The effect of corroded stirrups on shear behavior of reinforced concrete beams

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Abstract. The corrosion is a serious problem of construction projects that affect structural durability. The effect of corroded stirrups at the behaviour of reinforced concrete beams especially on ultimate shear strength and ductility was investigated in this study. Eight specimens of reinforced concrete beams were tested with four-point loading until failure. The dimensions of the specimen were 150 mm wide, 200 mm high and 1200 mm long. Six specimens were accelerated through an electrochemical process. The main variables of this study were the stirrups diameter and corrosion level. The results concluded that the stiffness and strength reduced in corroded beams when compared with control specimens. This reduction exhibited to increase with the level of mass loss in stirrups and a smaller diameter of stirrups. In addition to that, the ductility index trended to reduce from 118% to 68% for group A (Ø6 @ 200 mm c/c); while from 68% to 35% for group B (Ø8 @ 150 mm c/c) which indicates that brittleness of beams raised. At high corrosion level, failure modes may change from shear-compression failure to rupture of stirrups.

1. Introduction
The most significant deterioration problem of reinforced concrete structures is the corrosion of embedded steel reinforcement spatially in the marine environment and de-icing salt. As a result, the corrosion could decrease the stiffness, shear capacity, the serviceability and ultimate strength of structural elements. As known, stirrups had the main effect in shear stress of reinforcement beams, and the sufficient number of stirrups in reinforcement concrete (RC) member made the dowel action more efficient to restrict the diagonal cracks and improve the shear capacity of the member. As the stirrups are the nearest reinforcement bars to the concrete’s surface, the stirrups exposed firstly to chlorides attack before the longitudinal steel bars especially at the marine environment and find a result, the opening of cracks will quickly increase, while the cracks in the area without stress [1].

Rodriguez et al. [2] had been studied the effectiveness of corroded reinforcement in RC beams. The main results absorbed that change of failure mode could transfer from bending failure in control beams to shear failure in corroded beams. The deterioration of structures happens because of the reduction in the cross-sectional area of the reinforcing steel bars and bond losses between steel and concrete. This resulting from corrosion rust that occupied six times the original steel volume, which causes cracking and spalling of surrounding concrete so that the distribution of stresses can be affected [3].

The mechanism of mode failure in corroded beams is determined either by the shear-span ratio or by degree of corrosion [4]. Christopher et al. (2010) [5] concluded that the maximum depression in the ultimate shear strength of corroded beams had happened with the lowest a/d ratio, shear span-to-depth ratio, about 53%. The result due to the ultimate strength of corroded beams with a small shear span effected by cracking and spalling of concrete cover. Moreover, the bond strength of stirrups had little effect on the shear performance of RC beams [6]. On the other hand, Zhao and Jin (2001) and...
Morigawa et al. (2007) [7, 8] found that the mechanism of load-carrying capacity may change due to degrade the bond strength of stirrups.

Shear strength and ductility decreased significantly due to the reduction in the cross-sectional area. As a result, the failure mode of disturbed beams changed from shear-compression failures to stirrup fracture at a higher mass loss that due to localized yielding of stirrups [9]. However, if beams with shear-critical subjected to chloride penetration for a long time (26 years), the failure mode was compression strut only which reduced the shear strength and ductility of the beams [10]. In addition, the shear behaviour of deep beams subjected to corrosion would not be influenced by the presence of stirrups and the ultimate strength increasing about 150% than the control beams [11]. In slender beams, when the corrosion level increases and the stirrup spacing decrease the stiffness and shear strength of the corroded beams decrease [1,12]. Ashhad and Abo Kalam (2016) [13] also found that the loss in shear strength is mainly contributed to the mass loss in stirrups and the corrosion crack in concrete cover. In general, the crack width induced by corrosion steel in the concrete cover can be used to estimate the corrosion level.

To measure the width of the cracks, Vidal et al. [14] had reported that the equivalent width equal to the width of one side crack induced by corroded longitudinal bars only, if the crack were extended to the adjacent side, the equivalent crack equal to the sum of cracks at these sides. Later, some researchers such as Xia et al. [15] had applied the equivalent cracks induced by corrosion of both stirrups and longitudinal bars, which used to propose equations to calculate the shear strength for corroded beams.

In this paper, the research intended to explore the shear behaviour of RC beams with different rates of corrosion and study the effect diameter of steel stirrups bars on the behaviour of tested beams. Furthermore, relationships of maximum crack width and average crack width induced by corrosion with mass loss of steel stirrups will be derived.

2. Experimental Investigation

The experimental program involved a total of 8 reinforced concrete beams with a rectangular cross-section. Six of the beams were subjected to accelerate corrosion process in the stirrups at different corrosion levels. The main variables of this study were the diameter of stirrups and the corrosion level in the stirrups.

2.1 Specimen details

The beams were tested to failure in shear under four-point load. The reinforcement beams dimension was 1200 mm long, 200 mm depth, 150 mm wide rectangular cross-section, to increase the flexural capacity two 16-mm diameter main tensile reinforcement steel bars and two 6-mm diameter deformed steel top longitudinal reinforcing bars. Reinforcement steel bars in the top and bottom layer had coated by epoxy to protect steel bars from corrosion. The diameter of stirrups bars was taken as a variable. Four of the beams were designed as 6 mm @ 150 mm while the other 8 mm @ 200 mm. To prevent support failure, the bottom bars anchored by using a standard hook length of 140 mm out the test span as shown in Figure 1. Moreover, the beams were warping by CFRP sheets at supports for distance 150 mm from the edge of the beam after corrosion process because of corrosion crack extended to this region.

The beams description collected in Table (1). According to the stirrup diameter in the test span, the beams were divided into two main groups 6 mm and 8 mm, which described as letter D and number. The letter M referred to mass losses which are 5%, 10% and 15% of the stirrups weight.

| Group | Specimen | Diameter | Corrosion level |
|-------|----------|----------|-----------------|
| A     | D6M0     | 6mm      | 0               |
|       | D6M5     | 6mm      | 5%              |
|       | D6M10    | 6mm      | 10%             |

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2.2 Material properties

Beams were casted using normal concrete mixing with rotary drum mixer. The average compressive strength was 38.77 MPa (cylinder specimen test) and the clear cover was 20 mm. The water-cement ratio of concrete was 0.48 with a maximum coarse aggregate size of about 10 mm. The details can be shown in Table (2). The designed slump of the salted concrete constant was 70 mm. During mixing the concrete, the amount of 3% sodium chloride (NaCl) by the amount of cement was added to the water mixing. The purposes of chloride ions in concrete were breaking down the passive layer of steel to begin the corrosion process and to lower the properties of the concrete. The specimens were cured for 28 days at the wet conditions to achieve the design compressive strength. After that, the electrochemical process of corrosion was started. In the RC beams, deformed reinforcing steel bars were used. The main reinforcement steel bars have a two 16 mm diameter at the bottom while the reinforced bars at the top were 6 mm. The steel bars stirrups for first groups had a diameter of 6 mm while the second group had 8 mm diameter, as shown in Figure 1.

Table 2. Material of mix concrete

| w/c  | Water (Kg/m³) | Cement (Kg/m³) | Fine aggregate (Kg/m³) | Coarse aggregate (Kg/m³) | NaCl (salt) (Kg/m³) |
|------|---------------|----------------|------------------------|--------------------------|---------------------|
| Ratio| 0.48          | 200            | 420                    | 810                      | 1020                |

Figure 1. Details of the reinforcement beam specimen (units: mm).
The yield tensile strength, ultimate strength and elongation were obtained by following standard tensile tests as shown in Table (3). Take into mind that the diameter in Table (3) is the nominal diameter from the manufacturer, while the actual cross-section area was calculated from the weight of steel bars divided by the measured length and the steel density for every three bars and take the average.

### Table 3. Characteristics of the reinforcing bars

| Nominal diameter (mm) | Actual diameter (mm) | Actual cross section area (mm$^2$) | Yield strength (N/mm$^2$) | Ultimate strength (N/mm$^2$) | Elongation (%) |
|-----------------------|----------------------|-----------------------------------|--------------------------|-----------------------------|---------------|
| 6                     | 5.7                  | 25.52                             | 543                      | 625                         | 8             |
| 8                     | 7.8                  | 47.78                             | 523                      | 705                         | 16.16         |
| 16                    | 15.68                | 193                               | 603                      | 697                         | 13.5          |

2.3 Accelerated corrosion of stirrups

Stirrups in reinforcement beams were subjected to accelerated corrosion. An electrical current was impressed in stirrups by using (DC) power supply, as shown in Figure 2. The DC power supply which has an accuracy of 1% can provide a maximum direct current of 5A. As known, corrosion of steel bars in reinforcement concrete members is an electrochemical process. The corrosion process was generated by four steps. Firstly, specimens after 28 days cured were placed in a tank with a size of 4000 mm long, 1500 mm wide and 600 mm high which include salted water (5% of salt). Secondly, beams were put on 80 mm high wooden support and the salted water submerged 170 mm of the beam high. Thirdly, stainless steel plates with a length of 1000 mm and a depth of 200 mm placed at both sides of each specimen and connect together act as a cathode. Continuously, the stirrups wrapped by an electric wire after the electrical insulation stripped from wire to act as an anode, as shown in Figure 3. Fourthly, a current density of 0.2 mA/cm$^2$ was impressed through the stirrups. The stainless steel plates and specimens were connected to the DC power supply in parallel. However, Faraday’s Law used for determining the approximate mass loss in stirrups produced from the corrosion process [16]. The longitudinal steel reinforcement coated by epoxy resin (Sikadur-330) and attached by electrical tape at contact position with stirrups to protect these bars from corrosion.

![Figure 2. Schematic exemplification of the accelerated corrosion test](image-url)
3. Cracks induced by corrosion
The crack had appeared at the surface of the specimen mainly aligned with the position of stirrup due to corrosion. The cracks cleaned by a brush to remove rust staining then highlighted by a green color. The patterns of corrosion crack were mapped with a grid of 50 × 50 mm on the surface of corrosion beams, shown in Figure 4. A manual 50X microscope with accuracy 0.05 mm used to measure crack width as shown in Figure 5. It should be mentioned that, at least four measurements of equivalent crack width were recorded per every single crack at one side which represented the equivalent cracks of one side as mentioned in previous study Vidal et al. [14] noted Figure 6. Table (4) gives the result of actual mass loss and crack width.
4. Testing of specimens

Next the corrosion process and crack measurement, the specimens were loaded monotonically up to failure in four-point loading. The tested beams of a clear cover 1100 mm were placed over a simply supported. For measuring the mid displacement of tested beams, five electronic gauges and one were used. One of gauges with 0.01 mm accuracy was put under mid-span of beams and the other two gauges were placed below two points of loading, continuously, the other two point were placed at a distance equal to height of the beams from the support. The distance between the two points load was 150 mm symmetrically about beams centreline. The directed load was gradually applied by a hydraulic actuator machine with a rate of 0.5 mm/min and a capacity of 200 kN. The applied load, deflection and crack pattern on the sides of the specimen were marked and recorded.

5. Corrosion level evaluation

Next to the loading test, the stirrups were extracted from RC beams. The stirrup bars must be carefully cleaning by brash to remove the wake layer of corrosion products and adhesive mortar. Chemical cleaning procedure was applied by using Clarke’s solution [1000 ml hydrochloric acid (HCl), 50g stannous chloride and 20 g antimony trioxide (Sb2O3)]. The stirrup bars were immersed in the solution for a period from 1 to 25 min or longer in some cases. Finally, the bars were weighted to find the percentage of mass loss $\eta_{cor}$ due to corrosion.

$$\eta_{cor} = \frac{m_i - m_f}{m_i}$$

(1)

Where $\eta_{cor}$ is the corrosion level; $m_i$ is the weight of stirrups exerted from uncorroded beams; $m_f$ is the corroded bars weights. The method of preparation, cleaning procedure and evaluation of level corrosion was accomplished depending on ASTM G1-3 [17].

6. Results and discussion

6.1 Effect of corrosion cracks

According to the visual inspection, rust staining had appeared after four hours from the beginning of the accelerated process, indicated that the corrosion in stirrups had started. As the stirrups were subjected to corrosion by the accelerating method, the cracks at the concrete surface had developed alignment to the corroded stirrups. The value of mass loss is stirrups average crack and maximum crack are listed in Table 4.

Figure 7. shows the bubble scatter between the average equivalent cracks, the average for all alignment cracks induced by stirrups at one beam, and the average mass loss of stirrups. In groups B (Ø8 @ 200 mm c/c), the crack widths were significantly developed as the mass loss increased than the group of A. The average crack width for beams of D8 began with 0.175 mm at 5% theoretical mass loss and increasing to 82% at high corrosion level. Besides that, the average crack width for beams of 6mm diameter increased by 21% between 10.18% and 15.3% actual mass loss. The maximum crack
widths at a high corrosion level for D8M15 raise by 37.5% proportion to D6M15. In addition, the concrete cover deterioration had increased as the diameter of the bars of stirrups became larger by expanded cracks and splitting of concrete cover. This means that crack widths induced by corrosion were significantly affected by the diameter of stirrups bars.

Table 4. Mass loss and corrosion crack width

| Groups | Beam | Mass Loss % | Average Crack width (mm) | Maximum Crack width (mm) |
|--------|------|-------------|--------------------------|--------------------------|
| A      | D6M5 | 10.18       | 0.2                      | 0.35                     |
|        | D6M10| 12.82       | 0.211                    | 0.35                     |
|        | D6M15| 15.3        | 0.243                    | 0.4                      |
| B      | D8M5 | 4.1         | 0.175                    | 0.25                     |
|        | D8M10| 8.94        | 0.207                    | 0.35                     |
|        | D8M15| 11.78       | 0.32                     | 0.55                     |

Figure 7. Relationship between the average mass loss in stirrups and cracks induced by corrosion.
(a) mass loss versus average cracks width, (b) mass loss versus maximum cracks width
The correlation between the width of average crack and the maximum crack for each beam shows in Figure 8. It should be clearly noticed that, the maximum cracks of groups A and B exhibit a rapid increase, compared with the widths of the average cracks as the corrosion propagate to a higher level. This is perhaps caused by the development of stresses after the cracks had appeared at the concrete surface. This stresses cannot transfer to another area, when mature cracks are present at the concrete which confinement the stresses in a particular area. As a result, the opening of cracks will quickly increase, while the cracks in an area without stress.

![Figure 8. Relationship between the average and maximum cracks width](image)

6.2 Shear strength

The experimental load-deflection curve for each corroded beams compering with reference beams (Group A and B) is illustrated in Figure 9. The behaviour of incipient corrosion beams was similar to the behaviour of reference beams, because of the corrosion at the early stage of steel depassivation had no adverse effect on general behaviour. Therefore, the failure load at low corrosion level, Noticeable specimen D8M5, had increased by 4% than uncorroded beams. The main reason for this increase was that, rust staining produced by the reaction between steel surface and oxygen during the corrosion process, at moisture environments, full the pore of aggregate interlock. Therefore, the bond between concrete and steel surface enhances.

At moderate and severe corrosion rang, the degradation in shear strength can be observed compared with the shear strength of uncorroded beams. Shear strength reduction of corroded beams ranged from 7 to 14% for group A with stirrups of 6 mm diameter and 2 to 6% for group B with 8 mm diameter stirrups.

The stirrups play an important role in restraining the propagated diagonal cracking. As the corrosion process had decreased the area of the stirrups bars, the stirrups ability in restraining the shear cracks was decreased. This means that the beams with web reinforcement 6 mm diameter showed rapid degradation in ultimate shear strength and stiffness. The above observation elucidates that, the corrosion of small diameter stirrups without an adequate concrete cover shows a reduction in the general behaviour of beams. The mid-span deflection for group A ranged from 5.5 mm (for beams with 15% corrosion) to 6.28 mm (control beams), while group B had a little increased in deflection than uncorroded beams. These results indicated that the deflection at failure decreased as the mass losses in bars increased, which subsequently affected on brittleness of beams.

The load of diagonal cracks for specimens was recorded as shown in Table (5). The main observation in corroded beams that, the diagonal crack loads were increased as the cross-sectional area of stirrups was decreased due to corrosion compering to reference beams. The beam of 15% target mass losses in groups (B), stirrups of 8 mm diameter, had a larger diagonal cracks loads by 61% than
the uncorroded beam. This behavior returns to corrosion cracks alignment to the position of stirrups, which gradually opening during the loading test. So that, as the stress paths try to transmit from point load to the supports, it well be diffused in different direction which delaying the threshold of diagonal cracks. Therefore, at sever corrosion level, the diagonal cracks at the corroded beams with larger diameter stirrup appear at load that near to failure point. Besides, the ductility index was evaluated in this paper by dividing the deflection of the ultimate load and load of diagonal cracks threshold see Table.5.

Results appeared that, as the diagonal cracks load increased, the ductility index trended to diminish from 118% to 68% for groups A; while from 68% to 35% for group B. Owning to the corroding process, reduction in the steel bar section decrease its elongation, and so in the ductility of members reduce.

**Table 5.** Test results summery

| Specimens | Compressive strength (Mpa) | Load at first flexure crack (KN) | Load at first shear crack (KN) | Ultimate Measured load (kN) | Mid-span deflection at first shear crack (mm) | Mid-span deflection at failure (mm) | δu/δv | Failure Modes |
|-----------|---------------------------|---------------------------------|-------------------------------|-----------------------------|-----------------------------------------------|-----------------------------------|-------|---------------|
| D6M0      | 38.8                      | 40                              | 60                            | 121.19                      | 2.17                                         | 6.28                              | 2.894 | SC<sup>a</sup> |
| D6M5      | 40                        | 55                              | 65                            | 112.21                      | 2.67                                         | 5.83                              | 2.184 | SC<sup>a</sup> |
| D6M10     | 37.74                     | 50                              | 65                            | 109.23                      | 2.74                                         | 5.97                              | 2.179 | DS<sup>b</sup> |
| D6M15     | 36.84                     | 45                              | 75                            | 104.41                      | 3.27                                         | 5.5                               | 1.682 | SR<sup>c</sup> |
| D8M0      | 38.75                     | 50                              | 80                            | 137.28                      | 2.64                                         | 6.49                              | 2.458 | SC<sup>a</sup> |
| D8M5      | 42                        | 55                              | 95                            | 142.43                      | 3.75                                         | 7.21                              | 1.923 | SC<sup>a</sup> |
| D8M10     | 38.86                     | 50                              | 100                           | 135.1                       | 4.15                                         | 7.01                              | 1.689 | DS<sup>c</sup> + CC<sup>d</sup> |
| D8M15     | 36.64                     | 45                              | 110                           | 129.14                      | 5.1                                          | 6.92                              | 1.357 | DS<sup>c</sup> |

<sup>a</sup> Shear compression,
<sup>b</sup> Diagonal splitting,
<sup>c</sup> Stirrups Rupture,
<sup>d</sup> Crashing concrete
Figure 9. Experimental Load – displacement relationships. (a) incipit (b) moderate (c) sever corrosion level
6.3 Mode failure
The crack pattern during loading was began in pure bending zone as flexural cracks. Then, the diagonal cracks were appeared in the shear zone between point load and supports interrupted the corrosion cracks which is vertical. In addition, the corrosion cracks were expanding during loading. The flexural cracks propagate at earlier loading stages. Failure modes of beams were shear compression (SD), diagonal splitting (DS) and rupture of stirrups (RS). Each control beams and beams at an earlier level of corrosion D6M5 and D8m5 was failure by shear compression (SD) failure. The beam of 6 mm @ 150 mm at the higher mass loss was a failure by rupture of stirrups because of larger reduction in diameter of stirrups bars according to corrosion. This behaviour led to the serviceability problems of the corroded member. Figure (10) shows the mode failure for D6M15, D6M5 and D8M10.

![Shear- compression failure(D6M5)](image1)

![Rupture of stirrups (D6M15)](image2)

![Diagonal splitting (D8M10)](image3)

Figure 10. Shear failure modes

7. Conclusions
Behaviours of reinforced concrete beams subjected to different corrosion levels by the accelerated method in stirrups studied in this paper. The main outcomes of this study can be summed up as follows:

- The average or maximum crack widths on the surface of reinforcement concrete (RC) members induced by corrosion of steel bars used as the corrosion level indicators. As the diameter of bars increase with corrosion level of stirrup bars, the average and maximum crack width became wider which causes concrete cover delamination.
- The relationships between the average cracks and maximum cracks width have non-linear increasing as the bar size become large.
- Reduction in the ultimate load and stiffness of corroded beams tended to increase with the mass loss in the stirrups which causes the member more brittleness. This reduction clearly increases with the beams of small diameter stirrups.
- The deflection at load failure with beams of small diameter stirrups clearly tend to decrease as the corrosion level increase.
- As the corrosion crack width becomes wider, the diagonal cracks appear at load near to the ultimate stage, this meant the elements may reach to failure without prior warning which lowering safety requirements.
At severe corrosion range, failure modes may change from shear-compression failure to rupture of stirrups. This change in failure mode attributed to losses in diameter of stirrups or pitting from chloride attack.

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