Introduction

Numerous studies in the past have showed that corrosion of reinforcing steel has adversely affected the mechanical behavior of RC structures [1-2]. According to these studies, the structural performance of RC beam reduces with increase in the corrosion level. It can cause premature deterioration and failure of a member which can endanger the serviceability and safety of the structures. RC structures which are exposed to severe environment conditions, such as places where de-icing salts are sprayed during winters often encounter chloride ion penetration. Marine or coastal structures are always in contact with sea water and are more prone to chloride ion attack resulting in faster corrosion.

Corrosion causes expansion of reinforcing steel which exerts pressure on the surrounding concrete and cracks start occurring on the surfaces of concrete [3]. This phenomenon keeps on increasing with the higher levels of corrosion. The study of these cracks is very important to assess durability and service life of RC structures [4].

Many previous research showed the behavior of RC beams when only the longitudinal reinforcement is corroded or simultaneously corroded with the transverse (shear) reinforcement, such as stirrup. There is a considerable loss in ultimate strength and maximum deflection when both the reinforcement is simultaneously corroded [5]. When the stirrup is corroded, there will be reduction in cross section with some volumetric changes and spalling of concrete cover. These losses in an RC beam can lead to diagonal tension failure or shear failure which will cause brittleness and sudden failure [6]. The ductility of RC beam relies on longitudinal reinforcement elongation and good flexure control design but with the corrosion of stirrup it can result in diagonal tension and sudden failure which is not at all desired. The corrosion of stirrup aggravates localized failure which is more vulnerable as it is difficult to predict and control. Field investigations and tests on beams have showed that cover cracking and spalling is more prominent in areas with stirrup and especially if the stirrup is closely spaced, the effect is more adverse [7].

Moreover, the diameter of stirrup is generally small compared to that of longitudinal reinforcement, so relative loss of the cross-sectional area due to corrosion in the stirrup is expected to be much more significant than that of longitudinal reinforcement [8]. Since stirrup is generally located more close to the surface of RC member than longitudinal reinforcement, it is much easier to corrode due to chloride ion ingress from the environment. Therefore, the effect of stirrup corrosion on crack initiation, crack propagation and cover spalling needs to be investigated in more detail. Influence of corrosion of stirrup on the structural performance is a new field of study and got attention just recently, since 2006. Before 2006, the data on the detrimental effect of stirrup corrosion was not available in many of the esteemed international journals.

A detailed research program is carried out to investigate the effect of corrosion of stirrup in this study. The longitudinal rebars were factory epoxy coated to avoid corrosion. Thirty-nine beams of 1800 mm long, 100 mm wide and 150 mm high were casted, and corrosion of only stirrup was electro-chemically accelerated. For this purpose, three kinds of longitudinal reinforcement were used: two D10, two D13 and two D16 mm, all of which were epoxy coated to avoid corrosion. The stirrup was 6 mm in diameter with the spacing of 80 mm, 120 mm and 160 mm. The location of stirrup corrosion is also a significant feature in this research; accordingly, stirrup was locally corroded in the shear span, the middle span, or the full span while using 120 mm stirrup spacing. Mild and severe corrosion levels were prepared, and the targeted mass loss were 10% and 20%, respectively. After the corrosion accelerating treatment, corrosion cracks were marked and their widths were measured to observe their distributions and influence on flexural cracking in the bending test. Four-points bending test was applied to observe the mechanical behavior of the corroded beams. Finally, the stirrup was taken out to check the degree of corrosion. Although the stirrup do not have much contribution towards flexural strength in the middle span but results show reduction in flexural strength because of stirrup corrosion. Other results showed that the corrosion of stirrup has a considerable effect on the structural performance of RC beams.

Experimental Procedure

Materials and Beam Specifications

Thirty-Nine beams measuring 1800 mm long, 100 mm wide and 150 mm high were casted with concrete having compressive strength, $f'_c = 32$ MPa and W/C = 0.55. High early strength Portland cement was used for ensuring
strength and short curing time. The actual yield strength of the steel rebar, \( f_y = 387 \text{ MPa} \) was used for longitudinal reinforcement and was factory epoxy coated to avoid corrosion. For the stirrup, deformed steel bars 6 mm in diameter (D6) with \( f_y = 395 \text{ MPa} \) were used.

In this study, the two different design failure modes were considered with three different designs. Flexural tension failure which was designed by under reinforced sections and flexural compression failure (crushing of concrete) by over reinforced sections. For under reinforced beams, there were two designs (i) Beams with 2-D10 longitudinal reinforcement (ii) Beams with 2-D13 longitudinal reinforcement. The longitudinal reinforcement ratios of these beams were well below the ratio at balanced failure illustrating the ductile behavior and yielding of longitudinal reinforcement. In case of over reinforced beams, 2-D16 longitudinal rebars were used and the failure mode was flexural compression as the longitudinal reinforcement ratio was higher than the balanced failure conditions. All the three types of longitudinal reinforcement beam had 13 beams, three beams were the control beams with stirrup spacing 80 mm, 120 mm or 160 mm without stirrup corrosion, three with mild and severe corrosion respectively in the full span. Furthermore, the location of stirrup was also varied and stirrup was corroded in shear span, middle or full span using 120 mm stirrup spacing. The research plan follows the nomenclature of the beams and is defined as “B” beam no. mildly/ severely corroded or control beam (M/S/C) “,” location of corrosion (FS/MS/SS) “,” diameter of longitudinal reinforcement/spacing of stirrups. For example, B22S-SS-13/120 is beam no. 22, corroded in the shear span, longitudinal reinforcement as 13 mm in diameter and stirrup spacing of 120 mm. Figure 1 shows the research plan outline and Figure 2 shows the beam layout and loading arrangement.

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\begin{array}{c}
\text{Flexural Reinforcement} \\
\text{D10/D13/D16} \\
\text{Stirrup Spacing} \\
80 \text{ mm} \\
120 \text{ mm} \\
160 \text{ mm} \\
\text{Shear span corrosion} \\
\text{Middle span corrosion} \\
\text{Full span Corrosion}
\end{array}
\]

**Figure 1: Experimental Plan**

**Corrosion Process**

After 14 days of curing, the beams were subjected to direct electric current to induce accelerated corrosion. After preparing the beams, they were placed in a pool with 3% NaCl solution and the height of solution was maintained up to the mid-sponge level. Accelerated corrosion technique was applied for producing corrosion by using electric current. Direct electric current of 0.94 mA/cm² was passed for 13 days and 26 days for mild and severe corrosion respectively [9]. Corrosion was allowed only in stirrup and the joints of stirrup and the longitudinal reinforcement was covered by an insulated electric tape to avoid electric current passage.

**Beam Testing**

Corrosion cracks distribution and width were marked after corrosion and then four-point bending load was applied to observe the ultimate load carrying capacity of the corroded beam. After the failure of beam during bending test, flexural or shear cracks distribution and width were also marked and compared with each other. Finally the concrete was crushed and stirrup was taken out to measure mass loss. All the stirrups were weighed after cleaning with 10% diammonium hydrogen citrate solution and ensuring that all corrosion products are washed away.

**Specimen Preparation**

A wire was connected at the top of the stirrup using soldering to facilitate passage of electric current for accelerated corrosion. The stirrup was weighed after attaching the wire with soldering. Steel cage was prepared with 30 mm concrete cover. A sponge was placed on both sides of beam and then wrapped with three towels all around after curing.
TEST RESULTS AND DISCUSSION

Mass Loss

The mass loss of each stirrup depends on the amount of electric current passed through them. Different amounts of electric current passed from the stirrup as the electrical resistance changes for each of them. In this case, the electrical resistance depends on the pore size distribution and non-homogeneity of concrete. Different amounts of current resulted in different percentages of mass loss which also resembles natural conditions because corrosion is not uniform throughout the member. Figure 3 represents the mass loss in percentage of all the stirrups of five mildly corroded beams. The targeted mass loss for mild corrosion was 10% mass loss and the average of all the stirrups of one beam is almost 10% mass loss with a wide variation in the mass loss. B25M-FS-13/160 has an average mass loss of 11.41% and standard deviation of 3.99; while B38M-FS-16/160 had 11.04% and 2.67 respectively. These two beams had a little higher average mass loss. B30M-FS-16/80 and B33M-MS-16/120 had average mass loss approximately 10% and standard deviation of 3.79 and 3.31 respectively. B34M-FS-16/120 had mass loss a little lesser than 10%; which was 9.66% with the standard deviation of 5.04.

Figure 3: %age mass loss of mildly corroded beams

Figure 4 illustrates the mass loss in percentage of all the stirrups of four severely corroded beams. As observed in mild corrosion, the variations in the mass loss was also observed in the severely corroded beams with a variation in the average mass loss too. B18S-FS-13/80 and B5S-FS-10/80 had average mass loss approximately 20% with the standard deviation of 5.98 and 7.15 respectively. B36S-MS-16/120 and B37S-FS-16/120 had average mass loss a little less than the targeted value; 19.11% and 16.54% respectively with the standard deviation of 5.06 and 6.57 respectively. The high values of the standard deviation shows that the mass loss variations of severely corroded beams is much higher than the mildly corroded beams.

Figure 4: %age mass loss of severely corroded beams

Corrosion Cracks Formation

All the visible cracks appeared were marked and measured. The corrosion cracks in all the corroded beams had somewhat similar patterns. Wider corrosion cracks were observed near the ends of the beam. At the ends, the surrounded concrete is not enough to resist the tensile stresses induced due to corrosion resulting in the wider cracks. The corrosion cracks were present all around the four sides of the beam. The side surfaces of the beam had many corrosion cracks as the sides of the stirrup was focused to be corroded. The corrosion cracks on the sides of the beams can be divided in three types depending on the location: (a) Cracks along the depth of the beam (vertical cracks), (b) Cracks along the length of the beam (horizontal cracks), and (c) the diagonal cracks which are at an angle to horizontal and vertical cracks. In case of mild corrosion, the cracks were mostly vertical and to some extent horizontal with only a few diagonal cracks connecting the vertical corrosion cracks. However, in case of severe corrosion, the vertical and horizontal cracks both were in abundance and with a number of connecting diagonal cracks.

In both cases, mild and severe corrosion, the maximum corrosion cracks lied in the narrower crack width range of 0.03-0.05 mm. However, relatively wider corrosion cracks were observed for severely corroded beams. Mostly for mildly corroded beams, the cracks were not wider than 0.15 mm but for severely corroded beams, corrosion cracks wider than 0.2 mm was commonly observed. Figures 5 shows the percentage frequency of corrosion cracks in different crack width ranges for D13 as flexural reinforcement. It can be seen that about 60-65% of the corrosion cracks lie in the narrower crack width range of 0.03-0.05 mm in case of mild corrosion while for severe corrosion this percentage is reduced to 47-53%. This implies that wider corrosion cracks occurred for severely corroded beams. D10 and D16 beams also show almost same trends.
Load Carrying Capacity of Corroded Beams

The load carrying capacity depends on the beam design which includes flexural and shear reinforcement ratio and the degree of deterioration received due to corrosion. All D10 beams failed in flexure tension after stirrup corrosion except one beam which failed in shear. The load carrying capacities of all the corroded beams were less than those of the control beams, showing that the stirrup corrosion has tendency to lower the flexural capacity due to the formation of corrosion cracks. In case of D10 beams, the ratio of flexural reinforcement to shear reinforcement is lesser than D13 and D16 beams, making less probable to fail in shear. It was observed that as the shear reinforcement ratio increases, the load carrying capacity of the corroded beam decreases. Also, severely corroded beams receive higher capacity loss than the mildly corroded beams. Figure 7 shows the load-midspan deflection curves of all D10 beams.

Similar trends were observed for D13 and D16 beams after stirrup corrosion. In this case, the flexural reinforcement ratio is higher than D10 beams; thus an increase in the peak load was observed for the control beams. As the load carrying capacity increased for the control beams, the probability to get shear failure increased as the shear reinforcement ratio was kept constant and was same as D10 beams. This is the reason that shear failure was more common in D13 and D16 beams and all the severely corroded beams were failed in shear. It is interesting to note that a few beams were failed in flexural compression after stirrup corrosion. The stirrup corrosion induced corrosion cracks which were vertical and horizontal cracks, and during the application of load, the concrete at the top compression zone start to spall out reducing the width of compression zone in the Whitney stress block resulting in flexural compression failure. Figure 8 and 9 show the load-midspan deflection curves of all D13 and D16 beams respectively.
LOAD CARRYING MECHANISM OF STIRRUP CORRODED BEAM

When the shear force is applied to RC beam, the applied shear force is resisted by the concrete together with the stirrups [10]. The stirrup allows transference of the diagonal tension forces between the concrete matrix and steel reinforcement by adherence which is also known as the bond between the stirrup and the concrete matrix. This adherence or bond is affected at higher levels of stirrup corrosion and the transference of the diagonal tension forces is disturbed resulting in accumulating the shear stress at the interference of stirrup and the concrete [6]. Also, the cracked concrete under compression exhibits lower strength than un-cracked concrete [11]. This compression softening effect depends on the degree of transverse cracking and straining. The addition of stirrup is known to provide confinement to concrete, and therefore, enhances the contribution of basic shear mechanisms of concrete [12]. After stirrup is corroded, there is loss of confinement pressure lowering the shear strength of concrete. Moreover, the cross-sectional area of stirrup will be reduced due to stirrup corrosion resulting in lowering the shear strength of stirrup.

CONCLUSIONS

The following conclusions can be drawn from this research:

- The number of corrosion cracks increased as the shear reinforcement ratio increased. The total number of corrosion cracks were observed more in severe corrosion. The ends of the beam, irrespective of the corrosion levels had wider corrosion cracks.
- Narrower corrosion cracks were observed for mild corrosion beams. For all cases more than 50% corrosion cracks lie in the crack width range of 0.03-0.05 mm. For severe corrosion, relatively wider cracks were observed. Corrosion cracks wider than 0.2 mm were also observed in the case of severe corrosion.
- The failure mode of severely corroded beams was changed from flexural tension failure to shear failure. The failure mode of mildly corroded beams did not change in most of the cases. However, as the flexural reinforcement ratio increased, mild corrosion also changed the failure mode and shear failure was observed. In a few beams, failure mode was changed to flexural compression after stirrup corrosion. The corrosion cracks produced due to stirrup corrosion are vertical and horizontal cracks which facilitates larger parts of concrete cover to spall down and hence reducing the load carrying capacity. Due to this spalling of concrete cover especially from the top compression portion, the failure mode of the corroded beam changed to flexural compression failure.
- The ultimate capacities of all the corroded beams were less than those of the control beams. Even the failure mode was flexural tension after stirrup corrosion, decrease in the flexural capacity was observed. This depicts that the stirrup corrosion has tendency to decrease the ultimate load carrying capacity of the corroded beams even if the failure mode is not shear failure.
- The shear capacity loss was greater for the beams with higher shear reinforcement ratio. The shear capacity loss was not only contributed by the stirrup but also by the strength loss in the concrete.
- The available models to predict the residual shear capacity of stirrup locally corroded beam are not very reliable as these models have been mainly developed considering one or two straight corroded rebars with higher diameters which are mostly used as longitudinal reinforcement.
FUTURE WORKS

- Research should be carried out to investigate more precisely the load carrying mechanism and develop models to incorporate losses to concrete, stirrup and to the overall beam, after stirrup corrosion, especially when the failure is not shear. Finite Element Analysis (FEM) can be a handy tool for this investigation. The constitutive laws of concrete, stirrup, strength losses in concrete due to corrosion cracks, decrease in the compressive strength of the concrete; and the bond between concrete and corroded stirrups should be carefully examined.

- In this research all the important parameters were not altered. To fully understand the behavior of stirrup corrosion, different aspects of design parameters which are mostly used in real structures should be studied. For example, shear deformations are critical in deep beams and most of the contributions to resist shear force will be provided by stirrup. Different depths of beams should be studied to see the effect of stirrup corrosion, and the shear span to depth ratio (a/d) should also be varied. Nevertheless, the stirrup corrosion of short beams also has to be thoroughly investigated in order to fully understand and develop the behavior of stirrup corroded beams.

- As concluded in this research also, the stirrup spacing has a strong connection with the degree of deterioration. It is important to investigate the effect of stirrup spacing in more detail while varying the design and dimensions of the beam.

- This study is conducted using river coarse aggregates. Previous research show that the interlocking of aggregates is one of the critical factor for consideration of the shear strength of concrete. When the stirrups are corroded, the interlocking of aggregates is also deteriorated and shear failure may occur. Beams made with crushed coarse aggregate is recommended to be fully investigated.

REFERENCES