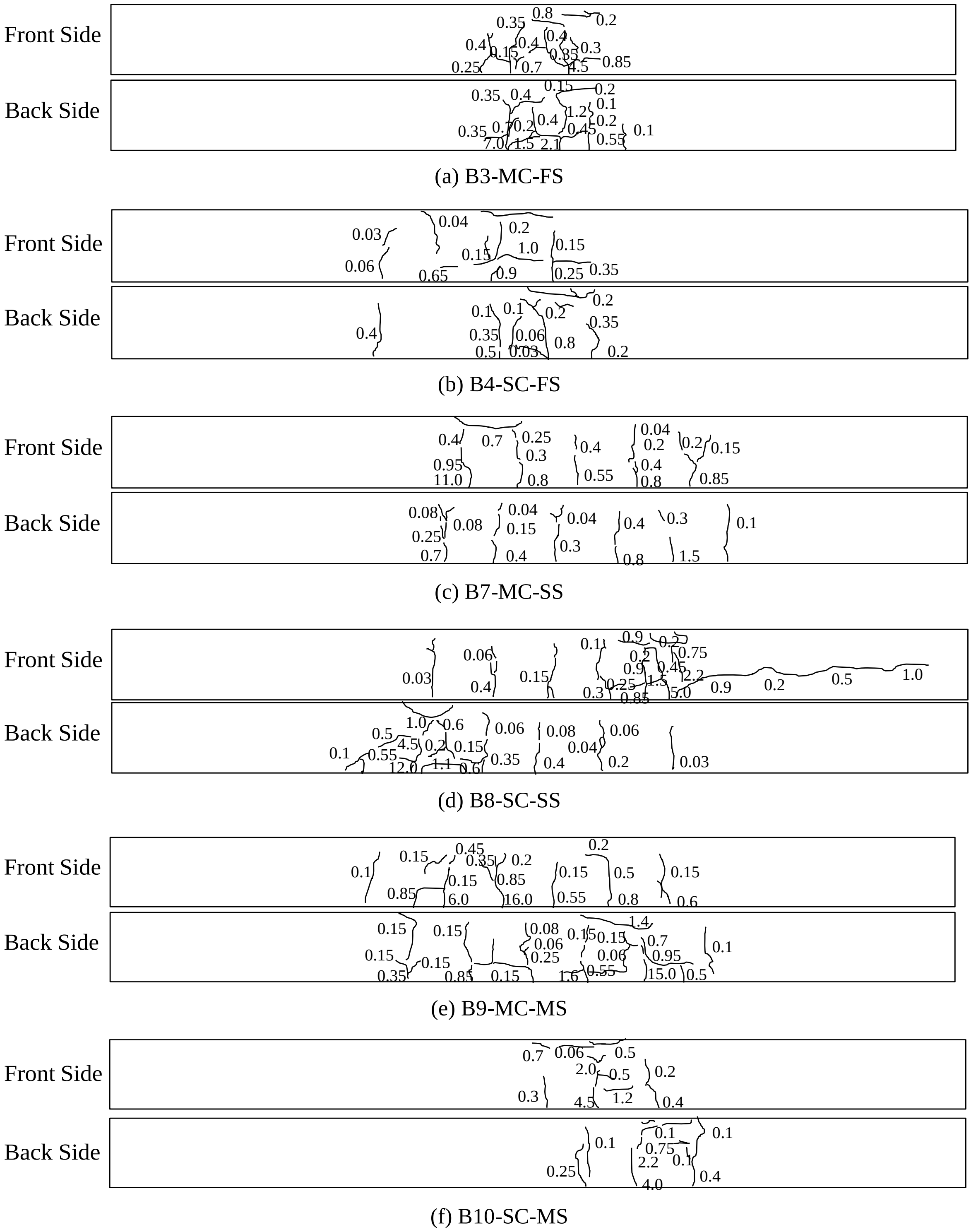
In case of severe corrosion (20% weight loss), the least flexural capacity was again observed in the beam in which stirrups were corroded in the middle span. B10-SC-MS, whose stirrups were corroded in the middle span, had a flexural capacity of 28.25 kN, with a 28.54% reduction in strength, as compared with control beam B2-STD. However, the maximum deflection was 23.96 mm, which is 9.11% more than the control beam B2-STD. For corrosion of stirrups in the full span, the flexural capacity and maximum deflection decreased considerably. The ultimate load for this beam B4-SC-FS was 31.39 kN, with a 20.59% reduction, and the maximum deflection was 14.76 mm, with a 32.79% reduction compared to the control beam B2-STD. The smallest reduction in load carrying capacity for severe corrosion was observed in B8-SC-SS, where shear stirrups were corroded in only one shear span, but the flexural cracks were in the middle span. The flexural capacity of B8-SC-SS was 33.26 kN, with a reduction of 15.86%, and the maximum deflection was 37.51 mm. There was a decrease in flexural capacity, but a considerable increase of 70.81% in maximum deflection was observed as compared to the control beam B2-STD.

With severe corrosion, although the flexural capacity was reduced but the maximum deflection was increased. This was only when stirrups were corroded and design and actual failure modes were flexure. This behavior was not seen in all the beams, but in the middle span and the shear span corrosion of stirrups for severe corrosion (B10-SC-MS and B8-SC-SS).

The comparison of mild and severe corrosion showed that, in both cases, the maximum reduction in ultimate load was observed when stirrups were corroded in the middle span. However, with the different degrees of corrosion, their maximum deflection changed. The trends observed for the shear span and the full span stirrup corrosion (B3-MC-FS and B7-MC-SS) were different for both mild and severe corrosion. For mild corrosion, full span stirrup corrosion B3-MC-FS had the maximum deflection (31.21 mm), whereas for severe corrosion, shear span stirrup corrosion B8-SC-SS had the maximum deflection (37.51 mm). Table 4 summarizes the flexural test results of all the beams.

3.5 Ductility

Ductility describes the ability of a structure or its components to provide resistance in the inelastic domain. It includes the ability to sustain large deformations and a capacity to absorb energy by hyst-



(a) B3-MC-FS

(b) B4-SC-FS

(c) B7-MC-SS

(d) B8-SC-SS

(e) B9-MC-MS

(f) B10-SC-MS

Fig. 10 – Flexural crack widths and distributions of corroded beams

eretic behavior, the characteristics that are vital for seismic loads. Ductility of RC beams is generally determined by the ductility ratio or ductility factor (μ), which is defined as the ratio of maximum (i) deflection (△), (ii) curvature (φ) or (iii) energy (E) at failure to the corresponding property at the yield point [9], as shown below:

Deflection ductility $\mu_{\triangle} = \triangle u/\triangle y$ (1)

Curvature ductility $\mu_{\varphi} = \varphi u/\varphi y$ (2)

Energy ductility $\mu_E = E_{tot}/E_y$ (3)

where, u = mid-span deflection at failure; y = mid-span deflection at yielding of tension reinforcement; φu = curvature at mid-span section at failure; φy = curvature at mid-span section at yield of tension reinforcement; E_{tot} = area under the load deflection curve at failure (total energy); and

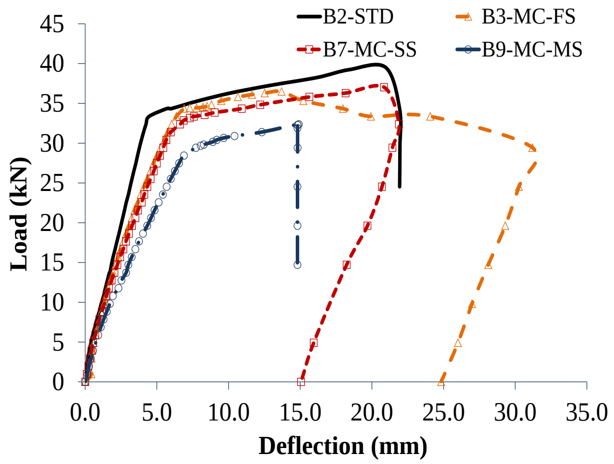


Fig. 11 – Load-deflection curves for mild corrosion

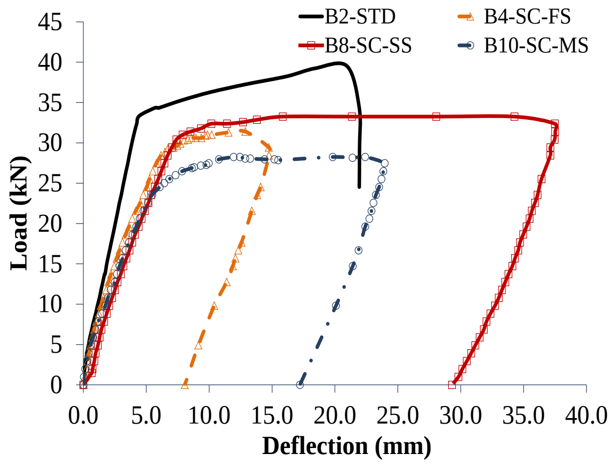


Fig. 12 –Load-deflection curves for severe corrosion

E_y = area under the load-deflection curve at yield of tension steel.

For the purpose of this paper, the ductility is determined by Eq. (1), deflection ductility. Figure 13 illustrates the deflection ductility factor of the corroded beams and the control beam. The deflection ductility factor is believed to depend on the failure mode and, in this study, all the beams failed in flexure after corrosion of stirrups only. However, the deflection ductility factor varied for all the corroded beams, as the location of the corrosion was not the same. The deflection ductility factor of the control beam B2-STD was calculated as 4.93. Mild corrosion beam B3-MC-FS had a slightly higher deflection ductility factor of 5.17 than the control beam B2-STD. B7-MC-SS had a deflection ductility factor of 4.19, which is almost the same as the control beam B2-STD, as the stirrups were corroded in the shear span but flexural failure was observed after corrosion. The corrosion cracks did not affect the deflection ductility significantly. B9-MC-MS had the least deflection ductility factor, with a value of 3.25.

Table 4 – Summary of flexural test results

Beam index	Peak load (kN)	Maximum deflection (mm)	Ductility factor	Failure mode
B2-STD	39.53	21.96	4.93	Flexural
B3-MC-FS	36.49	31.21	5.17	Flexural
B4-SC-FS	31.39	14.76	3.79	Flexural
B7-MC-SS	37.03	21.89	4.19	Flexural
B8-SC-SS	33.26	37.51	5.59	Flexural
B9-MC-MS	32.37	14.90	3.25	Flexural
B10-SC-MS	28.25	23.96	4.66	Flexural

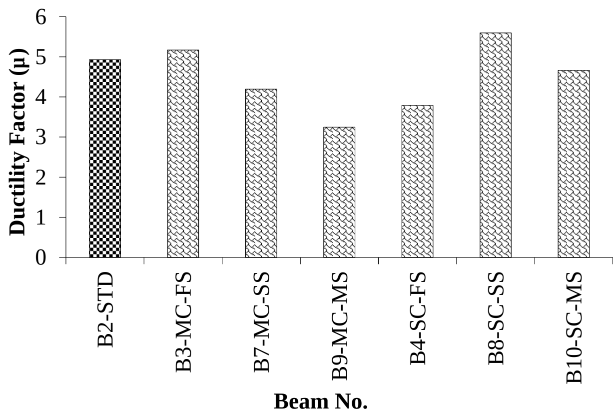


Fig. 13 – Deflection ductility factor of the corroded beams

In case of severely corroded beams, B8-SC-SS had the maximum deflection ductility factor of 5.59. This is because the stirrups were corroded in the shear span, but the failure was flexure after corrosion of stirrups. However, unlike the mild corrosion beam B7-SC-SS, the deflection ductility factor of B8-SC-SS was higher. For an identical load, both the strain of corroded tension bars and the deformation of cracked compression concrete of corroded beams become greater than that of the non-corroded and non-cracked control beam. As a result, the deflection ductility was improved for the B8-SC-SS [10]. B10-SC-MS had almost the same deflection ductility factor as the control beam, with a value of 4.66. B4-SC-FS had the least deflection ductility factor, 3.79, because the stirrups were more corroded than other beams, as reflected in Fig. 4 showing weight loss of corroded stirrups.

4. Conclusions

The following conclusions can be drawn from the presented study:

(1) The weight loss of stirrups was not constant, although the same current was applied for all stirrups. The weight loss varied because the electric resistance for each stirrup differed.

(2) There were some similarities in the cracking pattern after corrosion. For mild corrosion, all the beams had maximum corrosion cracks in the crack width range of 0.1-0.29 mm. For severe corrosion, the number of corrosion cracks gradually decreased with an increase in crack width ranges.

(3) The number of corrosion cracks was almost the same for similar location of corrosion and irrespective of corrosion level. However, the number of flexural cracks was much less in the severe corrosion.

(4) The flexural cracks in mild corrosion were wider than those in severe corrosion. For the severe corrosion, flexural cracks for smaller crack width ranges were observed.

(5) The ultimate capacities of all the beams were less than that of the control beam, and loss of capacity was greater for severely corroded beams. The maximum capacity loss was observed in the beams in which stirrups were corroded in the middle span.

(6) The corrosion of stirrups did not affect the deflection ductility of RC beams significantly.

References

1. Tavio and Teng, S. (2004) "Effective Torsional Rigidity of Reinforced Concrete Members," ACI Structural Journal, 101(2), pp. 252-260.
2. Maaddawy, T.E; Soudki, K.; and Topper, T. (2005) "Long-term performance of corrosion-damaged reinforced concrete beams." ACI Structural Journal, 102(5), pp. 649-656.
3. Yoon, S.; Wang K.; Jason, W.W.; and Shah, S. P. (2000) "Interaction between loading, corrosion and serviceability of reinforced concrete." ACI Materials Journal, 97(6), pp. 637-644.
4. Coronelli, D.; Hanjari, K.Z.; and Lundgren, K. (2013) "Severely corroded RC with cover cracking." ASCE Journal of Structural Engineering, 139(2), pp. 221-232.
5. Hanjari, K.Z; Kettil, P.; and Lundgren, K. (2011) "Analysis of the mechanical behaviour of corroded reinforced concrete structures." ACI Structural Journal, 108(5), pp. 532-541.
6. Dang, V.H. and Francois, R. (2013) "Influence of long-term corrosion in chloride environment on mechanical behavior of RC beam." Engineering Structures, 48, pp. 558-568.
7. Juarez, C.A.; Guevara, B.; Fajardo, G.; and Castro-Borges, P. (2011) "Ultimate and nominal shear strength in reinforced concrete beams deteriorated by corrosion." Engineering Structures, 33, pp. 3189-3196.
8. JSCE (2009) "Structural performance of concrete structures with materials deterioration." Concrete Engineering Series, 85, pp. 13-14.
9. Taranath, B.S. (2010) "Reinforced concrete design of tall buildings." Taylor and Francis.
10. Du Y.; Clark L.A.; and Chan A.H.C. (2007) "Impact of reinforcement corrosion on ductile behavior of reinforced concrete beams." ACI Structural Journal, 104(3), pp. 285-293.