Influence of Corrosion on Bond Stress Characteristics of Concrete

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Abstract – *Corrosion of reinforcement is a dangerous process that causes the diminished bond performance due to the reduction in cross sectional area of the steel subsequently leading to the failure of structures. Corrosion being an inevitable phenomenon, sufficient studies must be carried out to assess whether the residual bond strength that could be offered by a corroded steel bar satisfies the limits recommended in the IS456:2000. This paper hence studies the variations in the bond stress of pull out specimens with 16 mm diameter central reinforcement subjected to accelerated corrosion with variations in grade of concrete. The commonly used grades of M20, M25 and M30 were tested experimentally through pull out test and analytically using the Finite Element software ANSYS14.5. The extension of analytical study was done to higher grades of M35 and M40 to estimate the corrosion levels upto which they could provide the required minimum bond stress values. The residual bond stress at various corrosion levels was found to be comparatively higher for the higher grades of concrete.*

Key Words: **Corrosion, Bond Stress, Accelerated corrosion, Pull out test, Pull out specimen**

1.INTRODUCTION

Corrosion of reinforcing bar is now recognized as the major cause of degradation of concrete structures in many parts of the world. While the most obvious effect of corrosion is a reduction in cross sectional area of reinforcing bars, there are other associated effects caused by the build-up of corrosion products at the interphase between the reinforcement surrounding concrete. These corrosion products are expansive in nature and so induce radial pressures on the surrounding concrete resulting in cracking and spalling. Most cement provides ideal condition for the initiation of corrosion. Hence the problem of corrosion is inevitable. The failure mode due to the corrosion is mostly the bond failure. The efficiency of the load transfer from concrete to steel is primarily dependent upon the bond between the steel and the concrete. Adequate bond between concrete and steel is hence one of the most important prerequisites for the concrete construction. Composite action of the concrete and steel cannot be achieved without adequate bond. Adequate bond stress is a necessity for the proper transfer of the tensile stresses from concrete to steel. This makes the study of relation between the corrosion rates and the bond stress relevant. The previous researches in the specified area indicates that, the slight corrosion levels increases the bond stress whereas severe corrosion has an opposite effect [1], [5], [7].The initial increase in the bond strength is commented to be due to the friction offered by the corrosion products[11]. The corrosion could be artificially provided to the reinforcement through different methods such as accelerated impressed current technique, accelerated chloride ion diffusion and artificial climate environment [6]. However most of the researchers have preferred the impressed current technique otherwise called as electrolyte corrosion technique for providing the required levels of corrosion [2], [3], [4]. Irrespective of the method, the corrosion of reinforcing steel leads to cracking of concrete and subsequent loss in the load carrying capacity of a reinforced concrete member [2]. Corrosion of reinforcing steel also increases its brittleness which eliminate the warning prior to failure of a structure [2]. The load bearing capacity of the specimen could be determined through the pull out test conducted with a Universal Testing Machine [4]. The bond strength has proved to have an inverse relation with the diameter of bar embedded in the concrete [9]. Finite element analysis was also successfully employed by various researches for the determination of the bond strength [5], [8], [9], [12], [13]. The software ANSYS was preferred by most researchers for the finite element analysis even though the software ABAQUS was also used by a few. The comparison of the experimental and analytical results shows positive agreement. Most of the researches up to the date have concentrated only for limited levels of corrosion up to about 15%. This paper aims to conduct studies on bond stress by increasing the corrosion level with variations in grade of concrete to assess whether a corroded bar could be used as a reinforcement for a particular grade of concrete satisfying the limits suggested by the code.

2. EXPERIMENTAL INVESTIGATION

2.1 Concrete Mix Details

The commonly used mix of M20, M25 and M30 were used for this study. The M20 and M25 mix being the nominal mixes, proportioning was done as 1:2:4 and 1:1.5:3, respectively, according to IS 456:2000. The mix design for M30 was done according to the recommendations and calculations mentioned in IS456:2000 and IS 10262:2009. The materials were tested for various properties required for the mix design. After various trials, the mix proportion was arrived at 1:1.62:2.99. A super plasticizer was used at 0.5% by weight of cement for obtaining a desired slump range of 80-100 mm. The proportioning for various mixes are given in the Table -1.

Table -1: Concrete mix details

Mix	Cement	Fine aggregate	Coarse aggregate	W/C ratio	Admixture
M20	1	1.5	3	0.49	Nil
M25	1	1	2	0.45	Nil
M30	1	1.62	2.99	0.38	0.5%

3.2 Preparation of Test Specimen

The specimens for the pull out tests were prepared according to the recommendations given in IS 2770-1967-Part-1. Accordingly, the size of the cubes were fixed as 150 mmx150 mmx150 mm. The central longitudinal reinforcement extended for a length of 750 mm above the top surface of the cube for facilitating the gripping and for a length of 25 mm beyond the bottom surface of the cube for attaching the dial gauge. The various levels of corrosion were imparted to the specimens through the accelerated corrosion technique which is basically a galvanic cell setup in which a continuous direct current supply unit supplying current up to 5A was employed. The positive terminal of the power unit was connected to the steel reinforcement making it as the anode and the negative terminal to a steel plate making it as the cathode. The electrolyte used was the 5% NaCl solution. The specimens were dipped in the electrolyte solution such that the specimens were dipped upto the top surface of the cube. The direct current required for various levels of corrosion was determined by using the Faraday's law given below

$$Iapp = \frac{\rho w_i F}{100\pi DLWT} \quad (1)$$

where, I_{app} is the applied current, ρ is the degree of corrosion, wi is the initial weight of the steel in kg, F is the Faraday constant whose value is 96487As, D is the diameter of the bar in mm, L is the embedment length in mm, W is the equivalent weight of the steel which is 27.925g and T is the time in seconds. The casted specimens after 28 days of corrosion were subjected to required levels of corrosion and tested. The accelerated corrosion setup is shown in Fig-1.

3.3 Pull out test

Test set up used for the study is shown in the Fig-2. The specimens are tested in a Universal Testing Machine of capacity 1000kN. The strength at which the bond failure occurred was measured from the dial gauge of the machine. The slip values were recorded using the dial gauge attached to the bottom projection of the reinforcement.

Fig -1: Accelerated corrosion setup

Fig -2: Pull out test

3.4 Determination of Bond Stress

Average bond stress was obtained from the equation below

$$\tau_{bd} = \frac{P}{\pi DL} \quad (2)$$

where, τ_{bd} is the average bond stress in N/mm^2, P is the pullout strength in N, D is the diameter of the bar in mm and L is the embedment length in mm.

4. NUMERICAL INVESTIGATION

To model the pull out test for finite element analysis, ANSYS14.5 software package was used. Selection of ANSYS was done based on the better graphical utilities in ANSYS which enables to model different materials using its inbuilt element types.

4.1 Element Types and Material Properties

The element types assigned to the model in ANSYS14.5 are given in Table-2

Table -2: Element types

Material	Element Type
Concrete	SOLID65
Steel	LINK180
Interface	COMBIN39

The non-linearity of Combin39 element was defined by giving load-displacement relationship as the input. The relationship between local bond stress and slip at the bar concrete interface along the longitudinal direction is given below

$$\tau(s) = (61.5\,s - 693s^2 + 3.14\,x\,10^3\,x\,s^3 - 0.478x10^4\,x\,s^4)f_{t,s}\,x\sqrt{c/d} \quad (3)$$

Where, is the local bond stress, s is the slip value in mm, c is the thickness of cover layer in mm, d is the diameter of the reinforcement in mm, $f_{t,s} = 0.19 \times f_{ck}^{0.75}$, f_{ck} is the compressive strength of the concrete in N/mm^2[8]

In the finite element model, the relationship between the bond force L and slip value s can be calculated as follows,

$$L(s) = \tau(s)\pi dl \quad (4)$$

Where d is the diameter of the bar in mm and l is the distance between two adjacent spring elements in mm [12]

When corrosion rate is η, the equation (4) get changed as follows,

$$L(s) = ß\,\tau(s)\pi dl \quad (5)$$

Where ß is a reduction factor obtained through equation,

$$ß = \{1 + 0.5625\eta - 0.3375\,\eta^2 + 0.055625\,\eta^3 - 0.003\,\eta^4, \eta \le 7\%$$
$$ß = \{2.0786\,\eta - 1.0369\quad, \eta > 7\% \quad (6)$$

4.2 Finite Element Modelling

The specimen was a concrete cube of 150 mm sides, with single concentric steel bar. The model was created by defining the coordinates of the cube in the modelling section of the ANSYS. The reinforcement was modelled by creating a line and then assigning the element type to it. The coincident nodes at the interphase of the concrete and steel were merged. The COMBIN39 element was assigned to these merged nodes for the efficient analysis. Meshing is one of the most important of the entire analysis, for the decisions made at this stage in the model development will profoundly affect the accuracy and economy of the analysis. Mesh controls allow to establish such factors as the element shape, midside node placement, and element size to be used in meshing the solid model. The Mesh Tool provides a convenient path to many of the most common mesh controls, as well as to the most frequently performed meshing operations. Since the test to be conducted is a pull out test, the boundary conditions must be made such that the concrete cube must be in a fixed condition. Accordingly, the boundary conditions for the geometric model were applied by fixing the nodes of the cube in three directions except the nodes adjacent to the steel bar. The nodes adjacent to steel bar as well as the nodes of the unbonded length were fixed in two directions only.

4.3 Analysis

Small displacement static type of the analysis option was selected for carrying on the analysis. The Von-Mises stress distribution obtained from the General post processing result was used to obtain the resulting stress (fs) in the steel. The bond stress (τ_{bd}) was hence calculated from the equation (7) which is as follows,

$$\tau_{bd} = \frac{Ø1 fs}{4ld} \quad (7)$$

Where $Ø_1$ is the reduced bar diameter, f_s is the stress in steel obtained from ANSYS and l_d is the embedment length [12].

The reduced bar diameter $Ø_1$ of a bar of initial diameter Ø at a corrosion percentage η is given by the following equation

$$Ø1 = Ø\sqrt{1 - \frac{\eta}{100}} \quad (8)$$

The Von Mises stress distribution obtained from ANSYS14.5 is given in the Fig-3.

5. RESULTS AND DISCUSSION

The results obtained from the pull out tests conducted on pull out specimens with M20, M25 and M30 grade of concrete are tabulated in the Table-3. The variations are plotted in the Chart-1 .From the results it was observed that in all the three grades of concrete, the bond stress remain above the values specified by the IS456:2000 even upto the 25% corrosion level. But the reduction in bond stress is less for the specimens with M30 grade concrete compared to the lower grades.

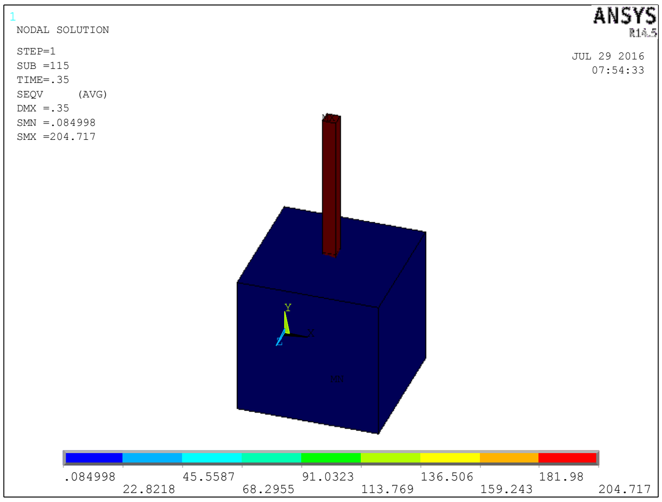

Fig-3: Von-Mises stress distribution from ANSYS 14.5

At 15% corrosion level, the bond stress of specimens with M20 and M25 grade concretes are reduced to about 60% whereas the M30 specimens loses only about 40% of bond stress at the same corrosion level.

Table -3: Results obtained from pull out tests

Mix	Level of corrosion	Residual Bond stress	Reduction in bond stress with respect to non-corroded specimens	Minimum bond stress required as per IS456:2000
M20	0%	9.82	-	1.92 N/mm²
M20	15%	4.11	58.15%	1.92 N/mm²
M20	20%	3.05	68.94%	1.92 N/mm²
M20	25%	2.52	74.34%	1.92 N/mm²
M25	0%	9.95	-	2.24 N/mm²
M25	15%	4.25	57.29	2.24 N/mm²
M25	20%	3.2	67.84	2.24 N/mm²
M25	25%	2.65	73.37	2.24 N/mm²
M30	0%	9.98	-	2.4 N/mm²
M30	15%	6.1	38.88%	2.4 N/mm²
M30	20%	4.38	56.11	2.4 N/mm²
M30	25%	3.32	66.73	2.4 N/mm²

At 25% corrosion levels, the loss of bond stress in M30 specimens is limited to about 67% which is about 75% in other two grades. However, the residual bond stress is found increasing with the increase in the grade of concrete.

The results obtained from ANSYS14.5 showed same trend of variation as that of the experimental results. The comparison of ANSYS and experimental results are given in Chart-2.The results obtained from finite element analysis done in ANSYS 14.5 are tabulated in Table-4. The plot of variations is given in Chart-3.

From the experimental results, it is clear that the specimen with M30 mix have higher bond stress than those with lower concrete grades at 25% corrosion level. The electric supply required for the accelerated corrosion purpose for the M30 specimens were also found higher compared to the lower grade concrete.

Chart-1: Variation of bond stress with corrosion level

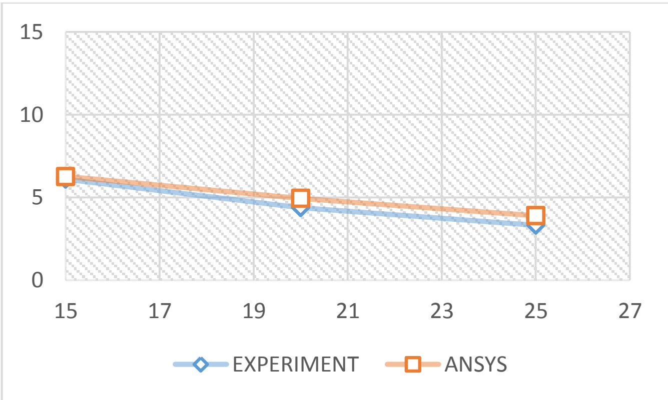

Chart-2: Comparison of ANSYS and experimental results for M30 specimens

L.Abossera et al [7] has conducted studies on the corrosion of steel reinforcement in concrete of different grades and commented that this superior performance of the higher grade concrete is attributed to its dense pore structure that inhibits the penetration of chloride and moisture to steel- concrete interface and also due to the higher electrical resistivity that retards the flow of

electrons from cathode to anode sites, thus impeding the propagation of corrosion process.
The specimens throughout the study have been given an embedment length of 150 mm. But according to IS 456:2000, the bond stress and the development length has an inverse relationship and the design bond stress increases with the increase in the grade of concrete. This implies that the higher grade specimen which has a higher design bond stress, according to the code, does not require a development length of 150 mm. This could reduce the wastage of steel as development length in real structures. Hence the observed increase in the bond stress of higher order graded specimens in the present study may be due to the larger development length provided to the specimen which is actually not required.

Table -4: Results obtained from ANSYS14.5

Mix	Level of corrosion	Residual Bond stress	Minimum bond stress required as per IS456:2000
M20	0%	7.57 N/mm²	1.92 N/mm²
M20	15%	5.02 N/mm²	1.92 N/mm²
M20	20%	3.76 N/mm²	1.92 N/mm²
M20	25%	3.15 N/mm²	1.92 N/mm²
M25	0%	7.79 N/mm²	2.24 N/mm²
M25	15%	5.78 N/mm²	2.24 N/mm²
M25	20%	4.33 N/mm²	2.24 N/mm²
M25	25%	3.55 N/mm²	2.24 N/mm²
M30	0%	7.94 N/mm²	2.4 N/mm²
M30	15%	6.26 N/mm²	2.4 N/mm²
M30	20%	4.94 N/mm²	2.4 N/mm²
M30	25%	3.90 N/mm²	2.4 N/mm²
M35	0%	8.24 N/mm²	2.72 N/mm²
M35	15%	6.55 N/mm²	2.72 N/mm²
M35	20%	5.55 N/mm²	2.72 N/mm²
M35	25%	4.27 N/mm²	2.72 N/mm²
M40	0%	8.24 N/mm²	3.04 N/mm²
M40	15%	6.76 N/mm²	3.04 N/mm²
M40	20%	5.93 N/mm²	3.04 N/mm²
M40	25%	4.72 N/mm²	3.04 N/mm²

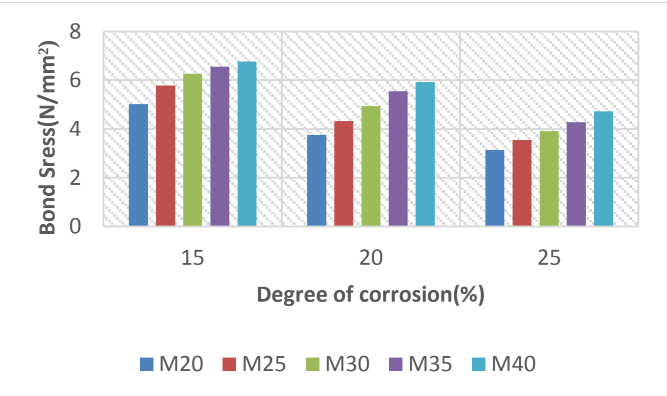

Chart-3: Variation of bond stress with corrosion level (ANSYS)

Also, deep groves are formed on the steel surface during the accelerated corrosion due to the ability of high concrete strength to keep the corrosive environment in a narrow zone [7]. This could also be the reason for the superior performance of specimens with higher grade concrete.
A multivariable regression analysis has been conducted based on the results from the study and the following regression equation has been obtained with R squared value equal to 0.96.

$$\tau_{bd} = 5.78 + 0.08m - 0.16\eta \qquad (9)$$

where, τ_{bd} is the bond stress in N/mm², m is the compressive strength of the concrete in N/mm² and η is the percentage of corrosion.
The above suggested multivariable regression equation holds good for grade of concretes from M20 to M40 subjected to corrosion levels upto 25%. The values obtained from the equation found to have a variation of 1-9% only from the analytical results.

CONCLUSION

Following conclusions are drawn based on the results obtained from experiment and numerical analysis.

i. Accelerated corrosion technique could be used as a feasible method to estimate the rate of mass loss of a steel bar embedded in concrete.
ii. The bond stress reduces with increase in the level of corrosion. The reduction in bond stress increases from 18% to 75% when the corrosion level was increased from 15% to 25%.
iii. The bond stress increases with the increase in the compressive strength of the concrete. As the corrosion level increases from 15% to 25%, the bond stress increases 7%-19% with the increase in compressive strength from M20 to M40.
iv. The finite element software ANSYS could be effectively used to study the variation of bond stress with the change in corrosion levels
v. The suggested multivariable regression equation could be used to determine the bond stress of the specimens with grades of concrete from M20 to M40 subjected to reinforcement corrosion levels upto 25% with 1-9% variation from the analytical results.

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