Structural Effects of Reinforced Concrete Beam Due to Corrosion

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Abstract. Corrosion of steel in reinforced concrete is one of the main issues among construction stakeholders. The main consequences of steel corrosion include loss of cross section of steel area, generation of expansive pressure which caused cracking of concrete, spalling and delaminating of the concrete cover. Thus, it reduces the bond strength between the steel reinforcing bar and concrete, and deteriorating the strength of the structure. The objective of this study is to investigate the structural effects of corrosion damage on the performance of reinforced concrete beam. A series of corroded reinforced concrete beam with a corrosion rate of 0%, 20% and 40% of rebar corrosion is used in parametric study to assess the influence of different level of corrosion rate to the structural performance. As a result, the used of interface element in the finite element modelling predicted the worst case of corrosion analysis since cracks is induced and generate at this surface. On the other hand, a positive linear relationship was sketched between the increase of expansive pressure and the corrosion rate. Meanwhile, the gradient of the graph is decreased with the increase of steel bar diameter. Furthermore, the analysis shows that there is a significant effect on the load bearing capacity of the structure where the higher corrosion rate generates a higher stress concentration at the mid span of the beam. This study could predict the residual strength of reinforced concrete beam under the corrosion using the finite element analysis. The experimental validation is needed on the next stage to investigate the quantitative relation between the corrosion rate and its influence on the mechanical properties.

1 Introduction

Corrosion reinforcement is one of the main causes of structural deterioration and the most predominant degradation mechanisms in the reinforced concrete structures. It is usually associated with carbonation phenomenon or chlorides penetration, which generally induces uniform and localized attacks respectively. Corrosion of steel in concrete causes internal

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damage to reinforced concrete elements, owing to the loss of steel area and the formation of associated expansive corrosion products.

The properties of oxide layers as the corrosion products have a great influence on corrosion crack in the concrete. The most influential factor is the expansion ratio of the oxide which depends on the specific type of oxide formed [1-2]. Depending on the level of oxidation, the volume increase due to rebar corrosion is commonly around 2.0 [3-4] and would be up to 6.5 times than the original iron volume which get consumed by the corrosion process because of the formation of various corrosion products [5]. Nevertheless Molina [4] claimed that the effective expansion ratio maybe less than that corresponding to a given type if the oxide diffuse in the porous structure of the concrete. Table 1 gives the typical characteristic relative volume ratios for different corrosion products [2].

When corrosion of reinforcement develops significantly, the corrosive products expand continuously and generate internal pressure to concrete around the steel bar. The continuous process of reinforcement corrosion does not only affects in structural serviceability by cracking, or even spalling the concrete cover, but also give serious impact on the structural safety by decreasing the load-bearing capacity. Besides, the physical effects of corrosion include loss of steel area, loss of bond strength between steel reinforcing bars and concrete, and reduce of concrete strength due to cracking.

Table 1. Correlation between ‘α’ and ‘α_1’ for various corrosion products.

	Name of corrosion products					
	FeO	Fe_3O_4	Fe_2O_3	$Fe(OH)_2$	$Fe(OH)_3$	$Fe(OH)_3.3H_2O$
α'	0.777	0.724	0.699	0.622	0.523	0.347
α_1'	1.80	2.00	2.20	3.75	4.20	6.40

where: α, ratio of molecular weight of iron to the molecular weight of corrosion products; α1, ratio of volume of corrosion products to the volume of iron consumed in the corrosion process.

In the present study, non-linear finite element analysis using MARC software is used to investigate the potential effects of corrosion damage on the performance of reinforced concrete beam. The main effects of corrosion are recognized and considered in the analysis. A series of corroded reinforced concrete beam are analyzed. Then, the numerical models are used in the parametric study to assess both the influence of different level of corrosion and their associated assumptions on the predicted response.

A reinforced concrete beam with size of 150mm x 200mm x 2300mm was modelled consisting of 8mm diameter steel bars as the upper rebar and the 10mm steel bars as the lower rebar. Meanwhile, 6mm diameter of stirrup was used to be the shear reinforcement and arranged at every 170mm intervals. The detail dimension and the rebar’s location of reinforced concrete beam are shown in Fig. 1.

2 Numerical Simulation

2.1 Finite element modelling of beam specimen

A three-dimensional finite element model is adopted in this study (Fig. 2) using the non-linear finite element code of MARC 2010. The reinforced concrete beam was modelled in ½ from the actual dimension by taking into account the symmetry condition along the y-axis. By using the 8 nodes of hexahedral elements, concrete and the main reinforcements was classified as solid while the shear reinforcement was designed using one-dimensional (axial) truss element. By considering the changes in the adhesion strength between the reinforcement bar and concrete, the interface element was applied by using 8 nodes hexahedral elements.

2.2 Corrosion damage model

Fig. 3 shows the material properties of concrete, rebar and stirrup which summarized in Table 2. The rebar was assumed as complete elasto-plastic body and constitutive law based on the von Mises yield condition is adopted. As for the concrete, elastic-plastic constitutive law based on the Drucker-Prager yield condition is applied. The degradation ratio due to the corrosion is defined according to the degree of damage in three principal axis direction as $\emptyset_x, \emptyset_y$ and $\emptyset_z$ by assuming the tension softening. To adequately assess the progress of cracks in the concrete, it is necessary to make the tension softening stress released by subsequent tensile strength. Then, only the extracted positive principal strain component, the degree of damage in principal strain direction D_x^L, D_y^L and D_z^L are converted to the whole coordinate axes of D_x^G, D_y^G and D_z^G. The degradation ratio of each coordinate axis direction was calculated by the following Equation (1).

$$
\begin{aligned}
\emptyset_x &= \sqrt{1 - D_x^G}, \quad \left(D_x^L = \frac{\varepsilon_x^L}{\varepsilon_u} \right) \\
\emptyset_y &= \sqrt{1 - D_y^G}, \quad \left(D_y^L = \frac{\varepsilon_y^L}{\varepsilon_u} \right) \\
\emptyset_z &= \sqrt{1 - D_z^G}, \quad \left(D_z^L = \frac{\varepsilon_z^L}{\varepsilon_u} \right)
\end{aligned} \tag{1}
$$

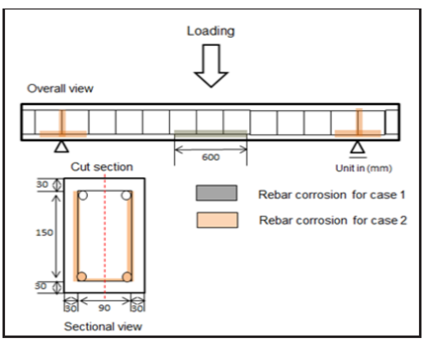

Fig. 1. Detailed dimension of Beam.

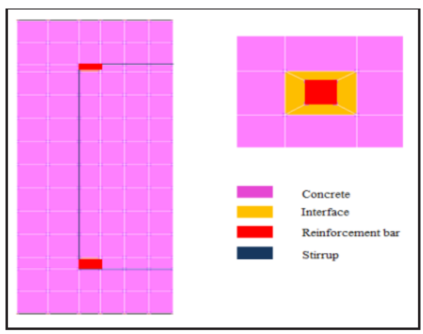

Fig. 2. Beam cross-section.

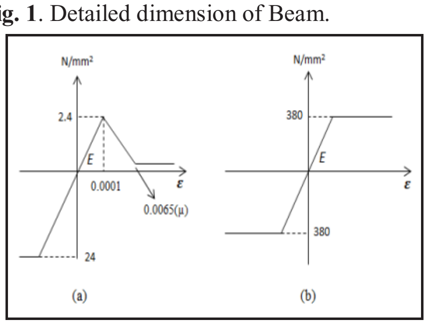

Fig. 3. Material properties of (a) concrete (b) reinforcement steel.

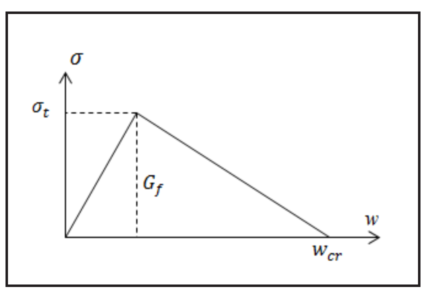

Fig. 4. Bond-slip between bond strength and the relative displacement.

Table 2. Material constants.

	Compression (N/mm^2)	Tension (N/mm^2)	Young modulus (N/mm^2)	Poison ratio
Concrete	24	2.4	25000	0.2
Reinforcement bar	380	380	200000	0.3
Stirrup	350	350	157000	0.3

Equation (1) shows the relationship between $\emptyset_x, \emptyset_y$, $\emptyset_z$ and D_x^G, D_y^G and D_z^G with the definition of D_x^L, D_y^L, D_z^L. Here, ε_u is defined as tensile strain limit. In addition, the relationship between the stress rate and the degradation ratio associated with the tension softening is defined in Equation (2).

$$\alpha_{xx} = \phi^2{}_x, \quad \alpha_{yy} = \phi^2{}_y, \quad \alpha_{zz} = \phi^2{}_z \tag{2}$$

Furthermore, in this analysis the degradation ratio was multiplied by elastic stiffness matrix and anisotropic constitutive law with damage influence is obtained as shown in Equation (3).

$$\{\sigma_{ij}\} = \{[D^e] - [D^p]\}\{\boldsymbol{\varepsilon}_{kl}\}$$

$$\left[D^e\right] = \begin{bmatrix} \phi_x^2(\lambda+2\mu) & \phi_x\phi_y\lambda & \phi_x\phi_z\lambda & 0 & 0 & 0 \\ \phi_y\phi_x\lambda & \phi_y^2(\lambda+2\mu) & \phi_y\phi_z\lambda & 0 & 0 & 0 \\ \phi_z\phi_x\lambda & \phi_z\phi_y\lambda & \phi_z^2(\lambda+2\mu) & 0 & 0 & 0 \\ 0 & 0 & 0 & \phi_x\phi_y 2\mu & 0 & 0 \\ 0 & 0 & 0 & 0 & \phi_y\phi_z 2\mu & 0 \\ 0 & 0 & 0 & 0 & 0 & \phi_z\phi_x 2\mu \end{bmatrix} \tag{3}$$

In order to avoid unrealistic local failure in the analysis, adequate element length is determined by using the fracture energy of concrete G_f. In this study, the maximum dimension of the material is 20mm, compressive strength of concrete is assumed to be 24 N/mm^2 and thus G_f is calculated as 78.3 (N/m) by Equation (4).

$$G_f = 10 \text{ x } (d_{max})^{1/3} \text{ x } (f`_{ck})^{1/3} \tag{4}$$

$$G_f = \frac{1}{2}\sigma_t \, w_{cr} \tag{5}$$

Using this G_f, corresponding w_{cr} is obtained as 0.06425mm and we finally determined element length is 10mm and corresponding tensile strain limit is 6500 (μ) by equation (6).

$$\varepsilon_u = \frac{w_{cr}}{d} \tag{6}$$

3 Mechanism of deformation process due to steel corrosion

3.1 Corrosion and expansion pressure

The corrosion in concrete causes volume expansion of steel bar. Generally, the expansive pressure due to the volumetric change of the steel bar in concrete induces the tensile strains in the surrounding concrete and they are proportional to the degree of corrosion. As the expansion process begins continuously, the tensile strains developed and induces cracks in the surrounding concrete and also at the surface of concrete cover. In order to analyze the cracking of concrete cover due to steel corrosion, it is necessarily to know the relation between the amount of corrosion of steel bar and the internal pressure arises from the corrosion. Therefore, a realistic relation between the amount of corrosion and the internal expansion pressure can be investigate in this study.

3.2 Deformation of corrosion layer

Kim [6] proposed a deformation model of steel bar corrosion. It was detailed out in Fig. 5 which consist r_0 as the initial radius of steel bar and x_p is the loss radius of steel bar due to corrosion. Meanwhile, the radius increment of steel bar due to corrosive expansion under restraint and unrestraint condition (mm) represent by Ur and Δr_b, respectively while the degree of corrosion of the steel bar which based on the ratio of weight loss due to corrosion to the initial weight of steel bar is known as w_{corr}.

The corrosion product layer is compressed by the strain ε_{rust} due to expansive pressure, P. Lundgren [8] derived the relationship between normal stress versus strain of rust evaluated from a combination of experimental results and analysis together with the chosen parameter K_{rust} and p. According to their research, analysis results have a good agreement with the experimental results using the value of K_{rust} = 7.0 GPa and p = 7.0. Thus the strain ε_{rust} and the expansive pressure P is defined as follows.

$$\varepsilon_{rust} = \frac{u_r - \Delta r_b}{x_p + \Delta r_b} \tag{7}$$

$$P = K_{rust}\, \varepsilon_{rust}{}^{p} \tag{8}$$

3.3 Mechanical behavior of the rust

The mechanical behavior of the corrosion products needs to be known in modelling the corrosion layer. Molina [4] assume that the rust is elastic but the mechanical properties of the rust should be replaced by initial property of steel. Meanwhile, a scratching test was used by Petre-Lazar & Gerard [10] to explore the mechanical properties of the corrosion products. They conclude that rust is cohesion-less assemblage of incompressible crystals. Al-Sulaimani [11] and Cabrera & Ghoudoussi [12] have carried out pullout tests on corroded reinforcement bars concentrically placed in concrete blocks. In their study, the reinforcement corroded until the specimen was cracked and corrosion penetration was measured by the weight loss method. In addition, they performed axisymmetric finite element analyses of the test specimens and only the concrete was modelled with expansive normal stress. In this study, we also considered only the concrete domain with a constitutive model based on elastic-plastic theory.

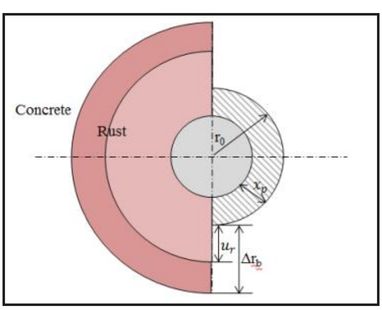

Fig. 5. Deformation process due to the evaluated steel expansion.

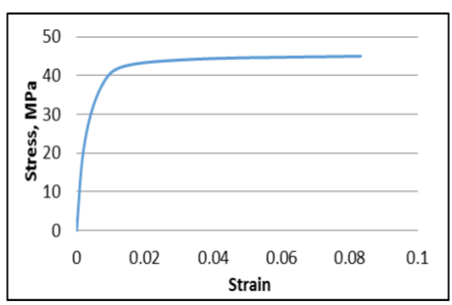

Fig. 6. Strain versus normal stress in the rust.

Since the Young's modulus of steel is much larger than concrete, Lundgren [8] assumed that the deformation of the reinforcement bar is negligible. Furthermore the stiffness of the bond layer is large enough and so the deformation of the bond layer is also negligible. Thereby, Lundgren [8] concluded that the deformation at the hole approximately equals the deformation in the corrosion layer, U_r. Therefore, the value of U_r can be calculated as the value of strain in the rust using Equation (7). This strain in the rust corresponds with the applied normal stress when cracking occurred in the analysis. The results are summarized in Fig. 6, where the normal stress versus strain in the rust is plotted. This figure indicate that the rust does not have a linear elastic behavior. In fact, the stress and strain increases monotonically until reach a point where the stress becomes constant in increasing of strain. This might be cause by the stiffness of the rust change and deteriorated. This mechanical behavior of the rust could be described by Equation (8).

4 Results and analysis

4.1 Influence of adhesion strength reduction due to rebar corrosion

In general, cracks and rebar corrosion of the reinforced concrete structures are caused by various environmental factors and reduction of adhesion strength is also observed. In this study, the adhesion strength of rebar was also considered with reference to the research by Lee [13]. The relationship of the corrosion rate and the adhesion strength of the corroded reinforcing bars were stated in Equation (9) and (10).

$$\tau_{\max} = 0.34\sigma_c - 1.93 \quad (9)$$

$$\tau_{\max} = 5.21e^{-0.0561\Delta w} \quad (10)$$

Here, σ_c is the compressive strength of the concrete and Δw represents the corrosion rate of reinforcing steel (%). Corrosion of the rebar was analyzed with respect to the 3 levels of degradation state which are 0%, 20% and 40%. The bond strength for each corrosion rate was summarized in Table 3. In general, a reinforced concrete beam is considered to have two types of damage state with different corrosion position. For case 1, the corrosion is modelled in the main rebar with 600mm length at the mid span. Case 2 takes into account the corrosion of shear reinforcement at both ends (Fig. 1).

4.2 Analysis results

At first, the influence of adhesion condition between concrete and main reinforcement is investigated by proposed analysis. Fig. 7 shows the load-displacement relationships using adhesion model (with interface) and in complete adhesion condition (without interface). From this Fig., the strength without interface has a higher strength compared to the strength with interface elements, however the presence or absence of the interface does not give a big effect to the bond strength under the pure bending condition. In general, the interface elements describe a relation between traction and the relative displacement which included both the frictional bond model and the corrosion model[9] and the mechanical behavior and the volume of the corrosion products were given as input for the corrosion layer. So that, structure with interface elements is weaker since the cracks is induced and generate at this surface. Then, the bond-slip may occur from the interaction of internal pressure by the reinforcement steel surface, which cause cracking to the concrete layer.

Table 3. Relationship between corrosion degree and bond strength.

Corrosion Degree (%)	Bond Strength (Mpa)
0	6.23
20	1.70
40	0.55

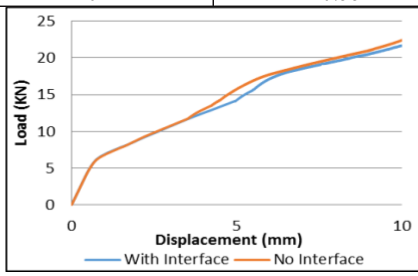

Fig. 7. The influence of the presence and the absence of interface.

4.3 Volume expansion of rust in corroded concrete

When a rebar starts to corrode, a gradual decrease of its diameter (axisymmetric corrosion is assumed) is produced, together with the generation of rust. The increase in volume induce the formation of cracks when the concrete's tensile strength is surpassed. The cracks are generated first at the bar-concrete interface and then propagate radially. As can be seen from Fig. 8, it is presented the rust expansion of 8mm diameter steel bar at 10% of corrosion degree. Under the unrestraint condition, Δr_b at α value of 0.523 and 0.622 correspond to the free rust expansion of 0.7135mm and 0.5445mm respectively. Meanwhile, under restraint concrete condition, the value of *Ur* at α value of 0.523 and 0.622 are 0.711mm and 0.5425mm respectively.

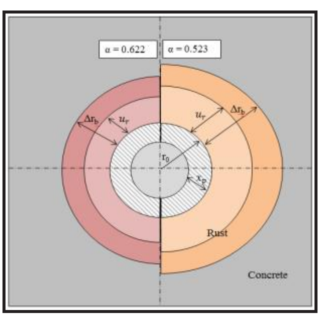

Fig. 8. The rust expansion under concrete constraint.

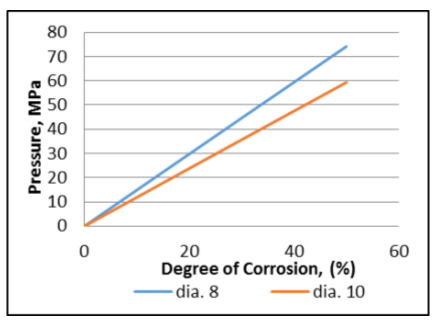

Fig. 9. Relationship between pressure and degree of corrosion.

The relation between pressure and the degree of corrosion could be expressed as a linear line shown in Fig. 9. It is also found that the gradient of this graph is decreased with the increase of steel bar diameter. This is because, the pressure created from 8mm steel bar diameter is higher than the pressure of 10mm diameter at the same degree of corrosion. The relationship between the pressure in function of degree of corrosion is stated in Equation (11) where u_r is identified to be the relative ratio of steel density to corrosion product density.

These results coincide with the results of previous research [14, 15] which reported a decrease in maximum pressure with an increase of internal diameter. On the other hand, if the specimens have the same cover thickness with different bar sizes, it is clear that the cover of the smaller bar specimen is stiffer and if the same load is applied to both specimens, the deflection in the cover of the larger specimen will be greater than that in the smaller bar specimen.

$$P = K_{rust}\left[\frac{u_r - r_b(\sqrt{1+(v_r-1)w_{corr}}-1)}{r_b[(1-\sqrt{1-w_{corr}})+(\sqrt{1+(v_r-1)w_{corr}}-1)]}\right] \tag{11}$$

4.4 Influence of structural strength reduction due to rebar corrosion

Further analysis was conducted to investigate the influence of corrosion to the structural strength in two cases. For case 1, the corrosion is considered in the middle of main bar with 600mm length while case 2 considered the corrosion of shear reinforcements at both ends.

4.3.1 Case 1

The analysis shows that there is a significant effect on the load bearing capacity of the structure. For case 1, the bearing force of the beam is decreasing in increasing of corrosion degree. It is found that the curve of 0% corrosion have a bearing force with 28.26KN. Meanwhile, the bearing force drop until 20.72 KN and 19.78 KN for the 20% and 40% curve, respectively. This results indicates that the corrosion in mid span will cause severe condition since the stiffness decrease due to the corrosion and caused noticeable strength reduction as shown in Fig. 10. It is also found that the 40% degree of corrosion case has almost the same bearing force with the 20% degree of corrosion case. This is because, higher corrosion rate generate higher stress concentration at mid span as shown in Fig. 11 and this beam has enough bending capacity, thus it get off the serious failure under this displacement range.

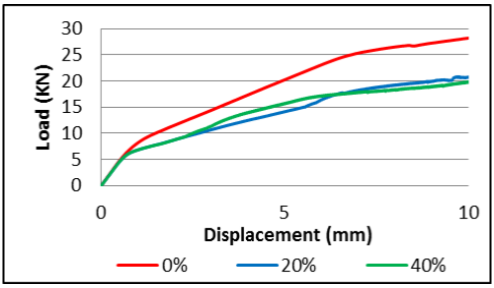

Fig. 10. Load-displacement graph of strength reduction for Case 1.

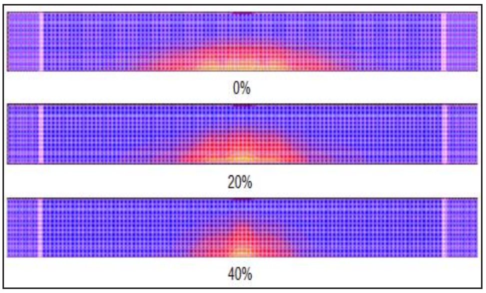

Fig. 11. Plastic strain distribution for Case 1.

4.3.2 Case 2

For the case 2 which considered corrosion state at the shear reinforcement of both ends, the bearing forces with 20% and 40% corrosion rate show around 20 percent decrease compared to the 0% corrosion case (Fig. 12). The distribution of stress at the cross section of the beam is presented in Fig. 13. Since the corroded areas consist of shear and lower reinforcement only, the stress distribution is concentrated at the lower reinforcement as the stress level increasing when the corrosion degrees increase. Overall, for this case, the corrosion at shear reinforcement have a better condition compared to the corrosion at the mid span. In general, the stress condition of the beam is influenced by the span length and cross-section. For longer span that is expected bending failure, case 1 is in danger while for shorter span that is expected shear failure, case 2 might be potential to have a failure earlier since the shear stress of the reinforcement is dominant.

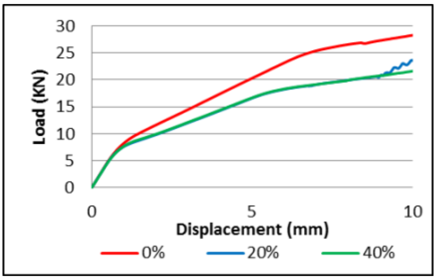

Fig. 12. Load-displacement graph of strength reduction for Case 2.

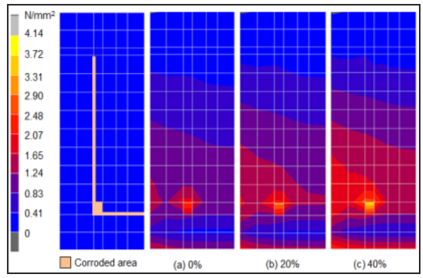

Fig. 13. Stress distribution for Case 2.

5 Conclusions

In this study, we could predict the residual strength of RC beam under the corrosion condition using the finite element analysis. However, the quantitative relation between the degree of corrosion and its influence on the mechanical properties are still needed to investigate. Thus, we are going to do the experimental validation in the next stage.

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