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EVALUATING THE FLEXURAL STRENGTH OF CORRODED REINFORCED CONCRETE BEAMS

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Abstract
Corrosion of reinforcing steel is one of the most deterioration factors that influence reinforced concrete structures. Quantifying the effect of corrosion before structural failure is significant for a cheaper and more efficient repair. In this paper, a simple model was used to predict the residual flexural strength of RC beams with varying degrees of reinforcement corrosion based on experimental results. The Model was developed from analysing several beam specimens available in literature, which have been damaged by accelerated corrosion. The validity of this study was compared with separate set of published data. The new proposed model in this study was able to successfully predict the residual flexural strength of corroded reinforced concrete beams. It is recommended to study in future work the applicability of this model to full-scale RC beams that underwent natural corrosion or failed in flexure by concrete crushing.

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

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 (Bertolini et al. 2004). 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 (Berto et al., 2008). The rehabilitation of RC structures affected by corrosion costs billions of dollars every year (Imam et al. 2015). 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.

Corrosion of reinforcements involves the movement of ions or charges from the active anodic sites, where iron atoms are being dissolved, towards the passive cathodic sites, where oxygen are being consumed (Imam et al 2015). These two reactions combine to produce very soluble and expansive rust products that cause progressive damage on RC beams. For prematurely corroding structures, assessment is required to administer appropriate maintenance and repair, or provide information about their remaining service life. However, evaluation practices normally utilize destructive techniques and costly technologies that are material and labor intensive (Wang et al 2008). Predictive models provide cheaper and more convenient alternatives to these advanced corrosion assessments (Bertolini et al. 2004).

Objectives of the study

(1) 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.

(2) Demonstrate the validity of the proposed models by comparing the computed residual flexural strength to the actual flexural strength obtained from bending tests.

Data gathering

Data used for this model development were analyzed from literature (Imam et al 2015). Reinforced Concrete beam specimens have been gathered with general layout drawn in Fig. 1(a) to (c). Experimental investigations generally involved partially immersing the beam specimens in 3.5–5.0% NaCl solution while an external current of intensities, varying from 1 to 3 mA/cm2, is being applied for periods of 4 days up to 3 weeks. Corroded samples were then tested in flexure by centerpoint (Fig. 1d) to get the residual moment capacity (*Mex,c*); after which, the reinforcing bars were extracted and cleaned chemically for mass loss measurement (Broomfield 2002).

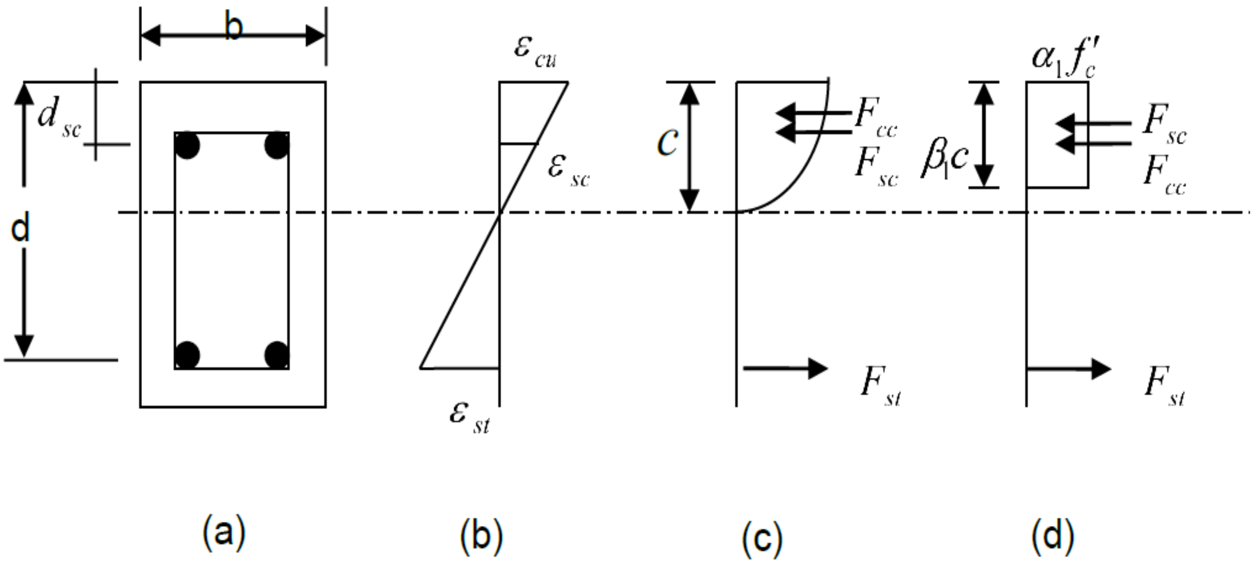

Figure 1: Vertical stress and strain distribution: (a) typical reinforced concrete beam section (b) strain distribution (c) actual concrete stresses (d) equivalent concrete stresses

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.

$$Mu = Ast * fy * (d - c) + Asc * fsc * (c - dsc\ ) + \alpha 1fc{,}\beta 1cb * (c - \beta 1c\ 2\ ) \qquad [1]$$

Where,

MU = Ultimate moment of resistance before corrosion

fy = steel yield strength

d = depth of tensile steel reinforcement measured from top face of the beam

c = depth of neutral axis measured from the top face of the beam

fsc = steel stress in compression

Ast = area of tensile steel reinforcement
Asc = area of compression steel reinforcement
fc = concrete compressive
dsc = depth of compression steel reinforcement
B = width of the beam
$\alpha 1$ and $\beta 1$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.

Data analysis

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, at any corrosion level xp is given as follows:

$$Fstx = nst * \pi * dstx * \tau bu * ld \qquad [2]$$

Where,
nst = number of reinforcing bars in tension
$dstx$ = reduced diameter of reinforcing bars in tension at corrosion level xp
τbu = bond strength of reinforcing bars in tension at corrosion level xp
ld = 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:

$$\varepsilon sc = \varepsilon c (c - dsc)\ c \qquad [3]$$

Therefore, the compression force carried by steel in compression is:

$$Fsc = Asc * ES * \varepsilon c(c - dsc)\ c \qquad [4]$$

From equilibrium,

$$F_{stx} = F_{sc} + F_{cc} \qquad [5]$$

The depth of neutral axis can be obtained from Equation 5, and the ultimate moment of resistance after corrosion can be determined as follows:

$$Mu = Fstx * (d - c) + Fsc * (c - dsc) + Fsc * (c - \beta 1c\ 2) \qquad [6]$$

Model development

Corrosion coefficient was first evaluated from the sample beams using Eq. (5) to initially assess how it is affected by other test variables. Results
suggest a noticeable decline in corrosion coefficient at higher percent mass loss (Fig. 2a) and rebar diameter (Fig. 2b). There is also an inverse relationship between and clear cover thickness (at tension side), but at slightly lesser degree (Fig. 2c). The applied current, on the other hand, has negligible influence (Fig. 2d). Henceforth, the model considered only the contribution from the first three parameters.

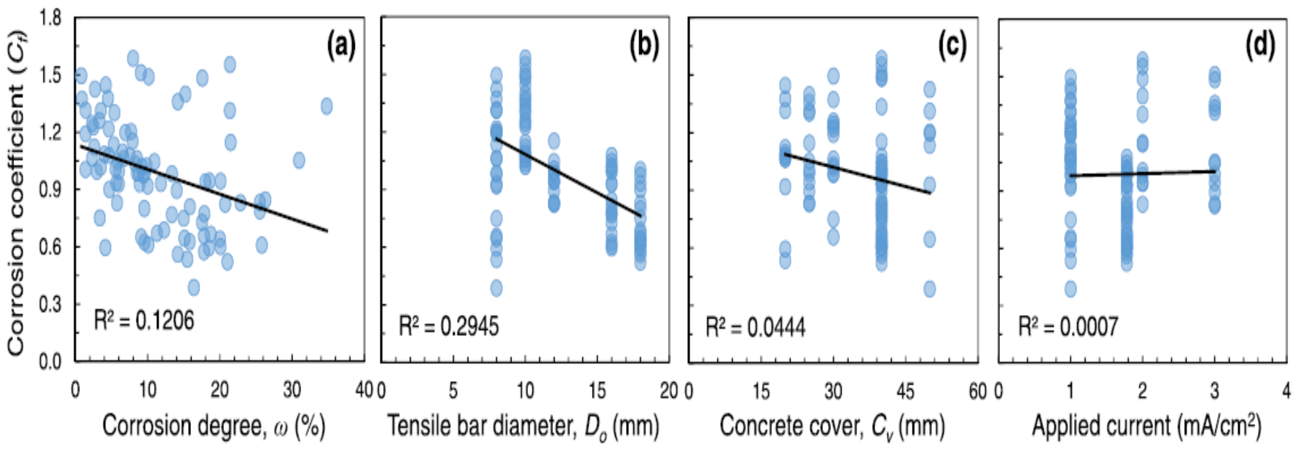

Fig. 2. Relationship between Corrosion coefficient and different RC beam parameters.

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 reinforced 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:

$$fyx = (1 - ML/96) * fy \qquad [7]$$

Where,

fyx = yield strength of corroded reinforcing bar at corrosion level xp,

fy = yield strength of sound reinforcing bar

ML = mass loss percent.

The tensile force, *stx F*, at any corrosion level xp is determined as follows:

$$Fstx = nst * \pi * d^2{}_{st} * fyx/4 \qquad [8]$$

The compression force carried by steel in compression, *scF*, and by concrete in compression, *ccF*, 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.

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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