RESIDUAL FLEXURAL STRENGTH OF CORRODED REINFORCED CONCRETE BEAMS

Luaay Hussein, Lamya Amleh[1]

[1] Ryerson University, Canada

Abstract: Corrosion of reinforcing steel is one of the most deterioration factors that influence reinforced concrete structures. Corrosion causes cracking and spalling of concrete structures, and reduces the bond strength at steel-concrete interface, and other related effects that weaken the serviceability and the ultimate strength of the reinforced concrete members. In this paper, a simple model that can be used to predict the residual flexural strength of RC beams with varying degrees of reinforcement corrosion based on experimental results using ANalysis Of VAriance (ANOVA). The moment resistance method which is based on flexural analysis of reinforced concrete beams was adopted. The results of the proposed model were validated by comparing the model with experimental results obtained by several researchers. The new proposed model in this study was able to successfully predict the residual flexural strength of corroded reinforced concrete beams.

Keywords: Serviceability, Reinforced Concrete, Corrosion, Flexural strength, Analysis Of Variance

1   INTRODUCTION

Corrosion of steel reinforcement is one of the most predominant causes of the deterioration of reinforced concrete (RC) structures, greatly shortening the service life of the structure and increasing maintenance costs (Broomfield 2002, Bertolini et al. 2004). The rehabilitation of RC structures affected by corrosion costs billions of dollars every year (ASCE Infrastructure Report Card 2013; Canadian Infrastructure Report Card 2016). Reinforcement corrosion should thus be of great concern to engineers when designing new structures. The residual strength of old structures should be properly estimated in order to ensure that the required repairs are performed on time to guarantee public safety.

The corrosion of reinforcement causes a decrease in rebar diameter, cracking and spalling of the concrete cover, which adversely affects the ultimate strength of RC structures. Furthermore, when the steel rebar corrodes, the corrosion products of reinforcing steel exert stresses within the concrete resulting in the formation of cracks along the reinforcing bars. These cracks weaken the bond and the anchorage between steel and concrete and lead to cracking and spalling of concrete which in turn facilitates the ingress of oxygen and moisture to the reinforcing steel and increases the rate of corrosion (Azad et al. 2007, Wang and Liu 2008, Berto et al., 2008).

Extensive experimental, numerical and analytical models to predict the flexural strength of corroded RC structures were undertaken (Cabrera 1996; Huang and Yang 1997, El Maaddawy et al. 2005, Azad et al.

2007, Wang and Liu 2010, Imam et al. 2015, Ahmad 2017). Cabrera (1996) investigated the effect of bond loss on the serviceability and ultimate strength of RC structures. Huang and Yang (1997) proposed a relationship between the corrosion of RC beams and load-carrying capacity. El-Maaddawy et al. (2005) investigated the combined effect of corrosion and sustained loads on the flexural behaviour of corroded RC beams. In their model to predict flexural behavior of corroded RC beams, the deflection of a RC beam was calculated from the elongation of the rebar between concrete cracks rather than from curvatures of beam sections. A two-step model based experimental results to predict the residual flexural strength of corroded RC beams was proposed by Azad et al. (2007). Wang and Liu (2010) proposed a simplified model to predict the residual flexural strength of corroded doubly reinforced RC beam. A model based on artificial neural networks to predict the residual strength of corroded RC members was proposed by Imam et al. (2015). Ahmad (2017) proposed an empirical model to estimate the residual flexural strength corroded RC beams based on corrosion current density and duration, and diameter of the reinforcement steel bar. However, some discrepancies between the proposed models and the actual experimental values have been observed. Furthermore, all these models required extensive calculations to predict the flexural strength of corroded RC beams. Therefore, it's very important to propose a simplified model to estimate the residual flexural strength of corroded RC beams.

2   RESEARCH SIGNIFICANCE

In view of the fact that corrosion damage reduces the strength of a reinforced concrete element, it is of great interest to develop a model that can be used to predict the relative flexural strength of corroded concrete members. The need for the prediction of the relative strength often arises to determine the underlying safety of the corroded members and to decide when the repair or strengthening must be undertaken without any further delay.

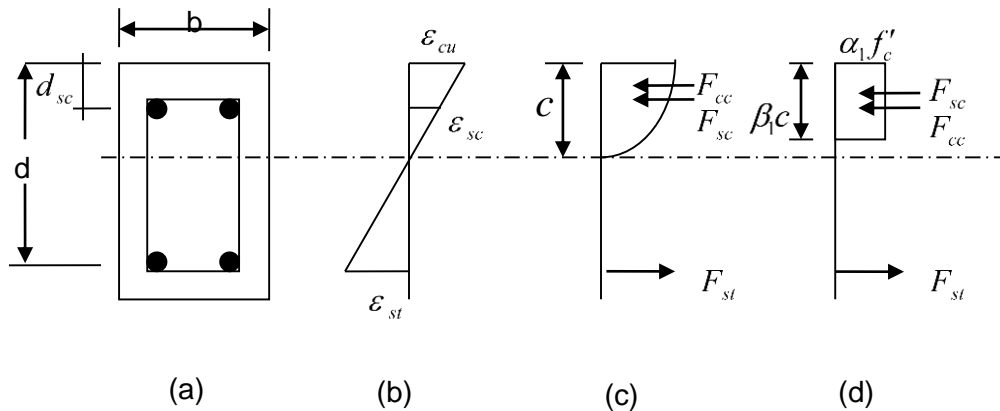## 3   FLEXURAL STRENGTH OF REINFORCED CONCRETE MEMBERS

Figure 1: Vertical stress and strain distribution: (a) typical reinforced concrete beam section (b) strain distribution (c) actual concrete stresses (d) equivalent concrete stresses

The stress and strain distributions of reinforced concrete beam are shown in Fig. 1. The flexural strength of reinforced concrete beams can be calculated from Equation 1.

$$[1] \; M_u = A_{st} * f_y * (d - c) + A_{sc} * f_{sc} * (c - d_{sc}) + \alpha_1 f_c' \beta_1 cb * (c - \frac{\beta_1 c}{2})$$

where, M_U Ultimate moment of resistance before corrosion, f_y steel yield strength, d = depth of tensile steel reinforcement measured from top face of the beam, and c = depth of neutral axis measured from the top face of the beam, f_{sc} steel stress in compression, A_{st} area of tensile steel reinforcement, A_{sc} area of compression steel reinforcement, f_c' concrete compressive, d_{sc} depth of compression steel reinforcement, b= width of the beam, α_1 and β_1 are concrete stress block factors as shown Fig. 1.

Equation 1 can be used for uncorroded beams, however when the beams get corroded there will be a reduction in the moment resistance due to the loss of the cross sectional area of the steel and the loss of the bond between the concrete and the steel. Therefore, Equation 1 cannot be used to determine the flexural strength of reinforced concrete beam.

3.1   Analytical Model for Flexural Strength of Reinforced Concrete members

Assuming a uniform corrosion over the surface of the reinforcing bar, and the concrete in tension is cracked and no longer contribute to the tensile resistance of RC beam; the tensile force for a beam designed to fail in bond, F_{stx} at any corrosion level xp is given as follows:

$$[2] \; F_{stx} = n_{st} * \pi * d_{stx} * \tau_{bu} * l_d$$

Where, n_{st} = number of reinforcing bars in tension, d_{stx} = reduced diameter of reinforcing bars in tension at corrosion level xp, τ_{bu} = bond strength of reinforcing bars in tension at corrosion level xp , l_d = development length.

When the reinforcing bar corroded, the stress in the steel is less than the yield stress. The reason for this is that the formation of corrosion products layer exerts an outward pressure on the concrete from inside and as the pressure builds, the ultimate result is cracking of the concrete, which in turns results in a loss of bond between steel and concrete. Therefore, stresses in concrete cannot be transferred to the reinforcing steel properly. Stress in the corroded steel bar cannot be obtained from the strain compatibility equation because plain sections before bending will not remain plain after bending. Thus, the strain compatibility becomes invalid for corroded bars (Wang and Liu 2008).

From compatibility requirement as shown in Fig. 1, the strain for steel in compression can be obtained from Equation 3:

$$[3] \; \varepsilon_{sc} = \frac{\varepsilon_c(c - d_{sc})}{c}$$

Therefore, the compression force carried by steel in compression, F_{sc} , is:

$$[4] \; F_{sc} = A_{sc} * E_S * \frac{\varepsilon_c(c - d_{sc})}{c}$$

and the compression force carried by concrete in compression is:

$$[5] \; F_{cc} = \alpha_1 f_c' \beta_1 cb$$

3

From equilibrium,

[6] $F_{stx} = F_{sc} + F_{cc}$

The depth of neutral axis can be obtained from Equation 6, and the ultimate moment of resistance after corrosion can be determined as follows:

[7] $M_u = F_{stx} * (d - c) + F_{sc} * (c - d_{sc}) + F_{sc} * (c - \frac{\beta_1 c}{2})$

3.2 Data Analysis

ANOVA is used in analyzing the data available (Mangat and Elgarf 1999, Rodriguez et al. 1997, Azad et al. 2007, El Maaddawy et al. 2005, Joyce 2008) to determine the residual flexural behavior of corroded reinforcing concrete beams. First an interpolation of the data has been done at different levels of corrosions (Mass Loss, ML %) 2.5%, 5%, 10%, 15%, 20%, 25% and 30%. To preform that analysis, the built-in function 'anovan' in MATLAB was chosen as the primary method of variance analysis. Based on the results of ANOVA, an equation to determine the yield strength of corroded reinforcing bar as follows:

[8] $f_{yx} = \left(1 - \frac{ML}{96}\right) * f_y$

Where, f_{yx} = yield strength of corroded reinforcing bar at corrosion level xp, f_y = yield strength of sound reinforcing bar, and ML = mass loss percent.

The tensile force, F_{stx} , at any corrosion level xp is determined as follows:

[9] $F_{stx} = n_{st} * \pi * d_{st}^2 * f_{yx}/4$

The compression force carried by steel in compression, F_{sc} , and by concrete in compression, F_{cc} , can be obtained from Equations (4), and (5) respectively. By using the equilibrium Equation 6, the depth of neutral axis can be obtained, and the ultimate moment of resistance after corrosion can be determined from Equation 7.

4 VALIDATION OF THE PRESENT EMPIRICAL MODEL

4.1 Validation of the model with the results of Mangat and Elgarf (1999)

Mangat and Elgarf conducted experimental results on reinforced concrete beams with and without stirrups. 111 reinforced concrete beams under different levels of corrosion have been tested to determine their flexural capacity, using 150 x 100 mm beam specimens in cross section and 910 mm in length with two 10 mm bottom bar. The concrete cover thickness was 19 mm, with a concrete compressive strength of $f_c' = 40 MPa$, and tensile yield strength of steel is $f_y = 520 MPa$. Some of the beams reinforced with 6 mm stirrups at 70 mm spacing and two 6 mm steel bars in compression. The experimental results and the predicted values of the proposed model with the increase of corrosion level is presented in Fig. 2. The corrosion level % represents the reduction in reinforcing bar diameter due to corrosion is determined as $2RT/D$ where R is material loss per year, T is the period of corrosion and D is diameter of the bar.
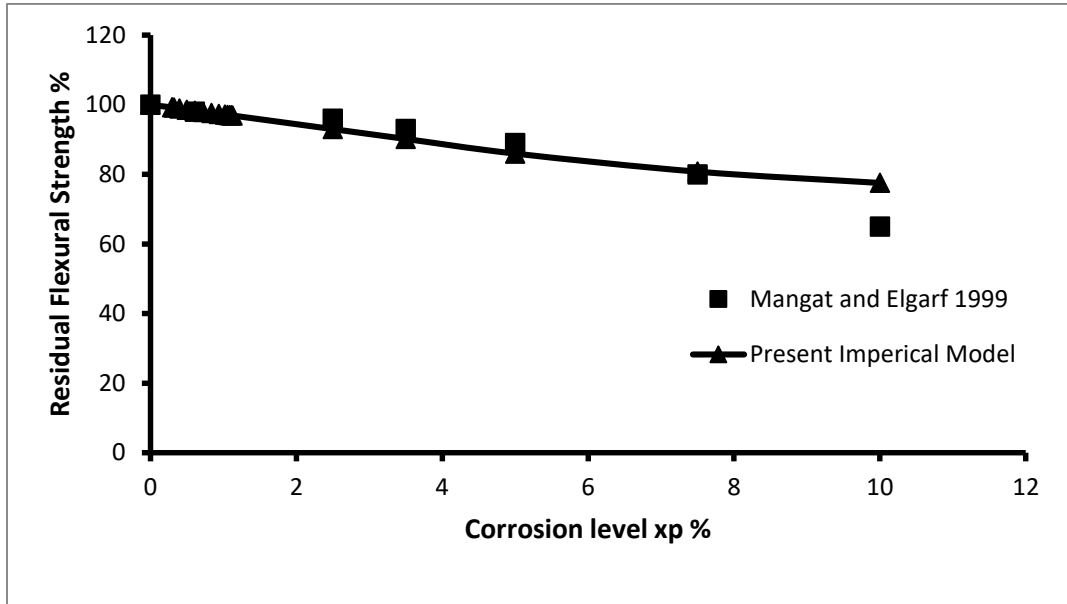
Figure 2: Comparison of predicted present model versus corrosion level with Mangat and Elgarf (1999) experimental results with stirrups

4.2   Validation of the model with the results with Maaddawy et al. (2005)

Maaddawy et al. studied the effect of corrosion on flexural capacity of reinforced concrete beam of 152 x 254 x 3200 mm each. Eight specimens were damaged by corrosion for up to a maximum of 33% steel mass, while one specimen was not corroded to serve as a control. The tensile steel reinforcement consisted of two No. 15 Grade 60 steel bars having a yield and ultimate strengths of 450 and 585 MPa, respectively. Two 8 mm-diameter plain bars having a yield and ultimate strengths of 340 and 500 MPa, respectively, were used as compression steel reinforcement. The average compressive strength of the concrete was 40 MPa, whereas the concrete strain at crushing was taken as 0.0038 according to Park and Paulay ("Reinforced concrete structures", 1975). One specimen was used as a control, while the other eight specimens were subjected to an accelerated corrosion for 50, 110, 210, and 310 days. Four beams, CN-50, CN-110, CN-210, and CN-310, were kept unloaded during the corrosion exposure, while the other four beams, CS-50, CS-110, CS-210, and CS-310, were corroded under a sustained load with an applied moment of 20 KN.m (approximately 60% of the yielding moment of the control beam). Corrosion was restricted to the constant moment region of the beam to ensure that a pure flexural mode of failure will dominate. The corrosion level % represents the reduction in reinforcing bar diameter due to corrosion is determined as $0.5ML$ where ML is material mass loss percent. The experimental results and the predicted values of the proposed model with the increase of corrosion level are presented in Fig. 3.
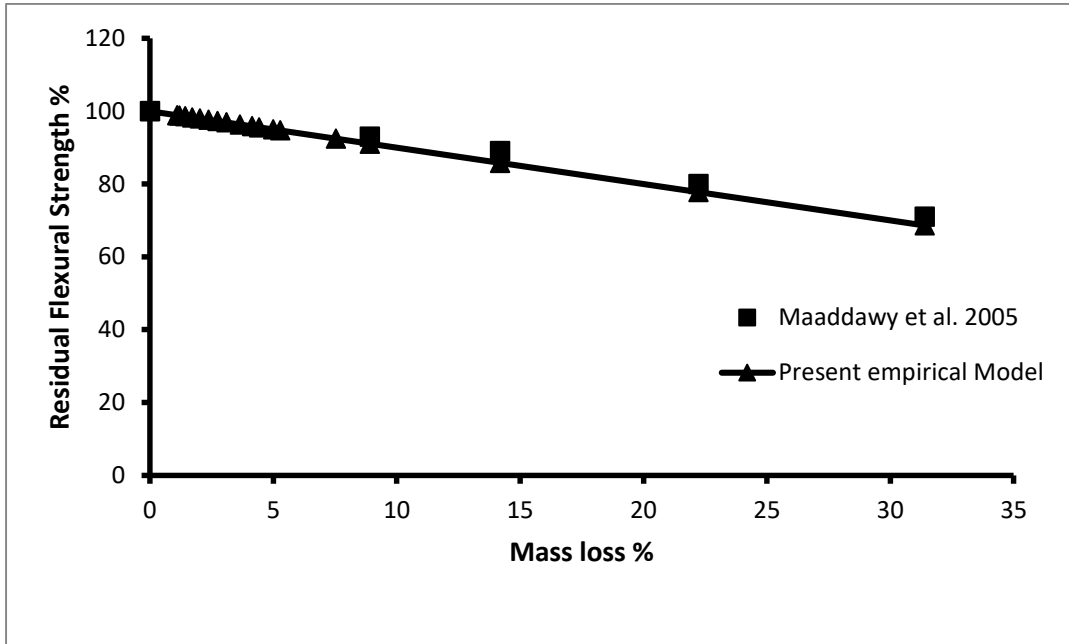
Figure 3: Comparison of predicted present model versus mass loss % with Maaddawy et al. (2005) experimental results without loading

4.3 Validation of the model with the results with Timothy Joyce (2008)

Timothy Joyce studied the effect of corrosion on the flexural behaviour of 12 reinforced concrete beams. Beam specimens with a cross section of 156 x 176 mm were reinforced with 16 mm steel bars. The tensile steel bars were epoxy painted in order to concentrate the corrosion near the mid span of the beam specimens. Double leg 8 mm stirrups with yield strength 400MPa were used in the experiments, the spacing between the stirrups is 67 mm; they were also coated to protect them from corrosion. The concrete cylinder compressive strength showed an average strength of 40.2 MPa. Timothy Joyce tested the corroded and uncorroded beams in the same identical setup in order to compare the results effectively. The experimental results and the predicted values of the proposed model with the increase of corrosion level are presented in Fig. 4
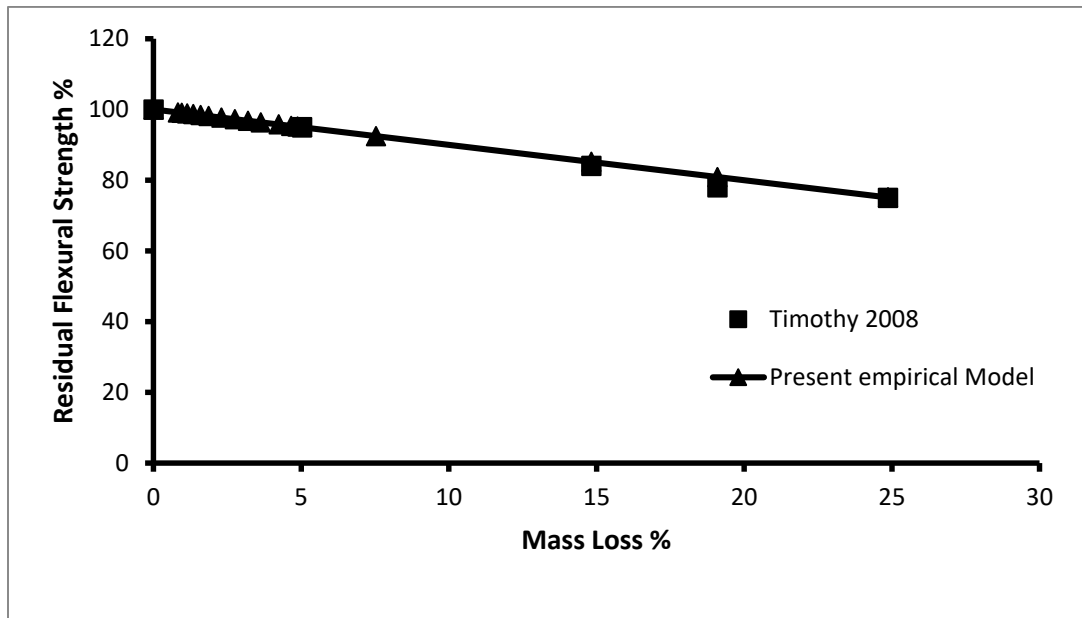
Figure 4: Comparison of predicted present model versus mass loss % with Timothy (2008) experimental results

4.4   Validation of the model with the results with Azher Syed (2007)

Azher Syed studied the effect of corrosion on reinforced concrete beams. Azher Syed developed a model to predict the residual flexural strength of reinforced concrete beams with varying degrees of reinforcement corrosion. The experimental variables included: applied corrosion's current density, corrosion duration, rebar diameter, and thickness of concrete cover. A total of 56 reinforced concrete beams (150 × 150 × 1100 mm) were cast using a common concrete mix, out of which 8 beams were earmarked as control beams that were not subjected to corrosion and the remaining 48 beams were subjected to corrosion by impressed current. The chosen clear covers were 25 mm and 40 mm. The tension reinforcement consisted of a pair of 10 mm or a pair of 12 mm diameter steel bars. The vertical stirrups were double-legged, 6mm diameter steel bars spaced uniformly at 90 mm centers throughout the length of each beam. While the top two 8 mm diameter bars that were used to serve as stirrup-holders were epoxy-coated to avoid corrosion, the stirrups were left uncoated so that they would be affected by corrosion along with the main tension bars. By allowing the stirrups to corrode, the corrosion damage of the tested beams reflects the practical case in which all bars are subjected to corrosion. BT2 and BT4 consist of 12 mm tension reinforcement with 25 mm and 40 mm respectively. BT1 and BT3 consist of 10 mm tension reinforcement with 25 mm and 40 mm respectively. The average values of 28-day compressive strength of concrete were 39.95 MPa. The tensile steel reinforcement yield and ultimate strength were 590 MPa, and 700 MPa respectively. The experimental results and the predicted values of the proposed model with the increase of corrosion level are presented in Figures 5 and 6.
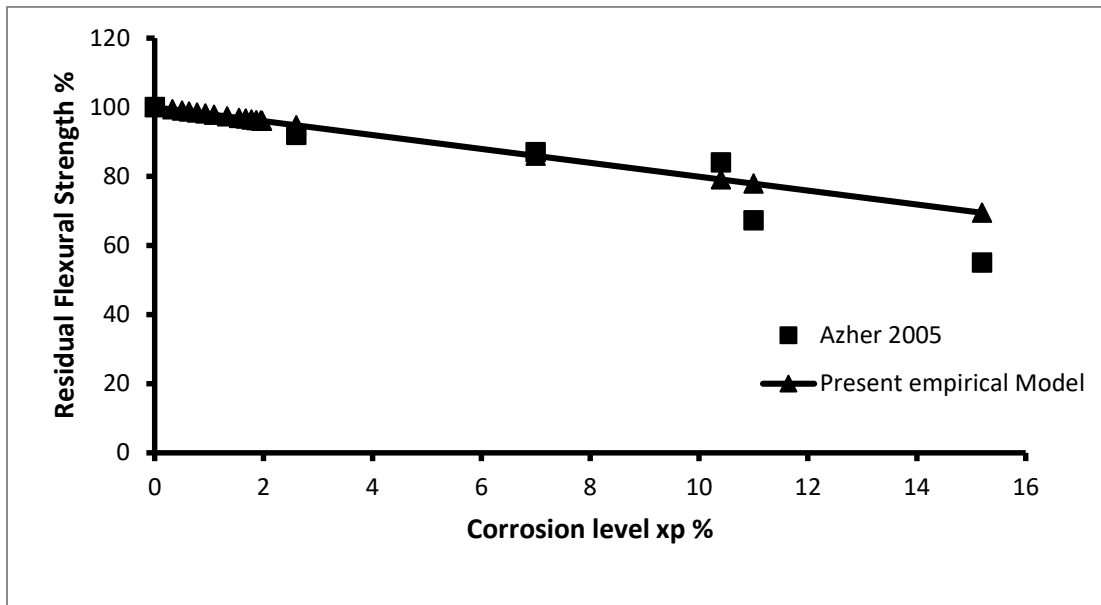
Figure 5: Comparison of predicted present model versus corrosion level % with Azher (2005) experimental results for beam BT1
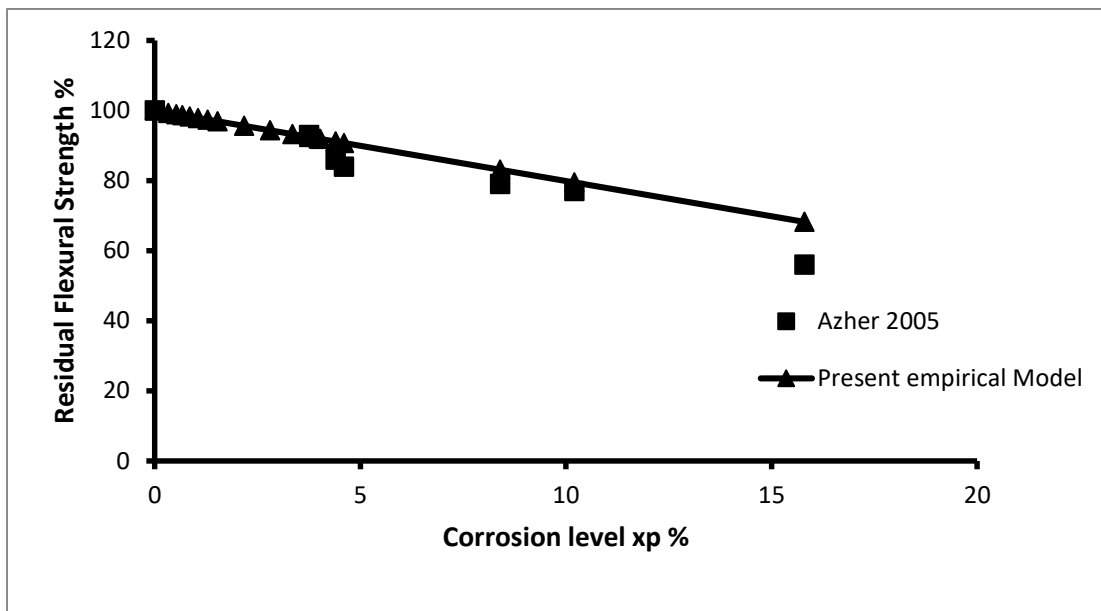

Figure 6: Comparison of predicted present model versus corrosion level % with Azher (2005) experimental results for beam BT3

5 CONCLUSIONS

The corrosion of steel reinforcement reduces the strength of a reinforced concrete element, thus, there is a need to predict the relative strength often arises to determine the underlying safety of the corroded RC members and to decide when the repair or strengthening must be undertaken without any further delay. In

this paper, a simplified model developed based on the experimental results in the literature using ANOVA. The predicted results of the present model correlated very well with the experimental results observed in the literature.

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