平成27年度　土木学会北海道支部　論文報告集　第72号

Load Carrying Capacity of RC Beams with Mildly Corroded Stirrups

Graduate School of Engineering, Hokkaido University　Student Member　Rahmat Ullah
Faculty of Engineering, Hokkaido University　Fellow　Hiroshi YOKOTA
Faculty of Engineering, Hokkaido University　Member　Katsufumi HASHIMOTO

1. Introduction

Numerous studies in the past have showed that corrosion of reinforcing steel has adversely affected the mechanical behavior of RC structures[1, 2]. Corrosion causes expansion of reinforcing steel which exerts pressure on the surrounding concrete and cracks start occurring on the surfaces of concrete. This cracking results in delamination and subsequent spalling of concrete cover. The study on these cracks is very important to assess durability and the service life of RC structures[3-5]. The bond strength between concrete and steel also reduces because of corrosion and this loss has a considerable contribution in the reduction of ultimate strength and maximum deflection[4].

Many previous research showed the behavior of RC beams when the main longitudinal reinforcement and transverse (shear) reinforcement, such as stirrup are corroded simultaneously. There is a considerable loss in ultimate strength and maximum deflection when both the reinforcement is corroded[5]. However, there are not much literature available when only the stirrup is corroded. The stirrup corrosion can lead to diagonal tension failure or shear failure in RC beams which will cause brittleness and sudden failure in the beam[6].

In this experimental research, the effect of corrosion of stirrups only has been studied. The amount of stirrup is always more than the amount of longitudinal reinforcement in the RC beams and it is distributed throughout the length of beam. Moreover, the concrete cover is relatively less for stirrups as compared with that for the longitudinal steel bars. There is a high probability that stirrup corrosion can start much earlier than the main steel bars. The stirrup corrosion is critical in the shear span of the RC beam. There is a high risk that the failure mode might change from gradual flexure failure to brittle shear failure. Therefore, it is important to study the behavior of RC beams with the stirrup corrosion in the shear span. In this research, six beams measuring 1800 mm long by 100 mm wide by 150 mm high were prepared and corrosion of only stirrup was accelerated by applying direct current. Stirrups were corroded in the shear span and the full span. Some of the literature showed that with the increase in the longitudinal reinforcement ratio, the decrease in the ultimate load capacity and deflection is more. To investigate this fact, two types of specimens were casted using 13 mm (D13) and 16 mm (D16) diameter deformed steel bars as longitudinal bars. The main longitudinal bars were epoxy coated to avoid corrosion. The stirrups were allowed to mild corrosion where 10% weight loss for the stirrups was expected.

2. Experimental Procedure

2.1 Materials and Specifications

Six beams were casted with concrete having the compressive strength of 32 MPa and water-to-cement ration of 0.55. Two types of specimens were casted. In one of the types, the failure mode of the control beam was flexure while the other was crushing of concrete. For the flexure failure beams, 2 deformed steel bars of 13 mm in diameter were used as longitudinal reinforcement while for the crushing of concrete failure 2 deformed steel bars of 16 mm diameter were used as illustrated in Figure 1. All the other parameters such as dimensions, spacing of steel bars etc. were identical. Only the longitudinal reinforcement ratio was varied. All the longitudinal steel bars were used after coating with epoxy to avoid corrosion. For stirrups, deformed steel bar of 6 mm in diameter with 120 mm spacing was used. All the steel used in this study had the nominal yield strength of 395 MPa.

2.2 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 accelerated current technique was applied for corrosion. Current of 2.6 mA/cm^2 was passed for 7 days to achieve 10% average weight loss which is termed as the mild corrosion[7]. Out of the six beams, two beams; one each with longitudinal reinforcement 13 mm and 16 mm diameter steel bars were the control beams. The stirrups of two beams were corroded in the shear span only while the other two had full span stirrup

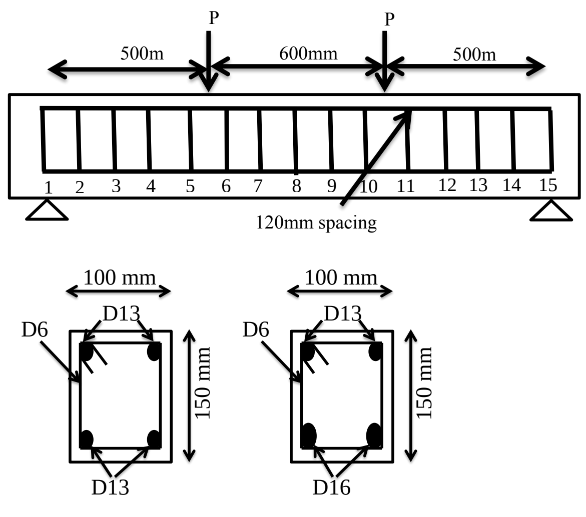

Fig. 1: Beams Layout and Specification

Table 1 Beam Casting Plan

Call No.	Corrosion State
Beam 1	No corrosion (0%) Control beam (D13 flexure rebar)
Beam 2	No corrosion (0%) Control beam (D16 flexure rebar)
Beam 3	Mild Corrosion (10%) Full span (D13 flexure rebar)
Beam 4	Mild Corrosion (10%) Shear span (D13 flexure rebar)
Beam 5	Mild Corrosion (10%) Full span (D16 flexure rebar)
Beam 6	Mild Corrosion (10%) Shear span (D16 flexure rebar)

corrosion. Table 1 summarizes the beam casting plan.

After corroding the stirrups of RC beams, the corrosion cracks width were measured and marked. The two-point loading test was carried out to investigate the load carrying capacity of the corroded RC beams. The flexure cracks after the two-point loading test were also measured and marked. Finally, the stirrups were taken out by crushing the concrete to measure the weight loss due to corrosion.

3. Results and Discussions

3.1 Weight Loss

The weight loss of each stirrup depends on the amount of current passed through them. Different amounts of current passed from stirrups as the resistance changes for each of them. The resistance depends on the distance between the electrodes and the electrolyte present between them. In this case, the resistance depends on the pour size distribution and non-homogeneity of concrete. Different amounts of current resulted in different percentages of weight loss which also resembles natural conditions because corrosion is not uniform throughout the member. All the stirrups were corroded and the average weight loss of each beam was around 10% which was almost the same as the targeted weight loss.

3.2 Corrosion Cracks

All the visible cracks appeared were marked and measured. Figure 2 shows the frequency of corrosion cracks for beams with D13 longitudinal reinforcement while Figure 3 shows the corrosion cracks of D16 longitudinal reinforcement. The cracking followed somewhat particular sequence. The maximum number of cracks lies in the crack width range of 0.1-0.29 mm for all the beams except beam 6. For the beam six maximum cracks lie in the crack width range of 0.06-0.099 mm. Some narrower cracks were also observed in these beams which are due to less degree of corrosion than other stirrups. As the maximum cracks lie in a certain crack width range, we can say that these are the corrosion cracks with approximately 10% weight loss and 120 mm stirrup spacing.

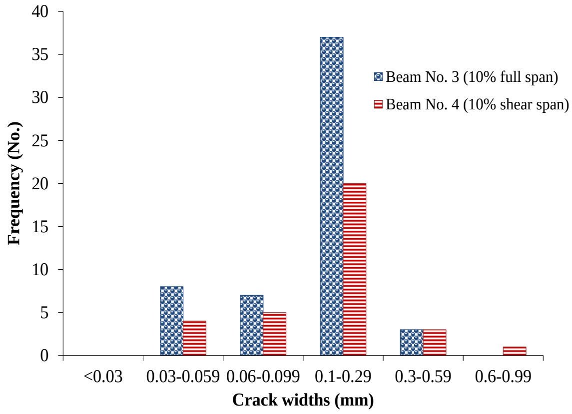

Fig. 2: Corrosion Cracks of RC beams with D16 longitudinal reinforcement

The narrower cracks are because of less degree of corrosion (less than 10% weight loss).

For the beams with D16 mm as longitudinal reinforcement, the frequency of narrower cracks are relatively more than the D13 beams. However the number of cracks is also more for D16 mm longitudinal reinforcement beams.

3.3 Two-Point Loading Test

Figures 4 and 5 show the results of two-point loading test and deflections for the mild corrosion with beams D13 and D16 longitudinal reinforcement respectively. Beams 1 and 2 have no corrosion and they are the standard or control beams. Beam 1 follows typical behavior of a reinforced concrete beam with an ultimate load capacity of 39.53 kN and maximum deflection of 21.96 mm. It is evident from the force-deflection curve that the failure mode of the control beam 1 is the flexure failure. Ductile behavior can be seen from Figure 4. The other beams with corrosion have less ultimate capacity but the ductility of all the beams are different. Design failure mode of all the beams with D 13 longitudinal reinforcement did not change and all failed in flexure after corrosion. The expected corrosion did not change the failure type although it was likely to be shear failed as the stirrups were corroded. However, the maximum deflection was increased after corrosion of stirrups which is unusual.

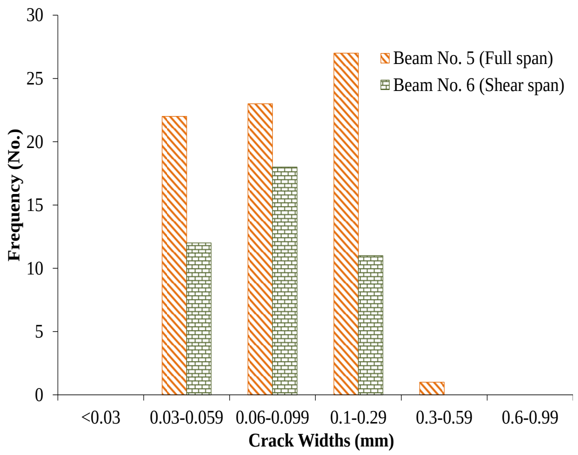

Fig. 3: Corrosion Cracks of RC beams with D16 longitudinal reinforcement

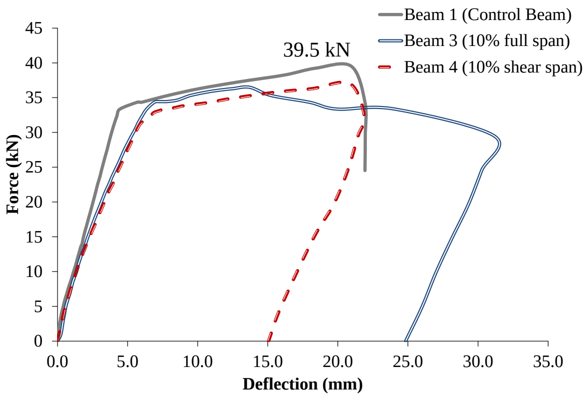

Fig. 4: Load-Deflection Curve of Beams with D13 longitudinal Reinforcement

Although the failure mode was flexure but when the stirrups of shear span were corroded, 6.3% reduction in strength was observed with the flexure failure. This shows that the stirrup corrosion also reduces the flexural strength of the RC beams. The beam with full span stirrup corrosion had 7.7% reduction in the ultimate load carrying capacity. During the two-point loading test, the flexure cracks followed the corrosion cracks. The corrosion cracks were providing the pre-defined path to the flexure cracks and at many places they overlapped.

For control beam 2 which has D16 longitudinal reinforcement, the design failure mode was the crushing of concrete. The ultimate capacity of the control beam is 73.6 kN with the maximum deflection of 67 mm. All the beams with stirrup corrosion and D16 longitudinal reinforcement had crushing of concrete failure after corrosion. A decrease in the ultimate load was observed for all the beams. Even for the beam, stirrups of which was corroded in the shear span had 13.3% reduction in the ultimate load. An increase in the maximum deflection was also observed for the beam whose stirrup was corroded in the full span. The reduction in ultimate load carrying capacity was more in the beams with stirrups corroded in full span. This is an unusual behavior observed in the stirrup corroded beam only.

4. Conclusions

The following conclusions can be drawn from the study:

1) All the beams have maximum corrosion cracks in the crack width range of 0.1-0.29 mm. This can be referred to the corrosion cracks with approximately 10% weight loss.

2) The ultimate capacities of all the corroded beams are less than that of the control beams.

3) The failure mode of all the corroded beams did not change after corrosion. Mild corrosion (10% weight loss) could not change the failure mode of the corroded beams.

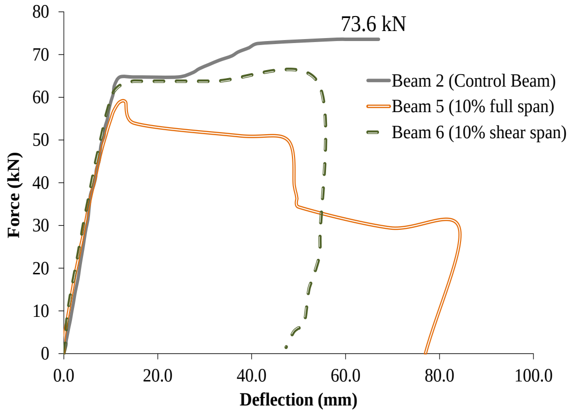

Fig. 5: Load-Deflection Curve of Beams with D16 longitudinal Reinforcement

4) The beams which have stirrup corrosion in the shear span also showed reduction in ultimate capacity despite having flexure failures.

5) With the increase in the longitudinal reinforcement ratio, more strength loss was observed.

6) The stirrup corrosion has a tendency to increase maximum deflection and hence improve ductility.

References

1) Maaddawy Tamer El, Soudki Khaled, and Topper Timothy, 'Long-term performance of corrosion-damaged reinforced concrete beams.' *ACI Structural Journal*, 102 (5), 2005.

2) Yoon Sanchun, Wang Kejin, Jason Weiss W, and Shah Surendra P. 'Interaction between loading, corrosion and serviceability of reinforced concrete.' *ACI Material Journal*, 97 (6), 2000.

3) Dario Coronelli, Kamyab Zandi Hanjari, and Karin Lundgren, 'Severely corroded RC with cover cracking.' *ASCE Journal of Structural Engineering*, 221-232, 2013.

4) Zandi Hanjari, K., Kettil, P., and Lundgren, K., 'Analysis of the mechanical behaviour of corroded reinforced concrete structures.' *ACI Structural Journal*, 108 (5), 532-541, 2011.

5) Vu Hiep Dang and Raoul Francois, 'Influence of long-term corrosion in chloride environment on mechanical behavior of RC beam.' *Engineering Structures*, 48, 2013.

6) C.A.Juarez, B. Guevara, G. Fajardo, and P. Castro-Borges, 'Ultimate and nominal shear strength in reinforced concrete beams deteriorated by corrosion.' *Engineering Structures*, 33, 2011.

7) JSCE, 'Structural performance of concrete structures with materials deterioration.' *Concrete Engineering Series* 85, 2009.