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Crack Analysis in Cement Paste Ring due to Corroded Rebar using FEM Tool

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***Abstract*-The serviceability of ageing reinforced concrete structures is greatly affected by internal rebar corrosion as corrosion products of rebar occupy larger volume than the original rebar, impose expansion pressure on surrounding concrete, and then cause concrete cover cracking. Cracks in turn provide a path for more rapid ingress of aggressive agents to the reinforcement, which can accelerate the corrosion process, thus cause damage to concrete structures. Major cause of corrosion is a porous zone at the interface of rebar and concrete which is due to poor compaction, high porosity and high bleeding at the Interfacial Transition Zone (ITZ) of reinforcement and Concrete. The compaction by using Rebar shaker has proved to improve the compaction and to reduce porosity of ITZ because it increases bond and adhesion of rebar and concrete. Also, this technique of compaction through steelbars (rebar shaker) leaves steel bars enveloped by cement paste i.e., it creates a paste ring around rebar. During corrosion activities this Cement Paste Ring experience much pressure, because the zone is on the interface with rebar and because it comprises of fine particles hence susceptible to cracking. Once CPR zone is cracked, the corrosion products are absorbed in these cracks hence reducing corrosion pressure toward the bulk concrete consequently reducing delamination of concrete cover. Also because of the difference of modulus and stiffness of CPR and bulk concrete, there is no continuity of crack propagation from CPR to Bulk concrete to the CPR hence reducing delamination of concrete cover.**

In this article the properties of bulk concrete and Cement Paste ring were determined, and the major inputs are concrete strength, Poisson ratio and Young Modulus. Two Finite Element (FEM) Software were used to determine the behavior of Cement Paste ring and bulk concrete (cover) under various corrosion pressures and on different bar sizes (12mm, 16mm and 20mm). The analysis compared Tensile strength limit of concrete and the tensile stresses induced after corrosion. Other aspects like strength factors, displacement and stress contours were analyzed and discussed

It has been observed that the CPR absorb corrosion pressure more than the bulk concrete, the stress contours are not continuous which suggest discontinuation of the crack propagation. The strength factor shows the damage of failure is less CPR than in bulk concrete. Even though the damage is less in CPR but delamination of concrete cover could be violent if measures like rehabilitation are not taken timely.

Keywords—Cracks, Cement Paste Ring, Corrosion, Cover, ITZ

I. INTRODUCTION

Reinforcement corrosion is the main cause of damage and early failure of reinforced concrete structures worldwide with subsequent enormous costs for maintenance, restoration and replacement. The corrosion of steel in concrete is a major cause of durability problems in reinforced structures (Klinghoffer et al., 2000). After steel de passivation, corrosion products are formed at the steel/concrete interface. Because the volume of the corrosion products is greater than that of the original metal, the formation of the corrosion products will induce a pressure on the surrounding concrete and generate stresses in the concrete cover. As the volume of corrosion products increases, cracks initiate at the steel/concrete interface and propagate outwards and eventually spread to the surface of the concrete cover. These cracks in turn provide a path for more rapid ingress of aggressive agents to the reinforcement, which can accelerate the corrosion process, thus causing damage to concrete structures. Cracking of reinforced concrete structures can occur in certain environments as a consequence of the corrosion of the rebar. The oxide layer growing around the bar exerts a pressure on the surrounding concrete which may be enough to crack the concrete cover (Yeomans, 2004, Wang and Liu 2008, Yuan and Ji 2009, Li et al., 2008, Zheng et al., 2005, Tamer and Khaled 2007, Chang et al., 2010)

The serviceability of ageing reinforced concrete structures is greatly affected by internal rebar corrosion as corrosion products of rebar occupy larger volume than original rebar, impose expansion pressure on surrounding concrete, and then induce concrete cover cracking. The corrosion of the reinforcement does not only cause concrete cover delamination and spalling but also reduce reinforcement cross sections, cause loss of bond between the reinforcement and concrete, reduce strength (flexural, shear, etc.), and ductility. As a result, the safety and serviceability of concrete structures are reduced, and their useful service lives shortened (Lounis and Amleh, 2004, Cabrera, 1996).

These consequences of reinforcement corrosion result into enormous costs for maintenance, restoration and replacement. It is desirable to reduce or eliminate cover delamination by introduction of Concrete Paste Ring around rebars. Initially, this can be evaluated using Finite

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Element Modeling tool. It is also necessary to predict the internal damage due to corrosion of rebars and to propose means which can extend the design life of a structure.

A. Experimental Model and Hypothesis

Rebar Shaking is a process of turning rebars into a vibrator (Bennet et al., 2003). This practice leaves steel bars enveloped by cement paste in other words; it creates a paste ring around rebar as shown in Figure 1(a). The cement paste ring (CPR) is synonyms of Concrete Paste Ring. Since in reality this zone is comprised of cement, fine sand, fine particles of aggregates and water. Since the Young modulus and stiffness of Cement Paste Ring is different from Bulk Concrete, hence it is hypothesized as shown in Figure 1(b), that once corrosion starts to cause cracks, the Cement Paste Ring will be in a position to experience much pressure, because the zone is comprising fine particles hence there will be lots of cracks at this zone, The advantages of these occurrence are; firstly there will be no continuous crack propagation from Bulk concrete to the CPR. On the other hand, the cracks at the CPR zone becomes a good space to accommodate corrosion products hence to reduce cover delamination. Tests shows that there is a porous zone at the interface of steelyard and cement paste ring and the best zone that has proved to be not permeable is at the interface of cement paste ring and bulk concrete. It is also known that for the same amount of corrosion, concrete cracking occurs much earlier for non-uniform corrosion than for uniform corrosion (Jang et al., 2010). Hence, non-uniform corrosion, or local pitting, is more dangerous to concrete structures than uniform corrosion. Introduction of CPR has proved to surround rebar/steel equally hence the corrosion is also assumed to occur uniformly.

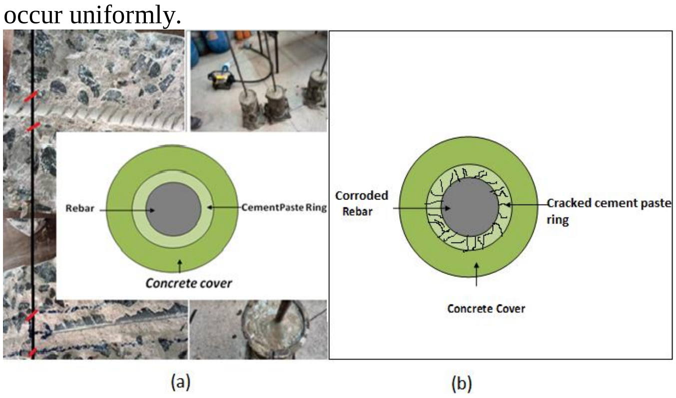

Figure 1: (a) Schematic diagram of cement paste ring: 1(b): Cracked Cement Paste Ring (CPR), R –rebar and C-cover

II. REVIEW ON EXPERIMENTAL STUDIES AND ANALYTICAL MODELS

The electric accelerated corrosion test has been used to evaluate cracking behavior of corroded sample which also led to measure surface crack initiation and surface crack width propagation (Alonso et al., 1998). Internal crack patterns due to rebar corrosion considering different ratios of concrete cover thickness to diameter of reinforcing bar were observed by using the electric accelerated corrosion test to verify the proposed criterion regarding the change of the internal crack patterns. Furthermore, some researchers confirmed mechanical properties of corrosion products of reinforcement in concrete (Chernin et al., 2010).

The first analytical model for prediction of corrosion induced cracking of the concrete cover was proposed by Bazant (Liu and Jin 20100. In the model, concrete surrounding a corroding reinforcing bar is considered as a homogeneous linear elastic material. Expansion due to a larger volume of corrosion products compared to that of the lost steel is modelled by a uniform increase, Δd, in the diameter of the cylindrical hole around the reinforcing bar. Deformations of the corrosion products and the remaining steel are not taken into account and Δd is found from the equation below,

$$\frac{\pi}{4}\left[(d+\Delta d)^2 - d^2\right] = \frac{W_{rust}}{\rho_{rust}} - \frac{W_{steel}}{\rho_{steel}} \qquad (1)$$

where Wrust and Wsteel are the masses of the corrosion products and the lost steel per unit length of the reinforcing bar, respectively, and ρrust and ρsteel the corrosion product and steel densities. Since Δd<< d, Δd2 can be neglected, while Wsteel can be expressed via Wrust as Wsteel = γWrust , where $\gamma$is the ratio of the molecular weight of iron to that of corrosion products, so that the following formula for Δd can be derived from Equation 1.

$$\Delta d = \frac{2W_{rust}}{\pi d}\left(\frac{1}{\rho_{rust}} - \frac{\gamma}{\rho_{steel}}\right) \qquad (2)$$

To estimate Wrust at time t after corrosion initiation it is assumed that the rate of rust production, Jrust, does not change with time as shown in equation (3)

Wrust=Jrust.t (3)

A relationship between the expansion Δd and the pressure, P, caused by it, is found as the average of two solutions of the classic Lame ´ problem—one for a hollow thick-walled cylinder under plane stress; as shown in equation (4)

$$\Delta d = \frac{d}{E_{c,ef}}\left[1 + v_c + \frac{d^2}{2c(c+d)}\right]P \qquad (4)$$

And the other one for a circular cavity in an infinite medium (obtained an asymptotic result from when c→ ∞) is shown in equation (5)

$$\Delta d = \frac{d}{E_{c,ef}}\left[1 + v_c\right]P \qquad (5)$$

In equation (5) c is the thickness of the concrete cover, ϑc the Poisson's ratio of concrete, Ec, ef = Ec/ (1+φ) the effective modulus of elasticity of concrete, Ec the modulus of elasticity of the concrete at an age of 28 days, and φ the concrete creep coefficient. It is assumed that concrete cover cracking occurs after a long time since corrosion initiation so that φ = 2 corresponding to time t = ∞ is adopted. The concrete cover is fully cracked when the average tensile stress in it becomes equal to the tensile strength of concrete, fct that is equivalent to assuming perfectly plastic behavior of the concrete before cracking. Tamer and Khaled 2007 depict the average tensile stress is estimated as the average tangential stress in the cylinder wall so that the internal pressure causing the concrete cover cracking, Pcr as shown in equation (6)

$$P_{cr} = \frac{2cf_{ct}}{d} \qquad (6)$$

The minimum stress required to induce cracking of concrete cover is apparently related to the tensile strength of concrete and the thickness of the cover. The concrete ring is assumed to crack when the tensile stresses in the circumferential direction at every part of the ring have reached the tensile strength of the concrete. The radial pressure required to cause cracking of concrete cover, Pcr, is then given by equation (7)

$$Pcr[D + 2(\delta_o + \delta_c)] = 2[C - (\delta_o + \delta_c)] f_{ct} \qquad (7)$$

In equation (7) fct is the concrete tensile strength. Assuming, [D + 2(δ0 + δc)] = D, and [C (δ0 + δc)] = C as, 2(δ0 +δc) D, and (δ0 + δc) C, the radial pressure that causes cracking, Pcr, is given in equation 6

Based on the mechanism of corrosion induced concrete cracking, the volume of corrosion products is also related to the thickness of the pore band, δo at the interface of the reinforcement and concrete. According to Bazant (1979) and Liu and Weyer (1998), σt this can be expressed as:

$$\sigma_t = 2cf_{ct}\left[D + 2\delta_o\right] \qquad (8)$$

The thickness of the pore band, do is constant once concrete has hardened and is also important for time analysis. It delay stress development since this void space is firstly filled by corrosion product. Thus, if Jrust, ρrust, and γ are known, then the time from corrosion initiation to full cracking of the concrete cover (referred further as the time to crack initiation) can be found by substituting Equations. 2, 3 and 6, into equation 5.

In order to improve the agreement between analytical and experimental results Liu and Weyers suggested modifications to the Bazant's model which underestimate time to crack initiation

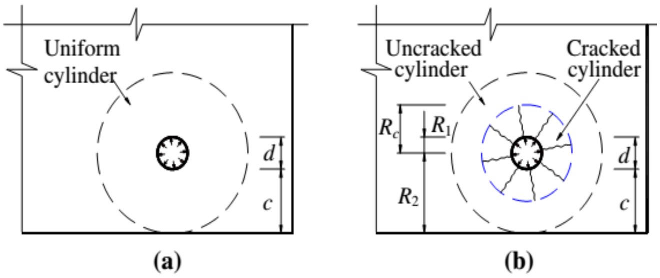

Figure 2.0 Thick walled cylinder (a) uniform cylinder (b) non- uniform cylinder due to cracked inner layer (after Chernin et al., 2010).

Firstly, they assumed that there was the so-called ''porous'' zone of finite thickness around a reinforcing bar and corrosion products accumulating around the bar did not exert any pressure on the surrounding concrete until they fully filled this zone. Introducing this assumption Liu and Weyers intended to account for the fact that part of corrosion products diffused into concrete pores and micro cracks and, therefore, did not contribute to the pressure exerted on the concrete; this was initially suggested by Molina et al, and then also observed in tests .As a result, the thickness of the porous zone, δ0, became one of the main parameters of the model and the expansion of concrete around a corroded reinforcing bar previously estimated by Equation 2 was expressed as;

$$\Delta d = \frac{2W_{rust}}{\pi d}\left[\frac{1}{\rho_{rust}} - \frac{\gamma}{\rho_{steel}}\right] - 2\delta_o \qquad (9)$$

Secondly, only Equation 4 which is the solution for a thick-walled cylinder (Figure 2a), was used to establish the relationship between the expansion Δd and the corresponding pressure P (and not the average of Eqs. 4 and 5). It should be noted that Figure 2(b) shows the zone of cracked cylinder which in this study is exactly like CPR zone.

Thirdly, it was assumed that the rate of rust production, Jrust, was not constant but inversely proportional to the amount of corrosion products and, hence, decreased with time. This led to the following relationship between the time to crack initiation, tcr, and the critical mass of corrosion products causing cracking, Wrust, cr

$$t_{cr} = \frac{W^2{}_{rust,cr}}{2k_p} \qquad (10)$$

In Equation (10) kp had to be a time-invariant constant. Wrust, cr was found from previous equations. Some researchers assumed that the rate of rust production decreasing with time led to underestimation of the mass of lost steel observed in accelerated corrosion tests (it is expected since in such tests the rate of rust production is constant). There is a direct proportionality in relationships between the internal pressure and the radial displacements on the inner surface. The time up to crack initiation was found from solution of a thick-walled composite cylinder which is well explained by Balafas and Burgoyne 2010. The assumption made in this thick walled cylinder is that model is made from two isotropic linearly elastic materials with different moduli of elasticity, which was subjected to internal pressure. Also the stiffness of concrete in the radial direction parallel to cracks is significantly higher than that in the radial direction normal to cracks. The tangential stiffness of concrete in the inner cylinder changed gradually depending on the radial coordinate and the corresponding tangential strain. (Pantazopoulou and Papoulia, 2001)

III. FINITE ELEMENT ANALYSIS

A. *Corrosion Analysis*

The corrosion damage analysis consists of several steps. The first one can be analyzed by the volume expansion of rust production with time. The second can be calculated by width or/and length of crack in the concrete element at a determined time. After studying the intensity of the corrosion and crack, the residual development capacity of reinforcement anchorages can be evaluated by the stress analysis of bond slip in the concrete members. Through finite element, stress contours can also be used to evaluate cracks development and possible cracks propagation and strength factors can be used to determine the potential crack occurrence at each location from interface to the cover

B. *Finite Element Inputs*

Finite element analysis, using MECWAY software and Phase 2 software, was carried in order to clarify the influence of corrosion of rebars in concrete cracking. Details of the six different cylindrical specimens and their analytical results are presented. In order to analyze the concrete cracking in a cylindrical specimen; the geometrical and material properties of the specimen were defined.

I. Materials properties for concrete used were;

- i. Comprehensive strength of concrete, fcu was assumed to be 25Mpa.
- ii. Poisson ratio of concrete, v = 0.2 (obtained from literature review)
- iii. Concrete density, ρc = 2400Kg/m3

Various mechanical properties of concrete were correlated to the compressive strength of concrete, a parameter which is easily measured in practice. According to ACI 318-05 the concrete tensile strength and modulus of elasticity is related to compressive strength as:

ft = $0.53\sqrt{fcu}$ (11)

Ec= $4600\sqrt{fcu}$ (12)

From equations 11 and 12, the tensile strength, ft and the modulus of elasticity, Ec was found to be 2.65Mpa and 23Gpa respectively.

Reinforcement properties were;

- i. Young modulus of rebars, Es = 209GPa
- ii. Poisson ratio, v = 0.3
- iii. Diameter used was 12mm, 16mm and 20mm.

II. Cement Paste Ring properties

These were obtained from different literature review and through previous experiments on this research. These properties its properties are not constant, and varies due to different properties of the cement paste such as water to cement ratio (w/c), the chemical properties of cement constituents, size of materials and other ingredients. The properties of hardened cement paste (Elastic and Poison ratio) have been reviewed and extracted from different sources of literature by (Haecker et al., 2005) for comparison with Cement Paste Ring which have slight different value due to the presence of fine sand particles. The adopted hardened cement paste properties for this study were taken as; Modulus of elasticity, Ecp was 22.8 GPa. Poisson ratio, v was 0.25.

III. Cracking Pressure in various Reinforcement diameter

Empirical formula for the computation of this minimum pressure of the produced rust material to cause cracking of the concrete cover was obtained from simplification equation 7 as follow:

$$P_{cr} = 2Cf_{ct} /(D+2d_o) \quad (13)$$

In Equation (13) the pore band, do = 12.5μm was obtained from literature review. D is a bar diameter, C is a concrete cover and fct is tensile strength of concrete.

The Table I below summarizes the minimum pressure required to induce cracking due corrosion;

TABLE 1: MINIMUM PRESSURE DUE TO RUST PRODUCT MATERIALS TO INDUCE CRACKING IN CONCRETE

Bar diameter, D (mm)	Cover, C (mm)	Pcr = 2Cfct/(D+2do) (MPa)
20	65	17.2
16	67	22.16
12	69	30.14

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3.4 Model Setup and Stress Distribution

The cylindrical concrete was modeled by using MECWAY software which uses FEM. The model was built, elements shape are hex 8 solid, materials properties was assigned, and the load was applied. The model was solved using static 3D and the results were displayed in terms of XY stresses. These stresses were compared with the tensile stress that has been found by Equation 11. Diameter D of cylinder was generally taken as 150mm and thickness of the cement paste was taken as 10mm from the surface of the rebar.

Phase two is 2D Linear Elastic, FEM which has Analysis Type: Plane Strain , Solver Type: Gaussian Elimination, Stress Analysis: Maximum Number of Iterations: 500, Number of Load Steps: Automatic, Mesh type: graded, Element type: 3 noded triangles. The Cement Paste Ring was taken as 10mm (0.01m) and the concrete cover of varying depth as in Table 1 was established.

Both tools have similar procedures and wide range of elements, load and material types i.e., build the model, inputs, meshing, analysis and interpretation. In linear elastic fracture mechanics algorithm, the stress distribution at the tip of crack can be presented as coordinate systems shown in Figure 3

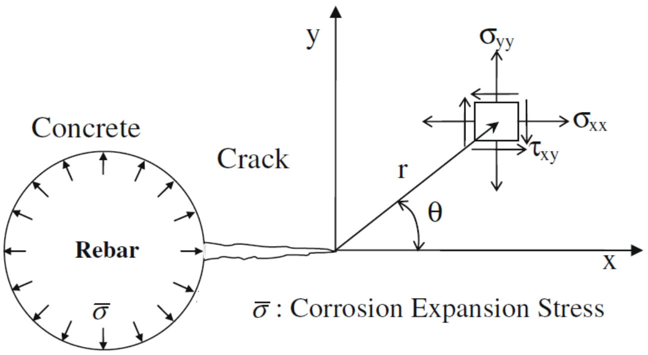

Figure 3: Coordinate system of corrosion expansion stress (Che Way Chang et al., 2010)

IV. ANALYSIS RESULTS AND INTERPRETATION

A. Mecway Results

The display results MECWAY is presented in section below for both rebar surrounded only by bulk (normal concrete) and for rebar surrounded by CPR are shown in figure 4 and figure 5

I. Display results from MECWAY software for the rebar surrounded by with bulk concrete

The concrete tensile stresses for concrete cylinders filled with bulk concrete embedded with bars of different diameters are shown in Figure 4.0

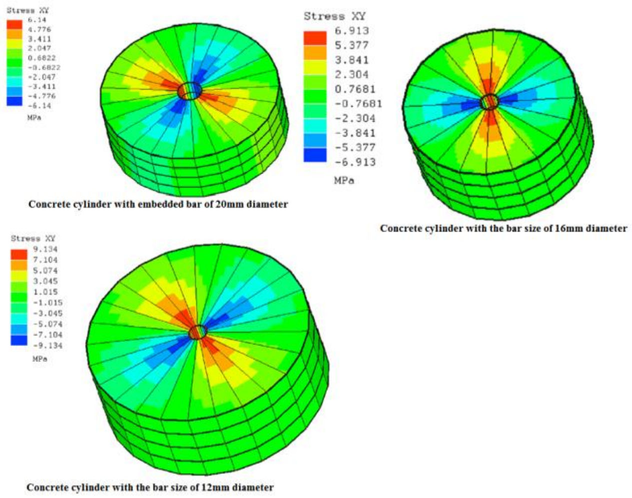

Figure 4.0 Concrete Tensile stresses on cylinder filled only with bulk concrete

II. Display results from MECWAY software for the cylinder filled with the concrete and Cement Paste Ring around a rebar

The concrete tensile stresses for concrete cylinders with cement paste ring embedded with bars of different diameters are shown in Figure 5.0

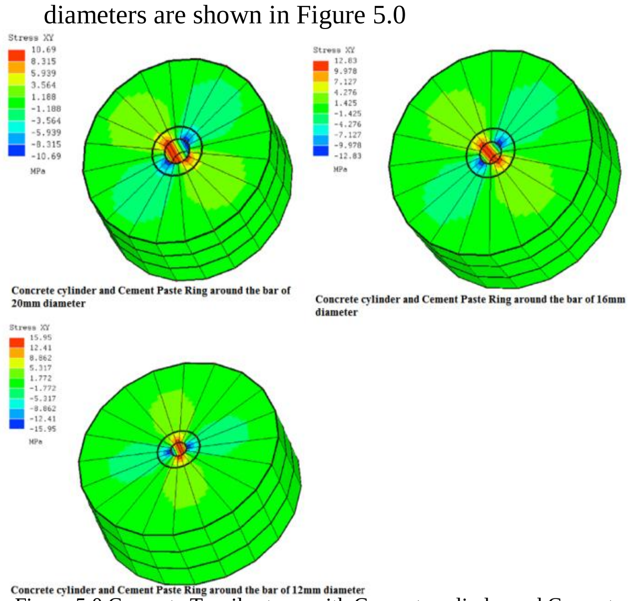

Figure 5.0 Concrete Tensile stress with Concrete cylinder and Cement Paste Ring around the rebar

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B. Phase 2(Two) Results

Phase two 2D model for corroded rebar) presented by corrosion pressure for both rebar surrounded with bulk concrete and for rebar surrounded with CPR and bulk concrete is shown in Figure 6 and typical analyzed model is shown in Figure 7.

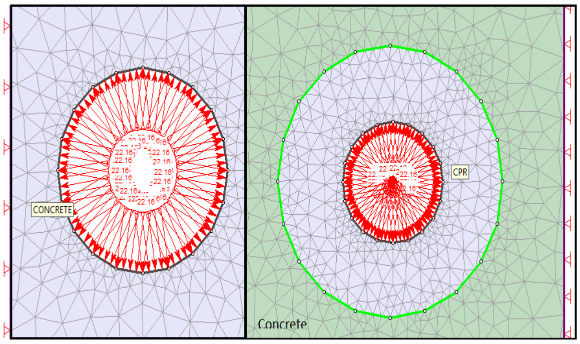

Figure 6: Typical Model for corrosion pressure model in bulk concrete and for CPR and bulk concrete

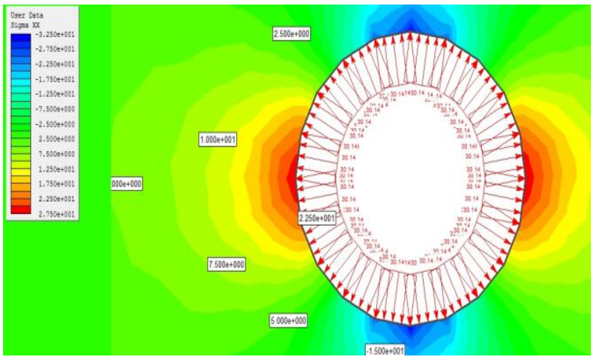

Figure 7.0: Typical Analyzed model which shows sigma xx

The results for sigma xx, displacement and strength factor for bulk concrete and for Cement Paste Ring were determined using software for all reinforcement sizes i.e. 12mm, 16mm and 20mm. Figures 8, 9 and 10 shows the combined results of Sigma xx, Displacement and Strength Factor respectively. Note that Y axis is the interface of steel and concrete.

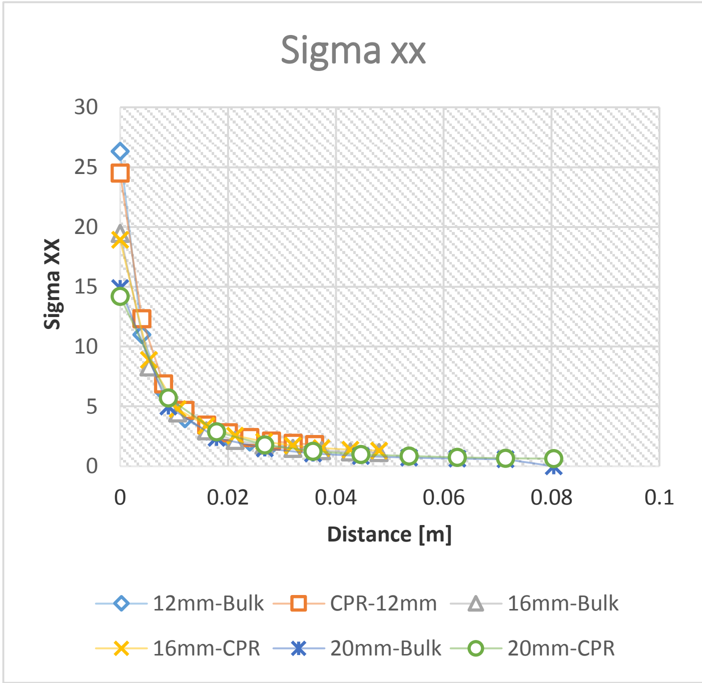

Figure 8: Results of Sigma xx for 12mm, 16mm and 20mm corroded rebar for both Bulk Concrete

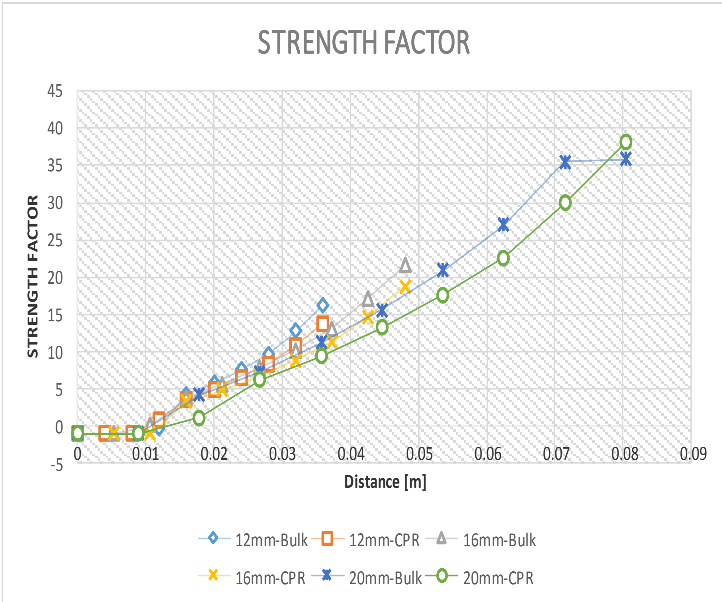

Figure 9: Results of Displacement for 12mm, 16mm and 20mm corroded rebar for both Bulk Concrete

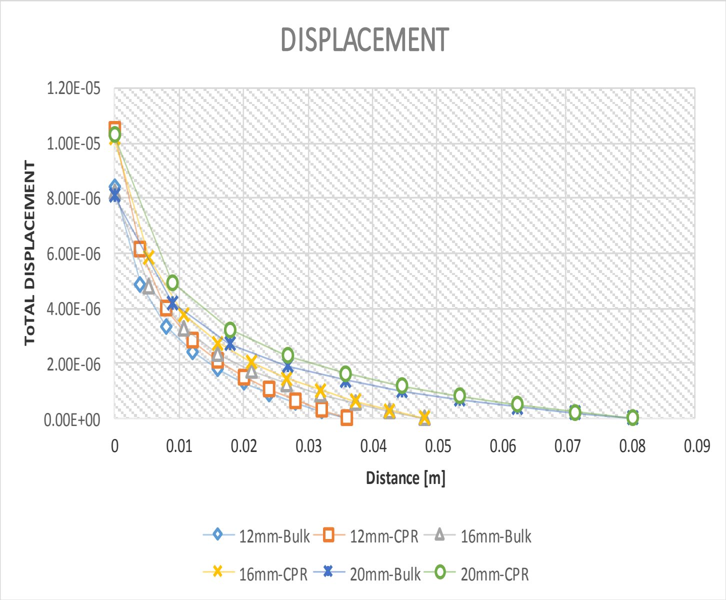

Figure 10: Strength Factor for 12mm, 16mm and 20mm corroded rebar for both Bulk Concrete

V. INTERPRETATION AND DISCUSSION OF RESULTS

A. In Mecway Version 5

The models shows the stress distribution of cracking pressure which causes cracks. As shown in Figure 4.0 and Figure 5.0 for the region which has a tensile strength of concrete more than 2.65MPa, this verifies that the cracks are occurring since they exceed tensile strength of concrete. Since the concrete cover is the same in all directions therefore the cracks propagate in only two opposite directions. That's means the compression regions are created between these tension regions. In Figure 4.0 models shows the rebar, Cement Paste Ring and bulk concrete. The corrosion pressure caused cracks on the cement paste ring which acted as a stress absorber. The stress zone on the bulk concrete decreased hence a minimal effect on the bulk concrete. The hardened cement paste tend to have more tension stress than the concrete, as a result the large part of the CPR zone reducing cracks before the bulk concrete. The formed cracks are filled with the rust material hence reducing the cracking pressure toward the bulk concrete. This therefore reduce the delamination of the concrete cover.

The radial expansion for internal cracking depends only on bar diameter, rather than the thickness of concrete cover and indicates that, when cracks first occur at the internal surface of the concrete cover, the normal pressure on the surface of the corroded reinforcement is in the range of 1.05 to 2.20 MPa and increases almost linearly with the ratio of c/d. This is because an increase of concrete cover provides more restraint to the radial expansion of corroded reinforcements (Du et al., 2006)

Balafas and Burgoyne (2010) suggested that the newly cracked concrete takes the form of teeth, and the cracks between them form more voids into which the rust materials can be accommodated. The radial pressure in the concrete teeth, and the corresponding strain, are governed by the pressure in the rust, while the tangential strain in the teeth is assumed to vary linearly from zero on the inner surface of the teeth to that on the inner surface of the non-cracked outer ring. The outer ring still behaves as a thick-walled elastic cylinder

B. In Phase 2

The 12mm rebar is posing higher corrosion pressure as compared to 16mm and 20mm rebars. The effects of 12mm rebar corrosion pressure is active (it reaches tensile strength limit) at distance of 16mm from interface of rebar and concrete for bulk Concrete and distance of 20mm from interface of rebar and concrete for CPR. In 16mm rebar the corrosion pressure is active (it reaches tensile strength limit) up to distance of 16mm from interface of rebar and concrete bulk Concrete and distance of 21mm from interface of rebar and concrete for CPR. In 20mm rebar the corrosion pressure is active (it reaches tensile strength limit) up to distance of 17mm from interface of rebar and concrete for bulk Concrete and 18mm from interface of rebar and concrete for CPR in Figure 8.

After reaching these tensile strengths threshold still 12mm rebar stresses are active up to the distance of 36mm from interface of bar and concrete, for 16mm rebar they are active up to 48mm from interface of bar and concrete for 20mm rebar they are active up to 80mm from interface of bar and concrete, the cover is 85mm. Because CPR absorb more energy and they also displace more than bulk concrete. This is shown in all rebars 12mm, 16mm and 20mm. The displacement becomes negligible at 36mm for 12mm rebar and at 48mm for 16mm rebar and at 71mm or 20mm rebar as shown in Figure 9.

Strength Factor defined by the ratio of concrete strength to the induced stress at each point, at the interface because of high stress concentrations strength factor cannot be defined. The CPR have shown to reduces damage as strength factor is lower in CPR for all rebars o 12mm, 16mm and 20mm. as shown in Figure 10.

For both FEM tool; for cover to delaminate literature show that there must be a joined cracks that form single-like crack that has been propagated from inner zone to outer layer to delaminate the cover. It is easier for corroded rebar in the bulk concrete to cause single-like crack that will delaminate the cover. It is not easy for corroded rebar within CPR to form this single crack because elastic modulus and stiffness of CPR is smaller compared to the bulk concrete. The Bulk concrete contour stresses are continuous while contour stresses in CPR are not continuous. The stress distribution contour in Phase 2 for both corrosion in bulk concrete and in CPR is all shown in Figure 11.

Because the CPR absorb stresses, and because the introduction of cracks to second layer (Bulk) initiate as if CPR emanates new stresses to the bulk concrete, this bulk concrete as second layer may experience much pressure that will lead to crack heavily before the cracks moves to the bulk concrete.

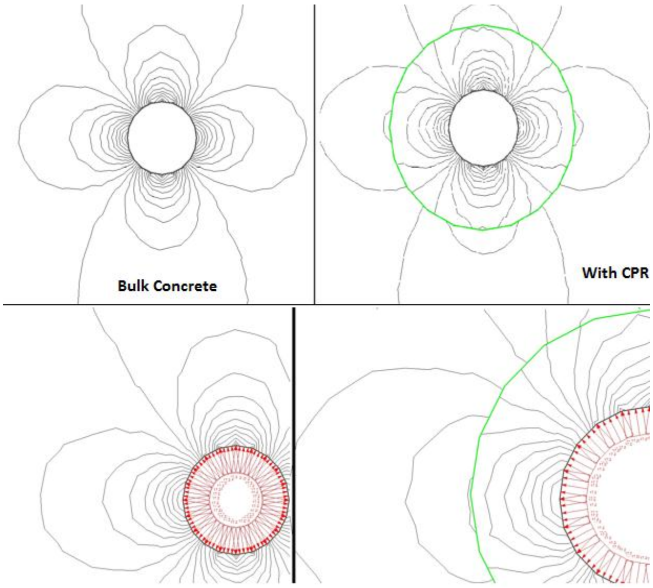

Figure 11: Contour Stress distribution for bulk concrete and for Cement Paste Ring

VI. CONCLUSIONS

Following are the conclusion of the study

1. The propagation of cracks in concrete depend on the bar size, which influence cracking pressure whereby the cracking pressure increases as bar size decreases.
2. The Cement Paste Ring reduces the cracking pressure toward bulk concrete hence increasing the chances of minimizing cover delamination. This is because Cement Paste Ring cracks easily hence accommodating rusting materials.
3. The position/location of failure where Tensile stresses are higher than tensile strength of concrete is closer for bulk concrete than for CPR surrounded rebar
4. The CPR absorbs corrosion pressure more than the bulk concrete, the stress contours are not continuous which suggest discontinuation of the crack propagation
5. The strength factor shows that the damage of failure is less in CPR than in bulk concrete. Even though the damage is less in CPR but delamination of concrete cover could be violently if measures like rehabilitation will not be taken timely.

VII. RECOMMENDATIONS

Following are the recommendations

1. Comparison of FEM model and experiments is needed for better discussion and for validation with typical corrosion tests
2. More study is needed to estimate the crack width in relation to corrosion pressure and location

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