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Cracking of concrete cover in reinforced concrete under various corrosion distributions

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ABSTRACT: It has been generally assumed that corrosion occurs uniformly around a rebar. However, corrosion may start from the outer portion of a steel bar because chlorides are generally penetrated into concrete in one direction under usual sea environments. Thus, the steel bar may not corrode uniformly around the rebar. The objective of the present study is therefore to investigate the cracking behavior of concrete cover under various corrosion distributions. Four different types of corrosion distributions were considered to study cracking behavior of concrete cover. The cover depth-to-rebar diameter ratios were also varied from 0.5 to 2. The present study indicates that the pressures to cause cracking of concrete cover under non-uniform corrosion conditions are much smaller than that under uniform corrosion. This means that cracking occurs much earlier under highly non-uniform corrosion condition and thus service life may be reduced considerably if one considers non-uniform corrosion realistically. The effects of rebar diameter and cover depth-to-rebar diameter ratio were also investigated.

1 INTRODUCTION

Chloride penetration is one of the major factors that affect durability of concrete structures (Gjoerv & Vennesland 1979, Oh & Jang 2003a, Oh & Jang 2003b, Oh & Jang 2004, Oh & Jang 2007). The corrosion products of a reinforcing bar in concrete induce pressure to the surrounding concrete due to the expansion of corroded steel. This expansion pressure induces tensile stresses in concrete around the reinforcing bar and the continuous increase of expansion pressure causes cracking through concrete cover. The cracking of concrete cover due to steel corrosion may accelerate corrosion process and lead to failure very rapidly. Therefore, corrosion-induced cracking of concrete cover is an important problem in concrete structures because it directly affects not only durability, but also safety of such structures (Tuutti 1980, Maage et al. 1996).

It has been generally assumed for simple application that corrosion occurs uniformly and thus expansion pressure is uniform around a rebar. However, since chlorides are penetrated in one direction in real sea environments, the corrosion may start from the outer region of the rebar and thus the steel bar may not corrode uniformly in a cross section. This has been verified from the authors' research (Oh & Jang 2003a) that the chlorides are accumulated in front of rebar because the chlorides do not diffuse through the rebar. This means that real state of corrosion is not uniform around a rebar and starts from pitting corrosion. This may cause non-uniform expansion pressure around the rebar.

Non-uniform distribution of expansion pressure may cause adverse effects for the cracking of concrete cover because higher pressure is concentrated at the outer region of rebar toward concrete cover. This may cause higher tensile stress development and fast occurrence of cracks in concrete cover which reduces time-to-cracking and eventually service life of concrete structures. The purpose of the present study is therefore to explore the effects of non-uniform corrosion on cracking behavior of concrete cover.

2 NON-UNIFORM CORROSION PHENOMENON

Steel bars may not corrode uniformly around the rebar because corrosion usually starts from the outer region of a rebar in real chloride environments. Figure 1 shows the cases of uniform and non-uniform corrosion around a rebar. It may be reasonably assumed for non-uniform corrosion case in Figure 1 that the corrosion depth of steel bar decreases linearly from the outer region of the rebar. The value of α in Figure 1 is defined as the ratio of the depth of non-uniform corrosion to that of uniform corrosion. It was reported from the experiments of González et al. (1995) that the value α ranges about 4～8 in natural conditions and 5～13 in accelerated testing of reinforced concrete, and is usually less than about 10.

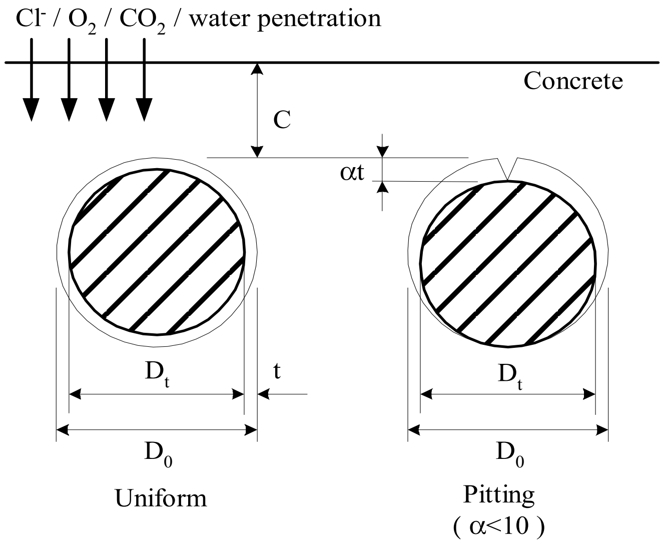

Figure 1. Typical uniform and non-uniform corrosion distributions.

3 STRESS ANAYSIS FOR NON-UNIFORM CORROSION

3.1 *Analysis variables*

González et al. (1995) reported that the ratio of the depth of non-uniform corrosion to that of uniform corrosion, α, ranges about 4～8 in natural conditions. Therefore, the values of α considered in this study were 1, 2, 4, and 8, respectively, in order to explore the effects of non-uniform corrosion distributions on the cracking behavior of concrete cover in reinforced concrete members. Figure 2 shows the various corrosion distributions for these cases of α = 1, 2, 4, and 8.

Major variables for analyses are the types of nonlinear corrosion distributions, cover-to-rebar diameter ratio, and compressive strengths of concrete, respectively. The values of α for non-uniform corrosion distributions are α = 1, 2, 4, and 8, respectively. The cover-to-rebar diameter ratios considered are c/d = 0.5, 1.0, and 2.0, respectively and the compressive strengths of concrete considered are f_c = 20.6 MPa and 44.1MPa, respectively. The corresponding elastic moduli of concrete are E_c, = 24,800MPa and 31,400MPa, respectively. The rebar diameter was 16mm for all cases in this study.

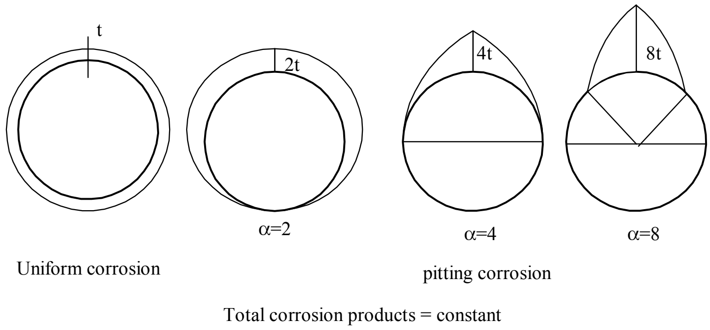

Figure 2. Non-uniform corrosion distributions according to α values.

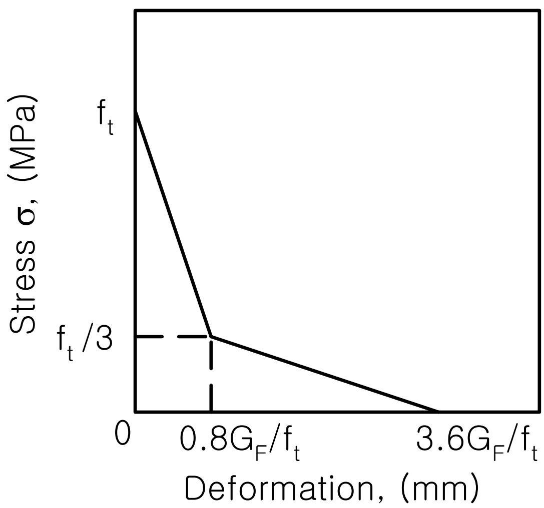

Figure 3. Bilinear tension softening curve of concrete.

3.2 *Finite element analysis models*

Mohr-Coulomb failure model was applied for the compressive regime of concrete. For the tensile regime, the smeared crack concept was employed to model cracking of concrete elements. A crack occurs if the major principal tensile stress exceeds the minimum of tensile strength f_t and $f_t(1+\sigma_{lateral}/f_c)$, where the lateral principal stress $\sigma_{lateral}$ considers the effect of biaxial stress. The direct tensile strength f_t of concrete may also be obtained from the split tensile strength f_{sp} and compressive strength f_c. For tension softening, bilinear tension softening model according to Hillerborg (1976) was used as shown in Figure 3. The value of fracture energy G_F was reasonably assumed as 100N/m for the present analysis which is a typical value in concrete (Hillerborg et al. 1976).

Eight-node plane strain elements were employed for the present finite element analysis. Figure 4 shows the finite element meshes for the nonlinear analysis of concrete members due to corrosion-induced expansion pressure.

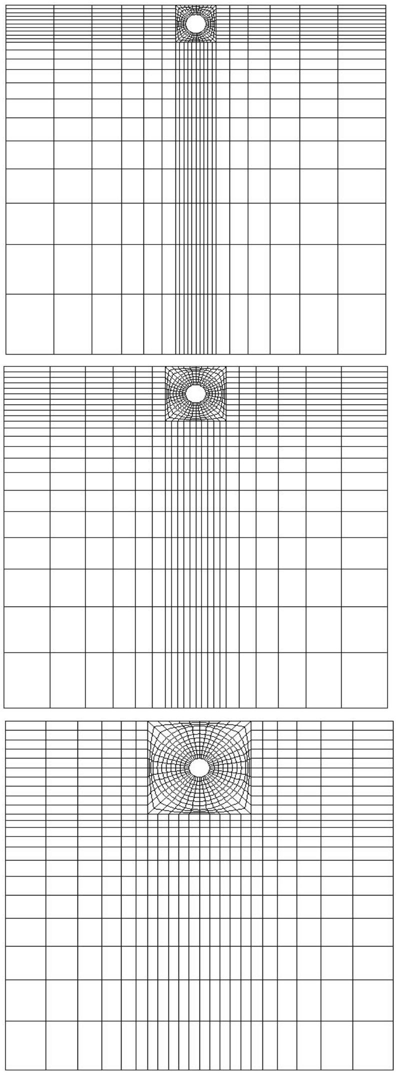

Figure 4. Finite element meshes for various cover-to-rebar diameter (c/d) values.

3.3 *Internal pressure distributions and iterative analysis scheme*

Figure 5 shows the typical distributions of corrosion-induced expansion pressure around a rebar used in this study for the cases of uniform corrosion $\alpha = 1$ and non-uniform corrosion $\alpha = 4$. This was deduced from the non-linear corrosion distributions according to the value of α as shown in Figure 2.

The internal pressures corresponding to the value α of non-uniform corrosion distributions were applied to the surrounding concrete in an incremental manner up to the crack occurrence of concrete cover. In order to analyze the nonlinear relation between load and displacement, an incremental iterative solution procedure is required. The equilibrium based on internal energy is iteratively achieved within each increment. In this study, convergence criterion was taken as the ratio of internal energy between two successive load steps and the tolerance, namely convergence criterion, was assigned to be 1×10^{-2}. Iteration is repeated until internal equilibrium conditions are fulfilled and convergence is obtained.

The regular Newton-Raphson method was applied for iteration procedure in which stiffness matrix is evaluated at every iteration. However, for descending parts after maximum load level, the Newton-Raphson method cannot find next load level. Therefore, Arc-length method was utilized for this region. This method makes it possible to find the next load step using predefined arc length at each step. With this path-following technique, the post-peak descending part has been reasonably investigated.

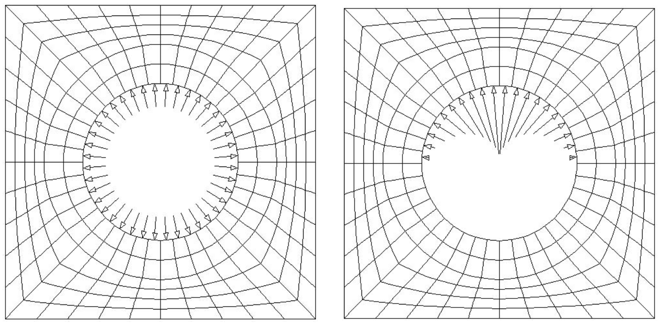

Figure 5. Uniform and non-uniform pressure distributions around a rebar.

4 RESULTS AND DISCUSSION

4.1 *Pressures to cause cracking on concrete cover*

The pressure to cause cracking of concrete cover, so-called cracking pressure, is here defined as the pressure at which the cracking occurs first on the surface region of concrete cover during the step-by-step incremental nonlinear analysis. The cracking pressures of concrete cover according to various design parameters have been obtained from the present nonlinear analyses and the results are shown in Figure 6 ~ Figure 13.

4.2 *Cracking pressure versus non-uniform corrosion distribution*

Figure 6 shows the cracking pressures according to the different types of non-uniform corrosion distributions (i.e., different α values) for concrete strength f_c = 20.6 MPa and cover depth c=8mm. It is shown in Figure 6 that the cracking pressure decreases greatly as the corrosion distribution around a rebar becomes sharper, i.e., the value of α for non-uniform corrosion becomes larger. The cracking pressures for non-uniform corrosion α = 4 and 8 are about 55% and 38% of that for uniform corrosion case in this case, respectively. This means that the cracking of concrete cover due to corrosion of steel bar occurs much earlier when the corrosion is localized at the outer region of rebar. This is the case of usual pitting corrosion occurring in actual concrete structures under sea environments (González et al. 1995).

Figure 7 depicts again the cracking pressures according to α value for the case of same concrete strength f_c = 20.6 MPa, but cover thickness c = 16mm, and Figure 8 exhibits the cracking pressures according to α value for same concrete strength f_c = 20.6 MPa, but cover thickness c= 32 mm. The decrease of cracking pressure according to an increase of α value is again shown in these figures. The equations for cracking pressure P_{cr} may be derived in terms of α value for compressive strength f_c = 20.6 MPa from Figure 6 ~ Figure 8 as follows (see Figs. 6-8 for derived equations).

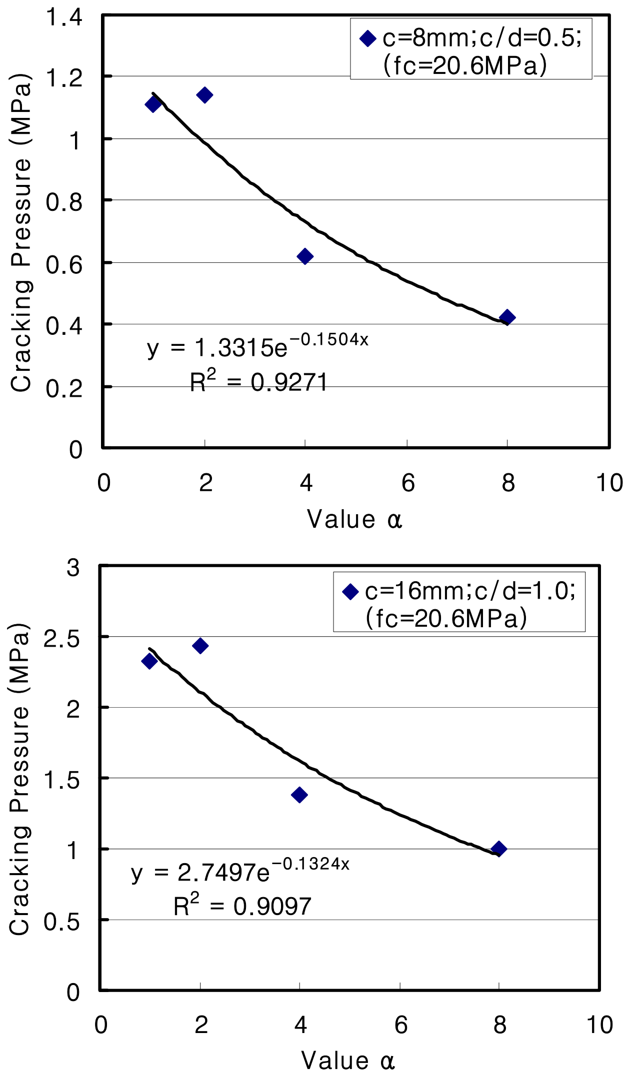

Figure 6. Cracking pressures according to α value (types of non-uniform corrosion) for concrete strength fc = 20.6 MPa and cover c = 8 mm.

$$P_{cr} = 1.33\ e^{-0.15\alpha} \quad \text{for } c/d=0.5, f_c = 20.6 \text{ MPa} \qquad (1)$$

$$P_{cr} = 2.75\ e^{-0.13\alpha} \quad \text{for } c/d=1.0, f_c = 20.6 \text{ MPa} \qquad (2)$$

$$P_{cr} = 5.64\ e^{-0.12\alpha} \quad \text{for } c/d=2.0, f_c = 20.6 \text{ MPa} \qquad (3)$$

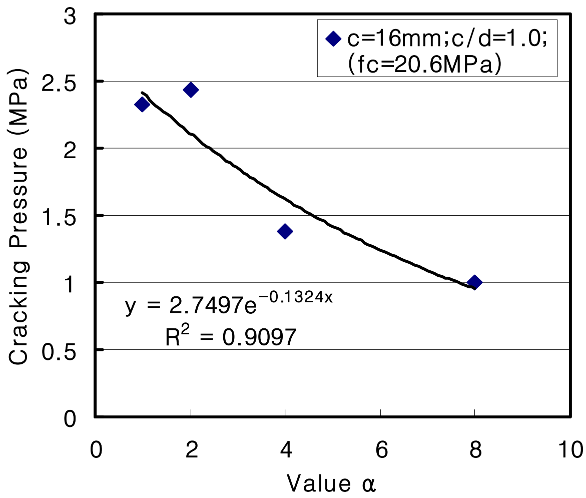

Figure 7. Cracking pressures according to α value (types of non-uniform corrosion) for concrete strength fc = 20.6 MPa and cover c = 16 mm.

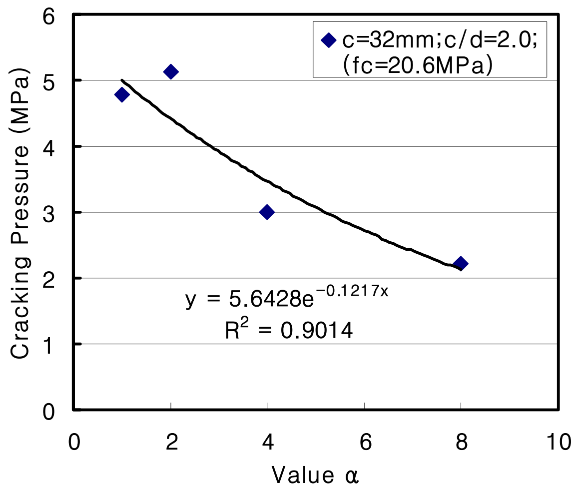

Figure 8. Cracking pressures according to α value (types of non-uniform corrosion) for concrete strength fc = 20.6 MPa and cover c = 32 mm.

Figure 9 shows the cracking pressures according to the value of α for high concrete strength f_c = 44 MPa and cover c = 8 mm. The cracking pressures for this case are 1.90 Mpa for α = 1 (uniform corrosion), 1.94 Mpa for α = 2, 1.06 Mpa for α = 3, and 0.72 Mpa for α = 4, respectively. It is again seen from Figure 9 that the cracking pressure decreases greatly as the value of α for non-uniform corrosion becomes larger. Namely, cracking occurs at much lower pressure when the corrosion distribution becomes sharper due to pitting corrosion.

Figure 10 also shows the cracking pressures according to α value for same high strength concrete f_c = 44 MPa, but cover thickness c = 16mm. The cracking pressures for this case are 4.00 Mpa for α = 1 (uniform corrosion), 4.20 Mpa for α = 2, 2.45 Mpa for α = 3, and 1.70 Mpa for α = 4, respectively. Figure 11 depicts again the cracking pressures according to α value for same high strength concrete f_c = 44 MPa, but cover thickness c = 32mm. The cracking pressures in this case are 8.01 Mpa for α=1 (uniform corrosion), 8.72 Mpa for α = 2, 5.06 Mpa for α=3, and 3.83 Mpa for α=4, respectively. It is also seen from Figure 9 ~ Figure 11 that the cracking pressure decreases greatly as the corrosion distribution around a rebar becomes sharper.

The equations for cracking pressure P_{cr} may be derived again in terms of α value for compressive strength f_c = 44 MPa from Figure 9 ~ Figure 11 as follows.

$$P_{cr}= 2.27\, e^{-0.15\,\alpha} \quad \text{for } c/d=0.5, f_c = 44 \text{ MPa} \tag{4}$$

$$P_{cr}= 4.78\, e^{-0.13\,\alpha} \quad \text{for } c/d=1.0, f_c = 44 \text{ MPa} \tag{5}$$

$$P_{cr}= 9.45\, e^{-0.11\,\alpha} \quad \text{for } c/d=2.0, f_c = 44 \text{ MPa} \tag{6}$$

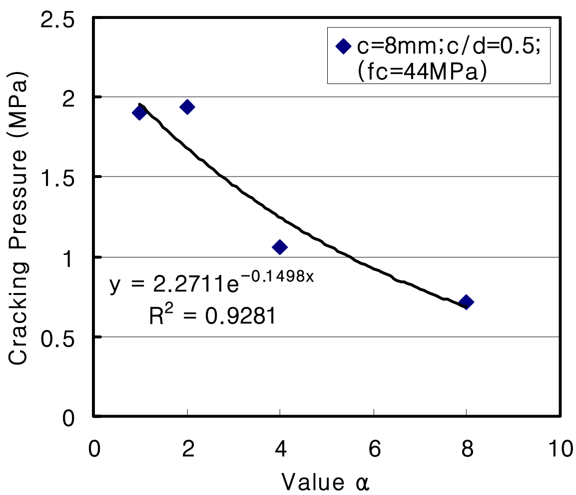

Figure 9. Cracking pressures according to α value (types of non-uniform corrosion) for concrete strength fc = 44 MPa and cover c = 8 mm.

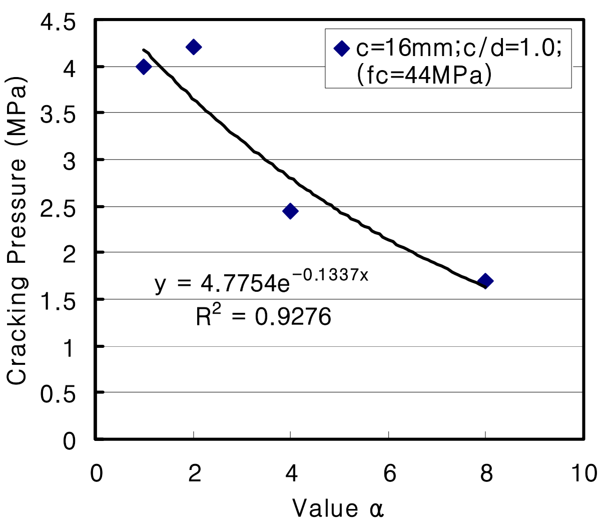

Figure 10. Cracking pressures according to α value (types of non-uniform corrosion) for concrete strength fc = 44MPa and cover c = 16 mm.

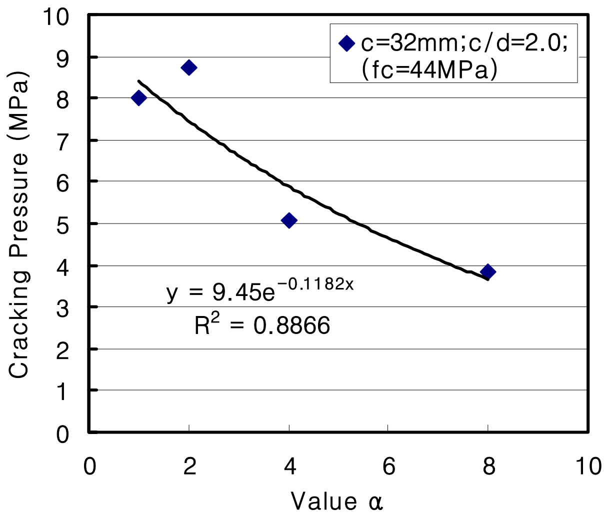

Figure 11. Cracking pressures according to α value (types of non-uniform corrosion) for concrete strength fc = 44 MPa and cover c = 32 mm.

The cracking pressures for α = 4 and α = 8(medium and severe non-uniform corrosions) are much smaller than that of uniform corrosion case, namely 40% and 60% decrease of cracking pressure, respectively. This means that a local corrosion in relatively small area at the outer face of rebar can cause the failure of concrete cover at a relatively low expansion pressure in case of pitting corrosion. This gives important implications in actual practice because the corrosion in real structures is usually of pitting and non-uniform nature. González et al. (1995) reported that the value of α ranges about 4~8 in natural corrosion conditions. It is therefore noted here that the corrosion distribution is a very important factor in corrosion-induced failure of concrete cover which affects directly the durability as well as service life of concrete structures.

4.3 *Cracking pressure versus concrete cover*

Figure 12 shows the relations between cracking pressure and concrete cover thickness (c/d ratio) for compressive strength f_c =20.6MPa. Figure 12 indicates that the pressure to cause cracking of concrete cover due to corrosion expansion increases with an increase of cover depth and is almost linearly proportional to the cover-to-rebar diameter (c/d) ratio as follows.

$$P_{cr}= 2.31\, (c/d)^{1.05} \quad \text{for } \alpha=1 \tag{7}$$

$$P_{cr}= 1.37\, (c/d)^{1.13} \quad \text{for } \alpha=4 \tag{8}$$

The correlation coefficients for above equations are almost 1 as shown in Figure 12 which represent almost perfect correlation between cracking pressure and cover-to-rebar diameter ratios.

Figure 13 shows the relations between cracking pressure and concrete cover thickness (c/d ratio) for compressive strength f_c = 44MPa. It is also shown that the pressure to cause cracking of concrete cover due to corrosion expansion is almost linearly proportional to the cover-to-rebar diameter (c/d) ratio as follows.

$$P_{cr} = 3.93\ (c/d)^{1.04} \quad \text{for } \alpha=1 \tag{9}$$

$$P_{cr} = 2.36\ (c/d)^{1.13} \quad \text{for } \alpha=4 \tag{10}$$

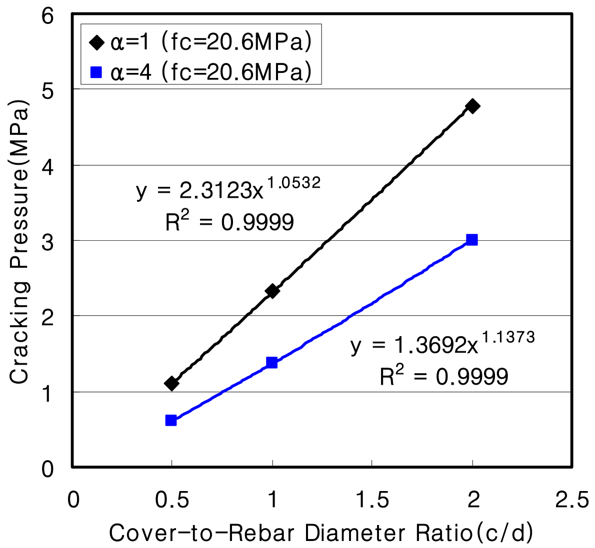

Figure 12. Cracking pressures according to c/d ratio for compressive strength fc = 20.6MPa.

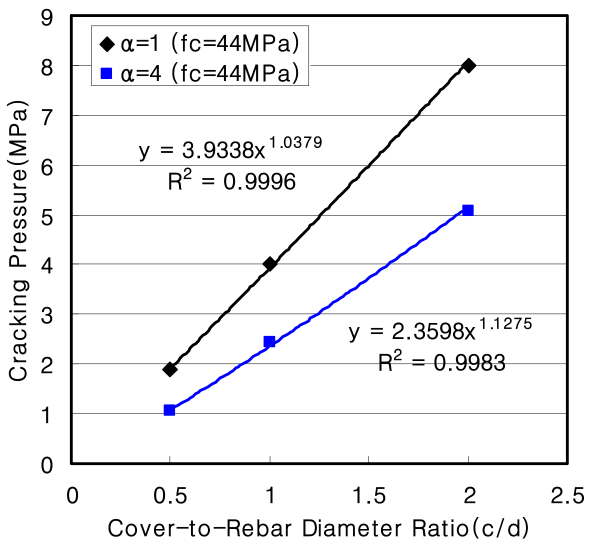

Figure 13. Cracking pressures according to c/d ratio for compressive strength fc = 44MPa.

4.4 *Cracking pressure versus concrete strength*

The present study indicates that the cracking pressures for same c/d = 1 and α = 1 are found to be 2.33 Mpa for f_c =20.6 MPa and 4.00 Mpa for f_c =44 MPa, respectively. The present results also indicates that the cracking pressures for same c/d = 1 and α = 4 are found to be 1.38 Mpa for f_c = 20.6 MPa and 2.45 Mpa for f_c = 44 MPa, respectively. This means that the cracking pressures increase with an increase of compressive strength and the ratio of increase of cracking pressure according to compressive strength for a same condition is about 1.75 times larger when the compressive strength increases from 20.6 MPa to 44 MPa. Figure 14 shows the cracking pressures in terms of compressive strength.

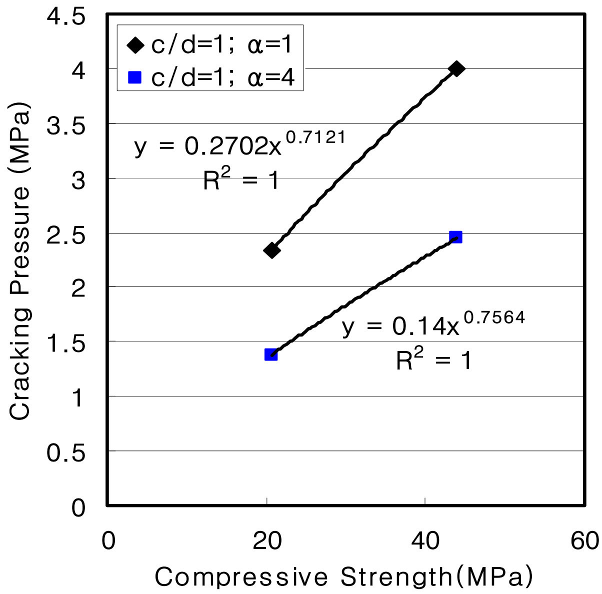

Figure 14. Cracking pressures in terms of compressive strength.

5 DISCUSSION ON TIME-TO-CRACKING

If accumulated chlorides in front of a steel bar exceed a certain critical value, then the steel bar starts to corrode. This critical value of chlorides is called the "threshold value" for corrosion initiation (Hope & Ip 1987, Hussain et al. 1996, Oh & Jang 2003b, Thomas 1996). After corrosion initiation, expansion pressure due to corrosion increases as corrosion products increases. The time-to-cracking is therefore important in assessing service life of concrete structures (Oh et al. 2009). The life time or service life of concrete structures may be reasonably defined as the time to corrosion initiation plus time to cracking (cover failure).

The present study indicates that the cracking pressures for non-uniform corrosion such as α = 4 and α =8 are about 55% and 40% of that for uniform corrosion case, respectively. This means that the cracking of concrete cover due to corrosion of steel bar occurs much earlier when the corrosion is localized at the outer region of rebar, which represents more real situation as reported by González et al. (1995). Therefore, the service life of concrete structures may decreases greatly if one considers realistically the effect of non-uniform corrosion distribution in cracking analysis. Neglect of non-uniform corrosion may induce unconservative estimation for service life of concrete structures. It is necessary in the future study to explore the relation among the time-to-cracking, cracking pressure, and amount of corrosion product and distribution.

6 SUMMARY AND CONCLUSIONS

The corrosion of steel bar in concrete may cause expansion pressure and this expansion pressure may then induce tensile cracking around the reinforcing bar. The corrosion may start from the outermost part of the rebar and thus the steel bar may not corrode uniformly in a cross section because chlorides are generally penetrated into concrete in one direction under actual sea environments. This has been reported by the experimental study of González et al. (1995). The purpose of the present study is to explore the effects of non-uniform corrosion on the cracking characteristics of concrete cover. The following conclusions have been drawn from the present study.

The pressures to cause cracking of concrete cover under non-uniform corrosion conditions are much smaller than that of uniform corrosion. The cracking pressure decreases up to 65% depending upon the type of non-uniform corrosion distribution.

It was reported from the experiments of González et al. (1995) that the value α (the degree of non-uniform corrosion) ranges about 4~8 in natural conditions. This means that a local corrosion at the outer face of rebar can cause the failure of concrete cover at very low expansion pressure.

The present study indicates that the pressure to cause cracking of concrete cover due to corrosion expansion increases with an increase of cover depth and is almost linearly proportional to the cover-to-rebar diameter (c/d) ratio.

Some realistic equations for cracking pressures of concrete cover due to steel corrosion were derived in terms of α value for various cover-to-bar diameter (c/d) ratios. The cracking pressure of concrete cover increases as concrete strength increases.

It is important to note that simple assumption of uniform corrosion may lead to unconservative assessment for service life. Continuous study is necessary to explore the effect of non-uniform corrosion on the time-to-cracking of concrete structures.

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