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# EFFECT OF REBAR CORROSION ON BOND STRESS-SLIP BEHAVIOR IN REINFORCED CONCRETE

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## ABSTRACT

*This study investigates the influence of rebar corrosion on bond stress-slip behavior in reinforced concrete at various corrosion levels. 24 concrete cylinders of 150 mm diameter and 300 mm long were used as test specimens. 12 of them were reinforced with a single 12 mm diameter 500W bar, while the others were reinforced with a single 16 mm diameter 500W bar and they were subjected to four different corrosion levels, namely 0%, 5%, 10% and 15%. The corrosion process was initiated by curing the samples at 5% NaCl solution. Galvanized current measurements were taken to monitor the corrosion initiation. After corrosion had initiated an external current was applied to expedite the corrosion propagation and responsive voltages were measured. The effects of parameters such as percentage of corrosion (0%, 5%, 10% and 15%) and bar diameter (12 mm and 16 mm) on bond stress-slip behavior were evaluated under direct pullout test. Test results revealed that corrosion had less impact on maximum bond stress up to 5% corrosion level. Beyond 5% corrosion, bond stress decreased with the increase of corrosion level while slip showed opposite behavior irrespective of the bar sizes. In general, both bond stress and slip of 12 mm diameter bar was found higher than the 16 mm diameter bar. A loss of bond stress about 34.5% and 37% was observed in 12 mm and 16 mm diameter bars, respectively, for reinforcement corrosion on level of 15%.*

**Keywords:** *Bond stress, slip, corrosion, rebar, reinforced concrete*

## 1. INTRODUCTION

Reinforced concrete is commonly used in Civil Engineering. It behaves as a composite member when reinforcing bars and concrete residing together and they offer most stiffness and durability than others. It is almost depends on their bond behavior (Paul, et al., 2013).

Steel-concrete bond is a fundamental property to ensure the integrity of reinforced concrete structural elements because efficient bond ensures reliable force transfer between reinforcement and the surrounding concrete. The reinforcement corrosion of reinforced concrete structures probably is the most significant problem and outweighs other forms of deterioration. There is growing concern for corrosion damage in reinforced concrete structures with several decades' service. The effect of reinforcement corrosion on bond stress-slip behavior in reinforced concrete is very important to the durability of the reinforced concrete structures.

Electrochemical is the most common form of corrosion in an aqueous medium and steel can corrode by chemical attack. In most cases electron transfer occurs under electro-chemical action in which there is a transfer operation taking place either between two dissimilar metals or between different areas upon a single material. The zone that releases electrons is called anode while the zone accepting those electrons is termed as cathode as in other electrical circuits. Reaction of anodes and cathodes are broadly referred to as "half-cell reaction''. It works with an anode, where electrochemical oxidation takes place; a cathode, where electrochemical reduction occurs; an electrical conductor, and an aqueous medium. At the anode which is the negative pole, iron is oxidized to ferrous ions, whereas reduction takes place at the cathode. In an acid medium the reaction taking place at the cathode is the reduction of hydrogen ions to hydrogen (Morshed, et al., 2014).

Every year a huge amount of revenue is spent to repair and rehabilitate the deteriorated structures in Bangladesh; especially, in the south-west regions due to severe salinity problem. Bond stress-slip behavior varies with varying degree of corrosion. So, the effect of corrosion on bond stress-slip behavior between concrete and rebar should be investigated to incorporate its effect on service life prediction, durability design and take necessary initiative to countermeasure the deterioration. The objectives of this study are to determine bond stress and slippage between Portland cement concrete and deformed steel bar for various bar diameters and degrees of corrosion.

## 2. METHODOLOGY

Bond refers to the interaction between reinforcing steel and the surrounding concrete, which allows transferring of tensile stress from the steel into the concrete. Bond stress is an important factor to design a reinforced concrete structure. Some factors affect negatively the bond strength such as corrosion, epoxy coating etc. To determine the effect of rebar corrosion on bond stress-slip behavior in reinforced concrete, some methods should be followed and these are given below.

### 2.1 Materials

For this study mainly four types of materials are used. These are mainly Portland cement, black stone chips, sea bed sand and reinforcing bar.

### 2.1.1 Coarse Aggregate

Black stone chips were used as coarse aggregate. Specific gravity, absorption and unit weight of black stone chips were found 2.66, 1.3% and 1683 kg/m$^3$ respectively.

### 2.1.2 Fine Aggregate

Coarse sand (Sea bed sand) was used as fine aggregate. Specific gravity, absorption, unit weight and fineness modulus of coarse sand were found 2.27, 2.3%, 1621 kg/m$^3$ and 2.84 respectively.

### 2.1.3 Binder

Portland cement was used as binder. Specific gravity, initial setting time and final setting time of Portland cement were found 3.02, 105 minute and 180 minute respectively.

### 2.1.4 Reinforcing Bar

500W deform steel reinforcement bar were used. Yield strength, Ultimate strength and elongation at maximum stress of 12 mm and 16 mm diameter bar were found 522 MPa, 645 MPa, 509 MPa, 633 MPa, 11.8% and 11.9% respectively.

### 2.2 Concrete Mix Design

The concrete mix for every specimen was based on the mix design. The weight portion of the concrete mixture was 1 (cement) : 2 (fine aggregate) : 4 (coarse aggregate), giving a water to cement ratio of 0.5.

Table 1: Concrete Mix Proportions

| **Cement (kg/m$^3$)** | **Coarse aggregate (kg/m$^3$)** | **Fine aggregate (kg/m$^3$)** | **Water (kg/m$^3$)** |
|---|---|---|---|
| 320 | 1280 | 640 | 160 |

### 2.3 Test Specimens

Eight group of concrete cylinders of dia 150 mm (6 in) x height 300 mm (12 in) were used as pullout test specimens. A single rebar was embedded at the center of the vertical axis of the test cylinders. Deformed rebar of 12 mm diameter used in four groups and deform rebar of 16 mm diameter used in another four groups. Every group contained three specimens. Rebar was casted vertically from the top of the cylinder. Dimensions of pullout test specimen are shown in Fig. 1. Four groups of specimen for each diameter of rebar were used for 0%, 5%, 10% and 15% of corrosion level. For compressive strength test and tensile strength test, same size of concrete cylinders was tested for 28 days sample.

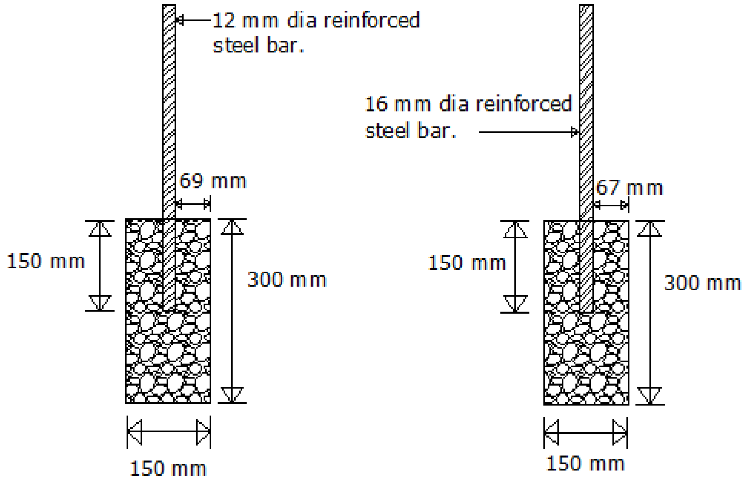

Fig.1: Dimension of pullout specimen

## 2.4 Corrosion Measurement

### 2.4.1 Galvanic Current Measurement

The corrosion process of the reinforcing steel in the present study was monitored by the use of galvanic current. A copper plate was placed in a 5% NaCl solution and electrically connected to the reinforcement through a shunt-resistor (2.2 ohms). The schematic of the corrosion cell is shown in Fig. 2. This type of corrosion cell, composed of two dissimilar metals in contact and sharing a common electrolyte (concrete pore solution), is called a galvanic cell (Devalapura, Kamel & Arumugasaamy, 1994). Among the two dissimilar metals, the metal with the more negative standard potential value serves as anode, while the noble metal with the less negative standard potential value serves as cathode (Berkeley & Pathmanaban, 1990). In this project, mild steel (E= -0.61 volt) served as anode and copper (E=-0.36 volt) served as cathode.

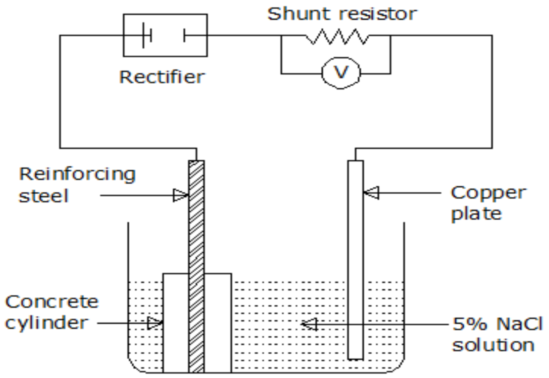

Fig. 2: Schematic of galvanic current measurement

The amount of galvanic current, which flows between the galvanic couple-mild steel and copper, indicates the degree of corrosion activity in the cell. In the present study, the galvanic current was monitored daily for each cylinder through a resistor as shown in Fig. 2. The galvanic corrosion current $I_j$ was calculated based on the measured voltage V across the shunt-resistor R using equation (1).

$$I_j = \frac{V}{R} \dots\dots\dots (1)$$

### 2.4.2 Application of External Current

After corrosion initiation, an external direct current was applied to some specimens through a rectifier to accelerate the corrosion propagation process. A group of three cylinders were connected in parallel. The rectifier had one end connected to the reinforcing steel in the specimens and the other connected to the copper plate via the shunt-resistor. The complete test setup is shown in Fig. 3. After 28 days of successive ponding of the concrete surface near the tension zone, a stagnant voltage (30 volt) was applied, to the group of three cylinders for required period of time to obtain a decent degree of corrosion propagation.

Fig. 3: Test setup for corrosion acceleration

The corrosion rate (defined as weight loss or percentage of weight loss of reinforcing steel in the present study) can be calculated based on the current going through the shunt-resistor. This corrosion current was measured by a multimeter. According to Faraday's law, the total weight loss of a reinforcing steel bar that is oxidized by the passage of electric charge can be expressed as follows

$$W_{loss} - [TC] \cdot \frac{EW}{F} - \left\{ \sum_{j=1}^{n} \left[ \frac{I_j + I_{j-1}}{2} \cdot (t_j - t_{j-1}) \right] \right\} \cdot \frac{EW}{F} \dots \dots (2)$$

Where,
$W_{loss}$ = total weight loss of reinforcing steel, gm;
TC = total electric charge, amp-s or coulomb;
EW = equivalent weight, indicating the mass of metal in grams, that is oxidized. For pure elements, the EW is given by EW= W/n; where W is the atomic weight of the element, and n is the valence of the element. For carbon steel, atomic weight is 55.845 gm and valence is 2;
F = Faraday's constant (F = 96490 coulombs or amp-s);
$I_j$ = current in amps, at time $t_j$ in seconds.
Above procedures were followed for each group of cylinders to obtain a decent degree of corrosion propagation.

### 2.5 Direct Pullout Test

The direct pullout test using Universal Testing Machine was adopted in this study to evaluate the bond performance of steel-reinforced concrete for various diameters (12 mm and 16 mm) and degrees of corrosion (0%, 5%, 10% and 15%). Because of differences in boundary conditions and stress state, the stress values obtained from direct pullout tests were not exactly the same as the stresses obtained in actual scenarios (Tastani & Pantazopolou, 2010). However, the test was adopted in this study because it is simpler, more convenient and costs less compared with other tests. This test setup is also practical as it represents the main longitudinal reinforcement, which is mostly subjected to tensile forces in a reinforced concrete beam.

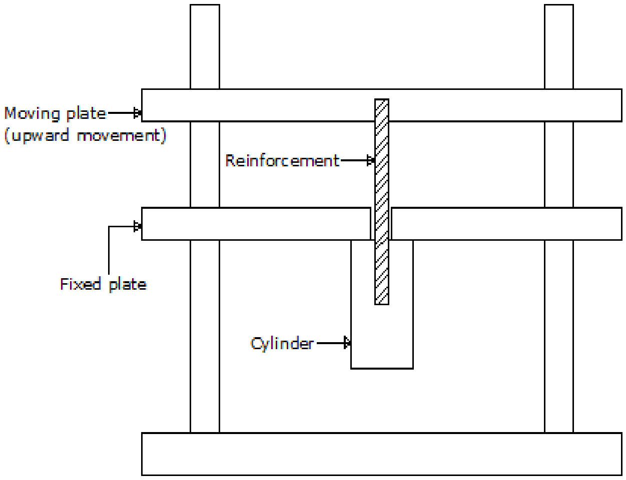

Fig. 4: Schematic diagram of direct pullout test

The schematic diagram of the test is shown in Fig. 4. In the test conducted, the specimens were positioned in a Universal Testing Machine. Concrete cylinder was kept below the fixed plate that has a hole in the center where the bar can pass through. The reinforcement was entered through the hole of the fixed plate and reached to the moving plate where it was gripped by clamp. Force was applied by the upward movement of the moving plate and slip was measured by using the scale of Universal Testing Machine.

## 3. ILLUSTRATIONS

### 3.1 Effect of Rebar Corrosion on Bond Stress-slip Behavior

Bond-slip relationship for 12 mm rebar is presented in Figure 5. Maximum bond stress and slip of 12 mm rebar at failure condition for 0%, 5%, 10% and 15% corrosion level were 9.31 MPa, 9.14 MPa, 7.83 MPa, 6.09 MPa, 2.3 mm, 2.4 mm, 2.8 mm and 3.25 mm respectively. Load for bond failure between 12 mm rebar and concrete were found 53.5 KN, 52.5 KN, 45 KN and 35 KN at 0%, 5%, 10% and 15% corrosion level respectively. It can be revealed that bond stress of 12 mm rebar without corrosion was maximum than reinforcement with corrosion. Slip increased with the increase of corrosion. Decreasing rate of bond stress increased with the increase of slip. This was because of the degradation in the profile of the bar ribs. Degradation of bar ribs was responsible for decreasing friction and adhesion between rebar and concrete. A loss of 34.5% bond stress was observed for 15% corrosion of 12 mm diameter bar.

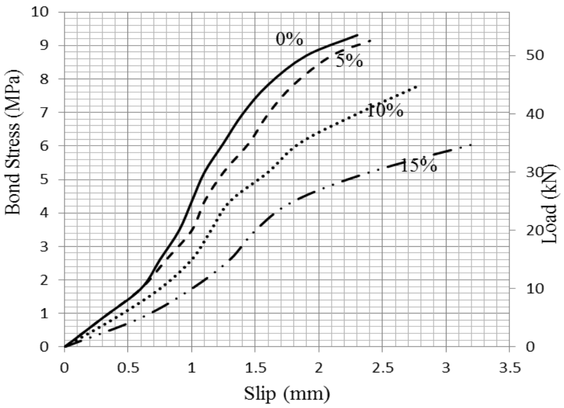

Fig. 5: Bond-slip relationships for 12 mm rebar

Bond-slip relationship for 16 mm rebar is shown in Figure 6. Maximum bond stress and slip of 16 mm rebar at failure condition for 0%, 5%, 10% and 15% corrosion level were 8.09 MPa, 7.96 MPa, 6.85 MPa, 5.09 MPa, 2.2 mm, 2.3 mm, 2.6 mm and 3.0 mm respectively. Load for bond failure between 16 mm rebar and concrete were found 62 KN, 61 KN, 52.5 KN and 39 KN at 0%, 5%, 10% and 15% corrosion level respectively. It can be revealed that bond stress of 16 mm rebar without corrosion was maximum than reinforcement with corrosion while slip showed opposite behavior. Bond stress was affected by corrosion. Friction and adhesion decreased with the increase of corrosion due to the degradation of bar ribs, which was main reason behind the bond stress reduction. Crack was observed at 10% and 15% corrosion level. Crack released energy which was also responsible for bond stress reduction. A loss of 37% bond stress was observed for 15% corrosion of 16 mm diameter rebar.

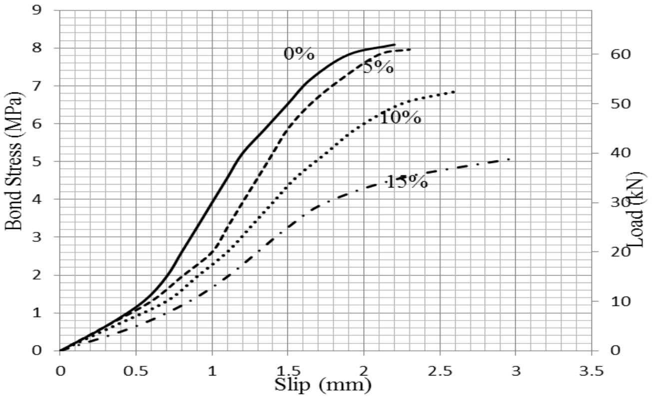

Fig. 6: Bond-slip relationships for 16 mm rebar

### 3.2 Effect of Diameter on Bond Stress-slip Behavior for Various Degrees of Corrosion

Bond-slip relationship at 0% corrosion level is presented in Figure 7. Maximum bond stress and slip of 12 mm and 16 mm rebar at failure condition for 0% corrosion level were 9.31 MPa, 8.09 MPa, 2.3 mm and 2.2 mm respectively. According to Aslani & Samali, 2013, maximum bond stress of 12 mm and 16 mm rebar at 0% corrosion level were 10.5 MPa and 9.42 MPa respectively at 20°C temperature. A loss of 11.3% and 14.12% bond stress were observed in the laboratory for 12 mm and 16 mm rebar respectively. This was because of the change in temperature and humidity. Load for bond failure of 12 mm and 16 mm rebar were found 53.5 KN and 62 KN respectively at 0% corrosion level. The results showed that, bond stress of 12 mm diameter reinforcement was greater than the 16 mm diameter rebar at 0% corrosion level. Slip of 12 mm diameter rebar was greater than the slip of 16 mm diameter rebar at failure condition. Large Poisson's ratio and shear lag effects were responsible for above results. Poisson ratio of 16 mm bar was higher than 12 mm bar that lead to a lower mechanical interlock and friction between the 16 mm rebar and reinforced concrete.

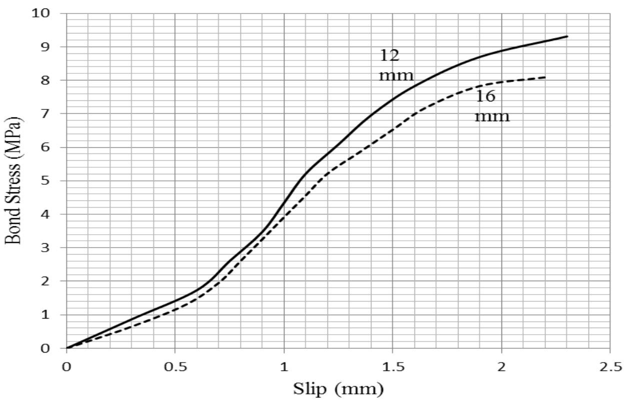

Fig. 7: Bond-slip relationships at 0% corrosion level

Bond-slip relationship at 5% corrosion level is shown in Figure 8. Maximum bond stress and slip of 12 mm and 16 mm rebar at failure condition for 5% corrosion level were 9.14 MPa, 7.96 MPa, 2.4 mm and 2.3 mm respectively. A loss of 1.82% and 1.61% bond stress were observed for 12 mm and 16 mm rebar respectively upto 5% degree of corrosion. Load for bond failure of 12 mm and 16 mm rebar were found 52.5 KN and 61 KN respectively at 5% corrosion level. The results revealed that, bond stress of 12 mm diameter reinforcement was greater than the 16 mm diameter rebar at 5%, corrosion level. Slip of 12 mm diameter rebar was greater than the slip of 16 mm diameter rebar at failure condition. This was because of the large Poisson's ratio and shear lag effects. Poisson ratio of 16 mm bar was higher than 12 mm bar that lead to a lower mechanical interlock and friction between the 16 mm rebar and reinforced concrete.

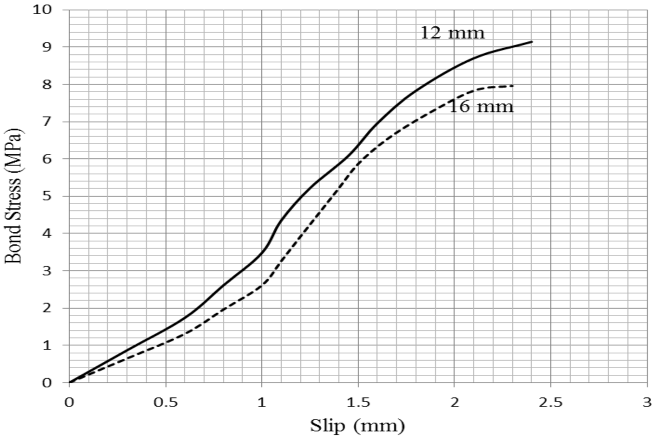

Fig. 8: Bond-slip relationships at 5% corrosion level

Bond-slip relationship at 10% corrosion level is presented in Figure 9. Maximum bond stress and slip of 12 mm and 16 mm rebar at failure condition for 10% corrosion level were 7.83 MPa, 6.85 MPa, 2.8 mm and 2.6 mm respectively. A loss of 14.33% and 13.94% bond stress were observed for 12 mm and 16 mm rebar respectively for increasing 5% degree of corrosion after 5% corrosion level. Load for bond failure of 12 mm and 16 mm rebar were found 45 KN and 52.5 KN respectively at 10% corrosion level. The results revealed that, bond stress of 12 mm diameter reinforcement was greater than the 16 mm diameter rebar at 10% corrosion level while slip showed opposite behavior. Large Poisson's ratio and shear lag effects were responsible for above results. Poisson ratio of 16 mm bar was higher than 12 mm bar that lead to a lower mechanical interlock and friction between the 16 mm rebar and reinforced concrete. Crack was observed at 10% corrosion level. Crack released energy which was also responsible for bond stress reduction.

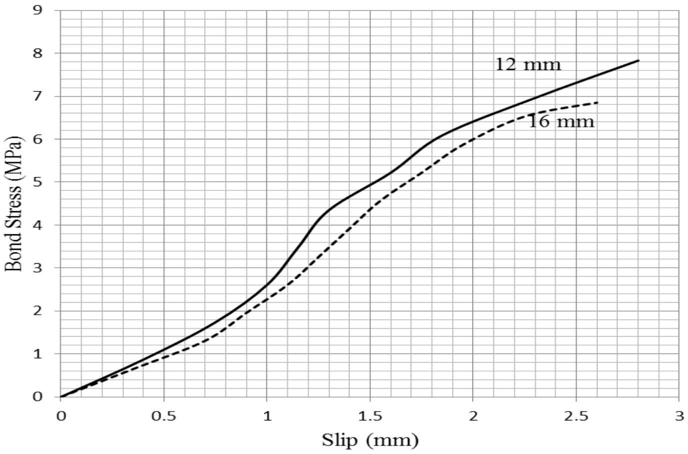

Fig. 9: Bond-slip relationships at 10% corrosion level

Bond-slip relationship at 15% corrosion level is shown in Figure 10. Maximum bond stress and slip of 12 mm and 16 mm rebar at failure condition for 15% corrosion level were 6.09 MPa, 5.09 MPa, 3.25 mm and 3.0 mm respectively. A loss of 22.22% and 25.69% bond stress were observed for 12 mm and 16 mm rebar respectively for increasing 5% degree of corrosion after 10% corrosion level. Load for bond failure of 12 mm and 16 mm rebar were found 35 KN and 39 KN respectively at 15% corrosion level. The results revealed that, bond stress of 12 mm diameter reinforcement was greater than the 16 mm diameter rebar at 15% corrosion level while slip showed opposite behavior. Large Poisson's ratio and shear lag effects were responsible for above results. Poisson ratio of 16 mm bar was higher than 12 mm bar that lead to a lower mechanical interlock and friction between the 16 mm rebar and reinforced concrete. Crack was observed at 15% corrosion level. Crack released energy which was also responsible for bond stress reduction. Bond stress reduction rate was higher for 15% corrosion than 10% corrosion level. This was because of the presence of larger amount of rust on the rebar surface for 15% corrosion level.

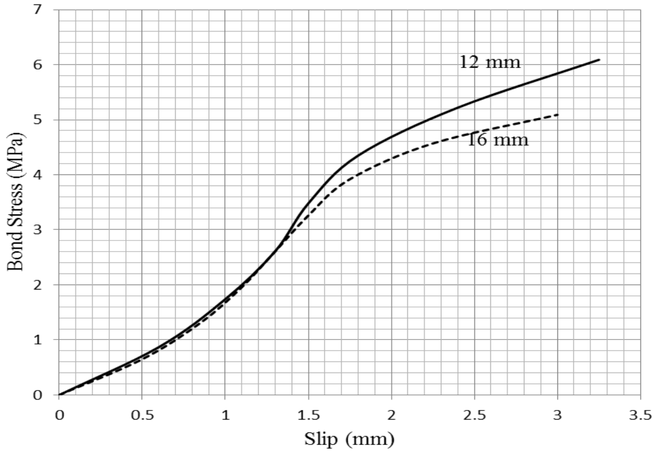

Fig. 10: Bond-slip relationships at 15% corrosion level

### 3.3 Effect of Rebar Corrosion on Maximum Bond Stress

Effect of corrosion on maximum bond stress is presented in Figure 11. Maximum bond stress of 12 mm and 16 mm rebar at 0%, 5%, 10% and 15% corrosion level were 9.31 MPa, 9.14 MPa, 7.83 MPa, 6.09 MPa, 8.09 MPa, 7.96 MPa, 6.85 MPa and 5.09 MPa respectively. According to Aslani & Samali, 2013, maximum bond stress of 12 mm and 16 mm rebar at 0% corrosion level were 10.5 MPa and 9.42 MPa respectively at 20°C temperature. A loss of 11.3% and 14.12% bond stress were observed in the laboratory for 12 mm and 16 mm rebar respectively. This was because of the change in temperature and humidity. It can be revealed that corrosion had less impact on maximum bond stress up to 5% corrosion level. Afterwards, it was found that maximum bond stress decreased with the increase of corrosion for both 12 mm and 16 mm diameter bar. Decreasing rate of maximum bond stress increased with the increase of corrosion level. Bond stress losses up to 34.5% and 37% were observed in 12mm-Ø or 16mm-Ø bar, respectively, for 15% corrosion level. This was because of the change in material properties of rebar surface due to corrosion. Adhesion and friction between rebar and concrete were decreased due to the presence of rust at the surface of rebar.

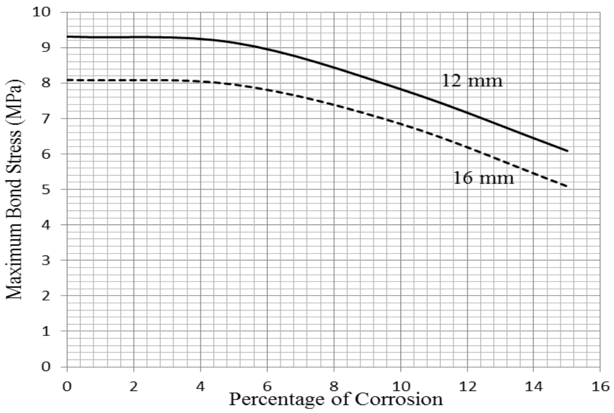

Fig. 11: Effect of corrosion on maximum bond stress

## 4. CONCLUSIONS

This study evaluated the bond performance of corroded rebar into reinforced concrete under direct pullout tests. The influence of parameters such as degree of corrosion and bar diameter to the bond between the rebar and reinforced concrete were investigated. Based on the results, the following conclusions are made:

- Bond stress of both 12 mm and 16 mm diameter reinforcement without corrosion is maximum than reinforcement with corrosion. corrosion had less impact on maximum bond stress up to 5% corrosion level. Afterwards, with the increase in degree of corrosion the linear behavior become defunct and then, bond stress decreases exponentially or at least shows abrupt behavior. On the other hand slip increases with the increase of corrosion. Decreasing rate of bond stress increases with the increase of slip. It is clear that, reinforcement without corrosion shows greater resistance against bond failure in comparison to the reinforcement with corrosion for both 12 mm and 16 mm diameter bar.
- Bond stress of 12 mm diameter reinforcement is greater than 16 mm diameter rebar at 0%, 5%, 10% and 15% corrosion level. Slip of 12 mm diameter rebar is greater than the slip of 16 mm diameter rebar at failure condition. It is also clear that, reinforcement of 12 mm diameter with or without corrosion shows greater resistance against bond failure in comparison to the reinforcement of 16 mm diameter bar.
- Resistance against bond failure decreases with the increase of corrosion level. So, it is required to take steps to protect reinforcement from corrosion for getting expected life time of the structure. If fully protection of reinforcement from corrosion is not possible or costly then reduce the maximum possible amount of corrosion.
- After reduction of the maximum possible amount of corrosion, a certain amount of corrosion will be present into the structure. So, bond failure can be occurred. To resist this bond failure, required amount of additional reinforcement should be used at the time of construction which fills up the lack of bond stress due to corrosion.

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