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# Analysis of Corrosion-induced Expansive Stress and Internal Cracking of Concrete under Considering Cover Thickness

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## Abstract

*After considering the actual dimension of reinforced concrete structure, the thickness and geometrical boundary condition of concrete cover, the model of corrosion-induced expansion can be simplified as a plane model of semi-infinite body. Through theoretical analysis, formulas are got to calculate corrosion-induced expansive stress of concrete cover. The results shows that: the corrosion-induced crack originated on the interface between concrete and the corrosion layer, if initial cracking is not in vertical direction to the surface of concrete cover, cracks along the rebar induced by the uplift and horizontal tension stress on the surface of the concrete cover may occur from its outer to inner, it also presents that the anti-rust ability of reinforced concrete structures could be improved by increasing the thickness of concrete cover, raising the grade of concrete, and increasing the diameter of rebar. Compared with the existing literatures, the precision of the theoretical solutions is verified.*

***Keywords**: Concrete cover; Uniform corrosion; Corrosion-induced expansive stress*

Corrosion of steel bar is one of the main causes affecting durability of concrete structures, and corrosion will lead to deterioration of mechanical performance of steel bar and flaking of concrete cover, thus effectively reducing the effective bearing area of member section and shortening the life of the structure. At present, many scholars have conducted studies on dimensions [1-4] of steel-bar corrosion mechanism, theoretical model of corrosion-expansion and corrosion rate model, etc. Among them, in the theoretical model analysis, scholars generally regard rebar and concrete around as the study object. Assuming that steel-bar corrosion is uniform to generate homogeneous corrosion expansion stress, and the concrete structure is considered as an infinite plate and simplified to single or double-walled cylinder subject to uniform internal pressure [4]. Based on this model, Jin Weiliang *et al* [5] have studied the expansive force mechanism using elastic mechanics method and have presented a theoretical calculation formula of expansive force, and have discusses the various influencing factors related to expansive force of steel bars. Bhargava *et al*. [6-7] have assumed that the elastic modulus and Poisson's ratio of steel-bar corrosion product are the same with those of rebar, taking the rebar and corrosion products as a whole, and assuming that its elastic modulus and Poisson's ratio are 210GPa and 0.3 Poisson's ratio respectively, thereby establishing analysis model of concrete cracking time. Zhao Yu Xi [8] has used the theory of damage mechanics and elastic mechanics, taking concrete damage into account, and has build corrosion-expansion cracking model of some cracked concrete covers.

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The concrete considered as an infinite plate and simplified to single or double-walled cylinder is actually to simplify the free surface of the protective layer into lines, and in this way, stress distribution pattern of protection layer surface cannot be obtained. In addition, it is also found [9] in simulation analysis using finite element that stress distribution is not circular in concrete near the side of the surface of protective layer, and the surface of protective layer has large tensile stress near the same direction of rebar. In terms of the actual size of reinforced concrete structure, it is more reasonable to consider the structure influencing the protective layer thickness as the semi-infinite plate than as the infinite plate, and limited to the complexity of theoretical derivation for the semi-infinite plate, there is rare relevant theoretical research. In this paper, the actual structure is simplified as a plane model of semi-infinite body, and the theoretical model for corrosion-expansion of concrete cover is established, and stress formula of protective layer corrosion-expansion has been obtained through theoretical analysis.

## 1. Rebar Corrosion-Expansion Model and its Computing Theory

In corrosion-expansion model used in this paper, concrete is considered as semi-infinite plate. Assuming that the radius of rebar is b, the elastic modulus of concrete as E and Poisson's ratio as ν, and the concrete affected by expansive force in contact with rebar results in balanced corrosion-expansion △displacement; the distance from rebar center to the cover surface is c, and the model is as shown below:

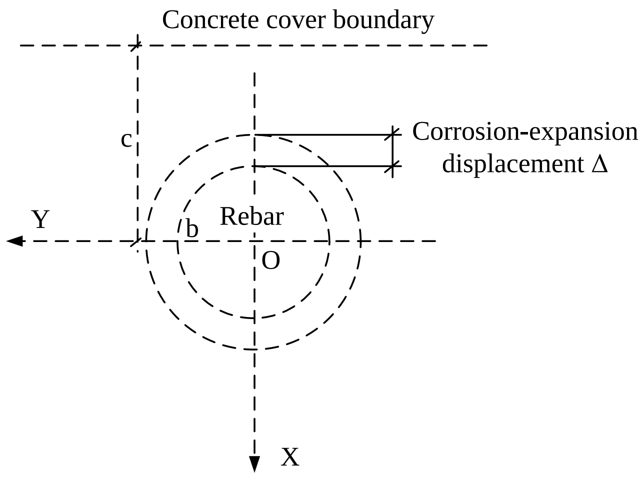


**Figure 1. The Model of Uniform Corrosion**

In the model shown in Figure 1, if the concrete is regarded as uniform infinite plate, the problem is converted to stress and displacement of axisymmetric plane strain. Literature [10] gives the expressions of corresponding stress and displacement components:

$$\begin{aligned} &\sigma_r = \frac{A}{r^2} + 2B; \sigma_\theta = -\frac{A}{r^2} + 2B; \tau_{r\theta} = 0 \\ &u_r = \frac{1-\nu^2}{\mathrm{E}}[-(1+\frac{\nu}{1-\nu})\frac{A}{r} + 2(1-\frac{\nu}{1-\nu})Br; u_\theta = 0 \end{aligned} \tag{1}$$

Wherein, A and B are the unknown quantities. Figure 1 shows that there are the following two boundary conditions of$(\sigma r)r=\infty=0$ and $(ur)r=b=\Delta$, and when brought into the formula (1), the expressions of stress components at any point in the concrete under polar coordinates can be obtained:

 

$$\sigma_r = -\frac{b\cdot \mathrm{E}\cdot\Delta}{r^2\cdot(1+\nu)}\ ;\ \sigma_\theta = \frac{b\cdot \mathrm{E}\cdot\Delta}{r^2\cdot(1+\nu)}\ ;\ \tau_{r\theta}=0$$

(2)

It should be noted that the above expression is a result of seeing concrete as analysis on infinite plate. In practical engineering structures, rebar is covered with concrete cover of certain thickness outside, and formula (2) does not consider the effect of the cover thickness on the stress state. Therefore, a cross-section is incised at x=-c of the infinite plate, and corrosion-expansion model is established as shown in Figure 1. Nevertheless, surface force exists on the concrete cover boundary at this time, and the expression of surface force may be obtained by formula (2):

$$(\sigma_x)_{x=-c} = \frac{(y^2-c^2)\cdot b\cdot \mathrm{E}\cdot\Delta}{(c^2+y^2)^2\cdot(1+\nu)} \quad (\tau_{xy})_{x=-c} = \frac{2\cdot c\cdot y\cdot b\cdot \mathrm{E}\cdot\Delta}{(c^2+y^2)^2\cdot(1+\nu)} \tag{3}$$

However, in practical engineering structures, concrete cover surface is in contact with the atmosphere without external forces. Therefore, surface force opposite to that described in formula (3) is superimposed, and the stress state caused by it can be presented by calculation results of stress component expressions under normal and tangential surface force on semi-plane boundary given in literature [10]. Wherein, the stress component expressions under the normal action on semi-plane boundary are:

$$\sigma_x = -\frac{2}{\pi}\int\frac{q\cdot x^3}{[x^2+(y-\xi)^2]^2}d\xi \quad \sigma_y = -\frac{2}{\pi}\int\frac{q\cdot x\cdot(y-\xi)^2}{[x^2+(y-\xi)^2]^2}d\xi \quad \tau_{xy} = -\frac{2}{\pi}\int\frac{q\cdot x^2\cdot(y-\xi)}{[x^2+(y-\xi)^2]^2}d\xi \tag{4}$$

Wherein, q is the normal stress of semi-infinite plate surface; ξ represents distance from any point in surface force q to the x-axis, and q is a function of ξ. Therefore, when q=-(σx)x=-c, the stress component expression at any point of cover can be obtained:

$$\begin{aligned}
\sigma_x &= \frac{2}{\pi}\cdot\frac{b\cdot \mathrm{E}\cdot\Delta}{(1+\nu)}\cdot\int\frac{\frac{(\xi^2-c^2)}{(\xi^2+c^2)^2}\cdot(x+c)^3}{[(x+c)^2+(y-\xi)^2]^2}d\xi \\
\sigma_y &= \frac{2}{\pi}\cdot\frac{b\cdot \mathrm{E}\cdot\Delta}{(1+\nu)}\cdot\int\frac{\frac{(\xi^2-c^2)}{(\xi^2+c^2)^2}\cdot(y-\xi)^2\cdot(x+c)}{[(x+c)^2+(y-\xi)^2]^2}d\xi \\
\tau_{xy} &= \frac{2}{\pi}\cdot\frac{b\cdot \mathrm{E}\cdot\Delta}{(1+\nu)}\cdot\int\frac{\frac{(\xi^2-c^2)}{(\xi^2+c^2)^2}\cdot(y-\xi)\cdot(x+c)^2}{[(x+c)^2+(y-\xi)^2]^2}d\xi
\end{aligned} \tag{5}$$

From J. H. Michell's solution in elastic mechanics, stress component expression under shear stress on semi-plane boundary can be obtained:

$$\sigma_x = -\frac{2}{\pi}\int\frac{p\cdot x^2\cdot(y-\xi)}{[x^2+(y-\xi)^2]^2}d\xi \quad \sigma_y = -\frac{2}{\pi}\int\frac{p\cdot(y-\xi)^3}{[x^2+(y-\xi)^2]^2}d\xi \quad \tau_{xy} = -\frac{2}{\pi}\int\frac{p\cdot x\cdot(y-\xi)^2}{[x^2+(y-\xi)^2]^2}d\xi \tag{6}$$

Wherein, p is the horizontal shear stress on surface of semi-infinite plate, and ξ is defined as above. Thus, when p=-(τxy)x=-c, the stress component expression for any point in the cover can be obtained:

$$\begin{aligned}
\sigma_x &= \frac{4}{\pi}\cdot\frac{c\cdot b\cdot \mathrm{E}\cdot\Delta}{1+\nu}\cdot\int\frac{\frac{\xi}{(c^2+\xi^2)^2}\cdot(y-\xi)\cdot(x+c)^2}{[(x+c)^2+(y-\xi)^2]^2}d\xi \\
\sigma_y &= \frac{4}{\pi}\cdot\frac{c\cdot b\cdot \mathrm{E}\cdot\Delta}{1+\nu}\cdot\int\frac{\frac{\xi}{(c^2+\xi^2)^2}\cdot(y-\xi)^3}{[(x+c)^2+(y-\xi)^2]^2}d\xi
\end{aligned} \tag{7}$$

$$\tau_{xy}=\frac{4}{\pi}\cdot\frac{c\cdot b\cdot \mathrm{E}\cdot\Delta}{1+\nu}\cdot\int\frac{\frac{\xi}{(c^2+\xi^2)^2}\cdot(y-\xi)^2\cdot(x+c)}{[(x+c)^2+(y-\xi)^2]^2}d\xi$$

In this case, the formula (2) is converted to the form in coordinate system in Figure 1, and it is superimposed with formulas (5) and (7), and then corrosion-induced expansive stress solution when concrete cover is free of external force can be obtained in graph model:

$$\begin{aligned}
\sigma_x &= \frac{(y^2-x^2)\cdot b\cdot \mathrm{E}\cdot\Delta}{(x^2+y^2)^2\cdot(1+\nu)}-\frac{2}{\pi}\cdot\frac{b\cdot \mathrm{E}\cdot\Delta}{(1+\nu)}\cdot\int\frac{\frac{(\xi^2-c^2)}{(\xi^2+c^2)^2}\cdot(x+c)^3}{[(x+c)^2+(y-\xi)^2]^2}d\xi \\
&-\frac{4}{\pi}\cdot\frac{c\cdot b\cdot \mathrm{E}\cdot\Delta}{1+\nu}\cdot\int\frac{\frac{\xi}{(c^2+\xi^2)^2}\cdot(y-\xi)\cdot(x+c)^2}{[(x+c)^2+(y-\xi)^2]^2}d\xi \\
\sigma_y &= \frac{(x^2-y^2)\cdot b\cdot \mathrm{E}\cdot\Delta}{(x^2+y^2)^2\cdot(1+\nu)}-\frac{2}{\pi}\cdot\frac{b\cdot \mathrm{E}\cdot\Delta}{(1+\nu)}\cdot\int\frac{\frac{(\xi^2-c^2)}{(\xi^2+c^2)^2}\cdot(y-\xi)^2\cdot(x+c)}{[(x+c)^2+(y-\xi)^2]^2}d\xi \\
&-\frac{4}{\pi}\cdot\frac{c\cdot b\cdot \mathrm{E}\cdot\Delta}{1+\nu}\cdot\int\frac{\frac{\xi}{(c^2+\xi^2)^2}\cdot(y-\xi)^3}{[(x+c)^2+(y-\xi)^2]^2}d\xi \\
\tau_{xy} &= -\frac{2\cdot x\cdot y\cdot b\cdot \mathrm{E}\cdot\Delta}{(x^2+y^2)^2\cdot(1+\nu)}-\frac{2}{\pi}\cdot\frac{b\cdot \mathrm{E}\cdot\Delta}{(1+\nu)}\cdot\int\frac{\frac{(\xi^2-c^2)}{(\xi^2+c^2)^2}\cdot(y-\xi)\cdot(x+c)^2}{[(x+c)^2+(y-\xi)^2]^2}d\xi \\
&-\frac{4}{\pi}\cdot\frac{c\cdot b\cdot \mathrm{E}\cdot\Delta}{1+\nu}\cdot\int\frac{\frac{\xi}{(c^2+\xi^2)^2}\cdot(y-\xi)^2\cdot(x+c)}{[(x+c)^2+(y-\xi)^2]^2}d\xi
\end{aligned} \tag{8}$$

x=-c is set, and stress component expression of the cover surface when corrosion-induced expansive displacement is $\Delta$ can be obtained:

$$\sigma_x=0;\ \ \sigma_y=\frac{4\cdot(c^2-y^2)\cdot b\cdot \mathrm{E}\cdot\Delta}{(c^2+y^2)^2\cdot(1+\nu)};\ \ \tau_{xy}=0$$

(9)

## 2. Contrastive Analysis on Theoretical Solution and FEM

In order to verify the theoretical solution, this paper has made simulated analysis on corrosion cases in the model using ABAQUS. FEM model uses 200mm × 400mm concrete specimens, concrete strength grade of C25, the elastic modulus of 28GPa, Poisson's ratio of 0.2 and design value of the tensile strength ft =1.27MPa; single central rebar is laid on vertical symmetry axis in the model, steel diameter of Φ16, protective layer thickness of 25mm, corrosion layer thickness of $\Delta$=0.001mm; the plane strain unit CPE4 is adopted, and on the concrete surface in contact with the rebar, applying uniform radial displacement indicates the effect of reinforced uniform corrosion-expansion on the surrounding concrete; constraint condition is the fixed constraint (away from the end of rebar) at bottom of the specimen, and circumferential stress in concrete cover is shown in Figure 2.

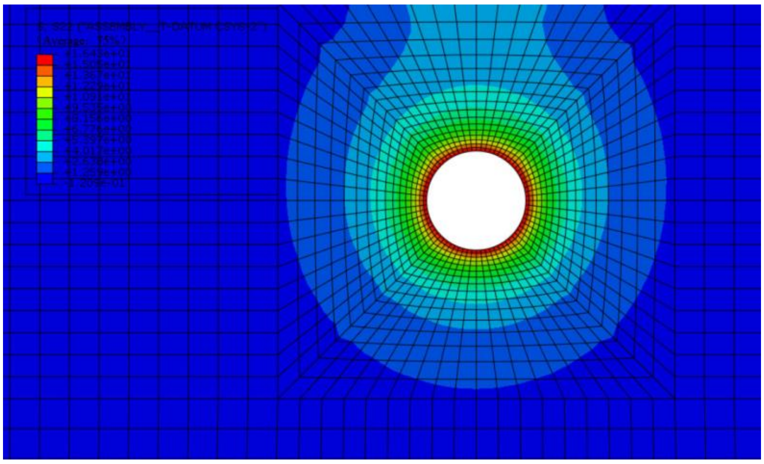

**Figure 2. Distribution of Circumferential Stress in Concrete Cover**

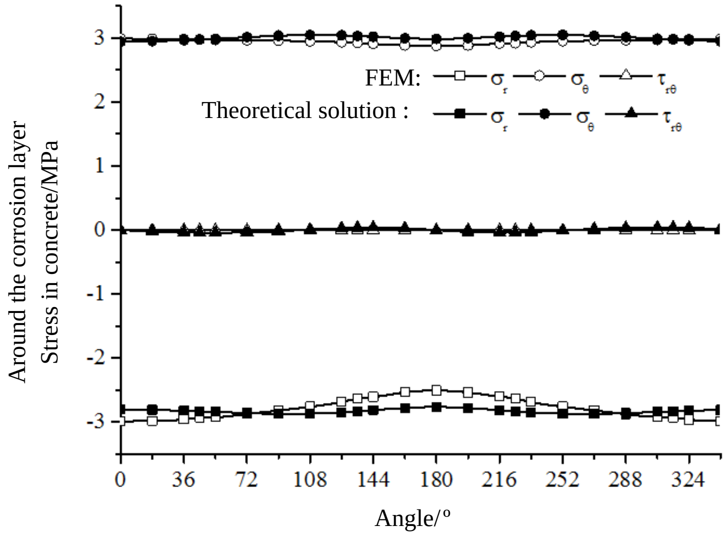


**Figure 3. Comparison of Corrosion-Induced Expansive Stress of Concrete around the Corrosion Layer**

From the distribution law in Figure 3: The distribution of σθ and τrθ in FEM and theoretical solution is basically consistent; the value of σθ is about 3Mpa, and the value of τrθ is about 0Mpa; seen from computational results of FEM: the value of σr near side of the protective layer is less than the value on the side in backward direction of the protective layer, and minimum point happens at 180 ° position, that is in the same direction of rebar, because the point has minimum thickness of protective layer, it is bound by concrete to a minimum, while the results of the theoretical solution show that: value of σr is approximately -3Mpa, with little change in the angle. Causes of error are that in the process of theoretical derivation, when the action of surface force of σx and τxy on the cover surface are considered, without considering the elastic modulus of rebar and the corrosion layer, the semi-infinite plate is taken as a homogeneous plain concrete for deduction of integral term.

 

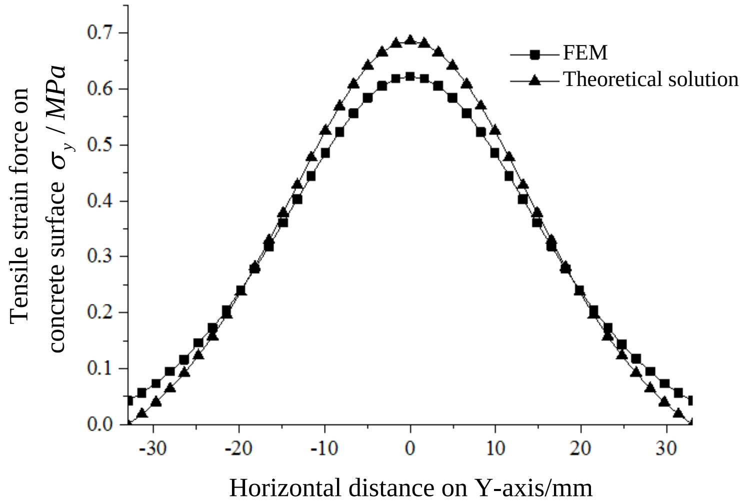


**Figure 4. Comparison of Tensile Stress on the Surface of Concrete Cover**

Curve distribution in Figure 4 shows that: maximum tensile stress σymax on the cover surface is at a distance of closest to the rebar, which is namely in the same direction of rebar (at Y=0), and it gradually decreases to both sides in normal distribution. FEM and the theoretical solution have similar calculation results, the maximum error of 10.3%.

Based on the above analysis, the theoretical solution and FEM are basically the same in computing results, thus in the analysis on reasons for cracking of concrete cover below, the calculation results of theoretical solution are directly employed for discussion.

## 3. Initial Cracks and Analysis on Influencing Factors of Corrosion-Induced Expansive Stress

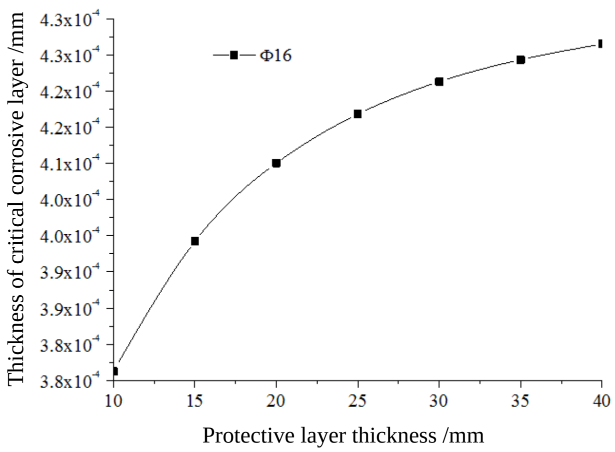


**Figure 5. Critical Corrosive Displacement of Concrete Cover**

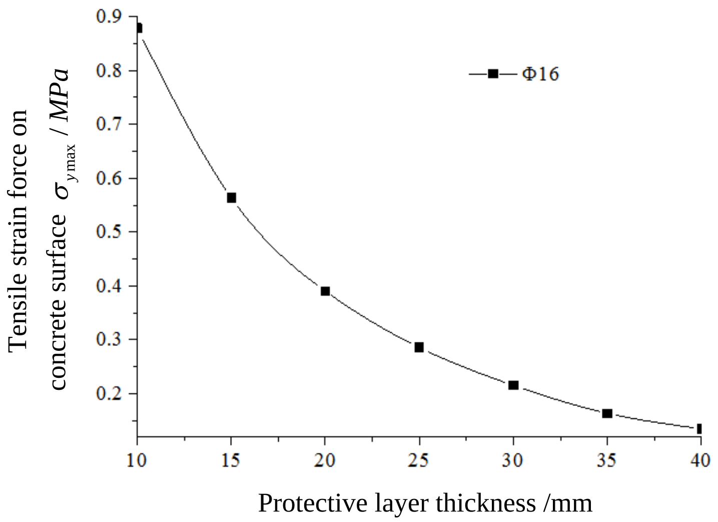


**Figure 6. Maximum Tensile Stress on the Surface of Concrete Cover**

Considering that the destruction of concrete is splitting-type damage of brittle fracture, this paper uses the maximum tensile stress criterion of Rankine for description. Figure 5 shows the corresponding critical corrosion-induced expansive displacement when concrete around corrosion layer reaches the maximum tensile strength (σθ=ft) . As can be seen from the figure, with the increase of thickness of the protective layer, critical corrosion-induced expansive displacement is increased constantly. Figure 6 is the corresponding maximum tension stress on the cover surface when concrete around corrosion layer reaches the maximum tensile strength. By comparison between Figure 5 and Figure 6, when concrete around rebar reaches the maximum tensile strength, the tension stress on the cover surface is lower than the tensile strength of concrete. Thus, the corrosion-induced expansive cracks of cover firstly appear in its subsurface, namely, the concrete in contact with corrosive layer. Since there is little change in the circumferential stress with angle, the angle of crack initiation is uncertain.

It has been found in simulation analysis on uniform corrosion made by Ji Cheng [9] using ABAQUS that when corrosion-induced expansive cracks of subsurface initiation is not perpendicular to the cover surface and cracks along rebars are expanded from the cover surface to the subsurface. In simulation of rebar corrosion-expansion through mechanical broaching, Wang Qiaoping [11] *et al*. have found that when vertical fractures and oblique cracks co-exist, the vertical cracks generally start with the outermost edge of the concrete and expand from the outside, while oblique cracks expand along the inside of the hole from within. This paper argues that with the development of internal non-vertical cracks, it leads to uplift of the protective layer, and the maximum tensile stress is just in the same direction of rebar, thus the tension stress on the cover surface is the cause for the cracks along rebars. In addition, the thinner the protective layer is, the greater the tensile stress on surface will be, and it is more likely to lead to development of crack along rebars from outside to inside.

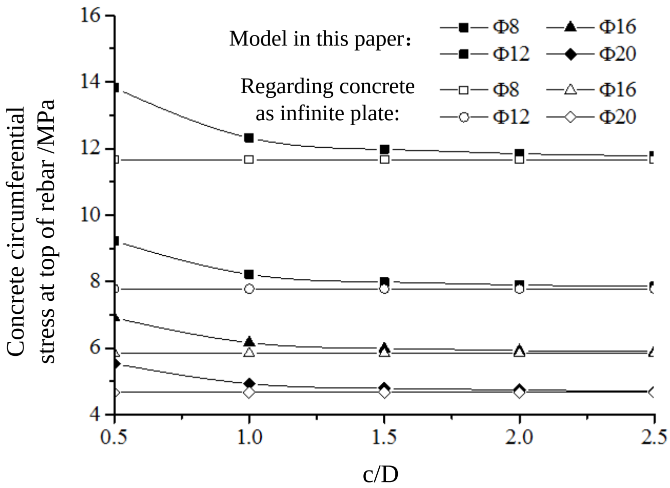


**Figure 7. Influence of the Protective Layer Thickness and Rebar Diameter on Corrosion-Induced Expansive Stress of Internal Concrete**

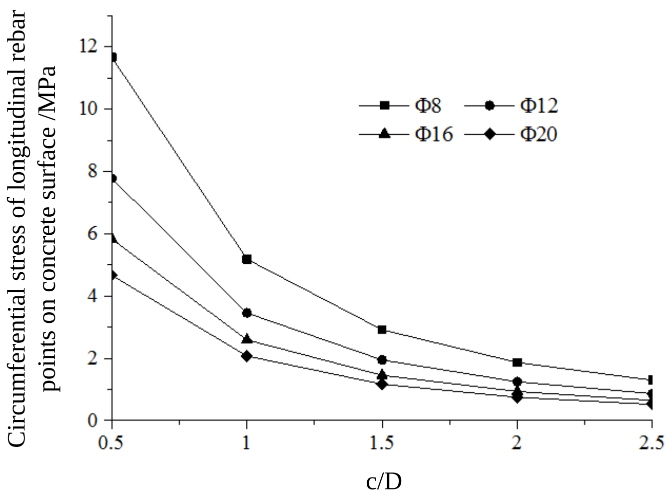


**Figure 8. Influence of the Protective Layer Thickness and Rebar Diameter on Corrosion-Induced Expansive Stress of Concrete Surface**

Figures 7 and 8 are the calculated results when thickness of corrosion-induced expansive layer equals to 0.002mm, and D is bar diameter. Figure 7 is a distribution graph of corrosion-induced expansive stress of concrete at the apex of the rebar inside the cover internal changing with rebars diameter and the thickness of the protective layer and gives the corrosion-induced expansive stress value by calculations of formula (2) when concrete is regarded as infinite plate without regard to impact of protective layer thickness. The distribution law in curves of the figure shows: With the increase of the thickness of the protective layer, the tensile stress of concrete around rebar is gradually lowered and tends to be the calculation result when concrete is regarded as infinite plate. When c/D=1, it is considered that the error of the calculation results between the cover thickness and concrete regarded as infinite plate is 5.3%, and when c/D=1.5, the error of both is about 2.56%.

 

Figure 8 is a distribution diagram of corrosion-induced expansive stress of longitudinal rebar points on cover surface changing with rebars diameter and the thickness of the protective layer. Comparison of distribution law in figures 7 and 8 shows that: increasing the thickness of the protective layer and rebar diameter all help reduce corrosion-induced expansive stress in concrete; under the same corrosion conditions, rebar diameter has greater impact on corrosion-induced expansive stress inside the concrete, and the way of increasing the rebar diameter is superior to that of increasing the thickness of the protective layer, but in terms of the surface of the protective layer, the protective layer thickness has greater impact on the corrosion-induced expansive stress, and the way of increasing the thickness of the protective layer is superior to that of increasing the rebar diameter. Given that the corrosion-induced expansive cracks of concrete firstly expand from its subsurface, and protective layer thickness ruled in concrete design specification should be not less than the nominal diameter of rebar. Therefore, compared to the increase in steel protective layer thickness, the increase in rebar diameter is more conducive to improving the durability of the structure. The tensile strength increases when the grade of concrete is improved, thus increasing the thickness of the protective layer, improving the grade of concrete and enlarging rebar diameter all help to improve the ability of resisting corrosion-cracking of concrete structures.

## 4. Comparative Analysis of Concrete Internal Crack Threshold

Currently, research of corrosion-cracking often focuses on cracking case on surface of concrete cover, and because of the brittle characteristics of concrete itself, once corrosion-induced expansive cracks occur in rebar and concrete interface, and namely corrosion-induced expansive internal crack of concrete occurs, which will develop into the surface of concrete cover in a relatively short period of time. Therefore, to determine the concrete internal crack threshold under the action of expansive force of interface is a very crucial issue in corrosion-cracking process of concrete structures [12]. Table 1 shows the comparison of internal crack threshold in concrete calculated by theoretical solution in the relevant literatures. As can be seen from the table, the obtained results using the maximum linear strain theory are relatively conservative, while when analysis is made using semi-infinite plate model, calculation results of greater cover thickness and under the infinite plate are close. A variety of assumptions are employed in the present theoretical analyses to facilitate deduction and calculations, thus the obtained results are very conservative. Limited to means of observation, there are rare experimental observations of the initial cracks inside, and further experimental study is required.

**Table 1. The Comparison of Critical Displacements Induced by Corrosion Expansion under Inner Cracking of Concrete**

| Data sources | Models | Judgment criteria for cracking | c mm | ft MPa | D mm | Δmax μm |
|---|---|---|---|---|---|---|
| Bingyan [12] | Infinite plate | Maximum principal tensile stress | — | 2.64 | 16 | 0.805 |
| | | | | 2.74 | 16 | 0.849 |
| Jiang Hui [13] | Infinite plate | Maximum linear strain | — | — | 16 | 0.8 |
| This paper | Semi-infinite plate | Maximum principal tensile stress | 40 | 2.64 | 16 | 0.86 |
| | | | | 2.74 | 16 | 0.9 |

NOTE: c- protective layer thickness; ft- concrete tensile strength; D- bar diameter; Δmax- critical corrosion-induced expansive displacement.

## 5. Conclusions

(1) Compared to the fact that corrosion-expansion model is simplified to single or double walled cylinder subject to action of uniform internal pressure, the corrosion-expansion model proposed in this paper has taken into account of geometric boundary conditions of protective layer, protective layer thickness and relative positions among rebars. By theoretical analysis, the relational expression between corrosive layer thickness and corrosion-expansion stress, as well as the corrosion-induced expansive stress formula of protective layer surface are obtained, so that when the corrosive layer thickness is known, the appropriate corrosion-induced expansive stress can be figured out, which is of great significance to analysis on structural durability.

(2) The comparison in calculation results between theoretical solution and FEM shows that: although some simplification of the theoretical formula has been conducted in the derivation process, calculation results of both are basically the same with small error; corrosion-expansion cracks firstly occur inside the protective layer and namely firstly appear in the concrete in contact with the corrosion layer; development of internal corrosion-expansion cracks can cause uplift of the protective layer, and the cover surface has the maximum corrosion-induced expansive stress in the same direction of rebar, thus tension stress of the cover surface is the reason for cracks along rebars, and affected by internal non-vertical cracks, crack along rebars may extend from outside to inside.

(3) Increasing the thickness of the protective layer, enlarging rebar diameter and improving the grade of concrete all help to improve the ability of resisting corrosion-cracking of concrete structures. By comparative analysis on two factors of rebar diameter and the thickness of the protective layer, and by reference to provisions of concrete design specification for ranging of protective layer thickness, compared to increase in the thickness of the protective layer, the enlargement of rebar diameter is more conducive to improving the durability of the structures.

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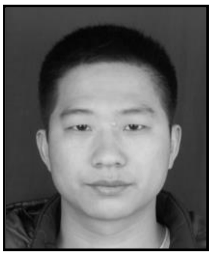
## References

[1] Hong Dinghai. Corrosion and Protection of Rebar in Concrete [M] Beijing: China Railway Publishing House, **(1998)**.
[2] Ji Yongsheng. All-life Process Life and Expectation of Reinforced Concrete [M] Beijing: China Railway Publishing House, **(2011)**.
[3] Li Fumin. Load-carrying Properties Evaluation and Design of Corroded Reinforced Concrete Members[M]. Beijing: China Railway Publishing House, **(2011)**.
[4] Zhao Yu Xi. Review on Concrete Structure Corrosion-cracking Caused by Steel-bar Corrosion [J]. Journal of Southeast University: Natural Science Edition, **(2013)**.43 (5): 1122-1134.
[5] Jin W L, Zhao Y X, Yan F. The mechanism of corroded expansion force of reinforced concrete members[J].Journal of Hydraulic Engineering, **(2001)**,(7):57-62.
[6] Bhargava K, Ghosh A K, Mori Y *,et al*, Modeling of time to corrosion-induced cover cracking in reinforced concrete structures[J].Cement and Concrete Research, **(2005)**,35(11):2203-2218.
[7] Bhargava K, Ghosh A K, Mori Y. Analytical model for time to cover cracking in RC structures due to rebar corrosion[J].Nuclear Engineering and Design, **(2006)**,236(11):1123-1139.
[8] Zhao Y X, Yu J, Jin W L. Damage analysis and cracking model of reinforced concrete structures with rebar corrosion[J].Corrosion Science, **(2011)**,53(10):3388-3397.
[9] Ji Cheng. Preliminary Study on Corrosion-expansion Cracking of Concrete Based on Smeared Crack Model. [D]. **(2013)**, Chongqing University
[10] ] Wang Guangqin. Elastic Mechanics [M]. Beijing: China Railway Publishing House, **(2004)**.
[11] Wang Q P, Wu S X. Test Study of Concrete Cover Crack from by Corroded Rebar[J].Industrial Construction, **(2005)**,35(3): 63-65.

[12] Hu Bingyan. Behavioral Research on Corroded Reinforced Concrete Interface [D] . **(2011)**, Zhejiang University.
[13] Jiang Hui, Yu Mengxiong, Liu Ronggui. Analysis on the internal cracking of concrete cover due to rebar uniform corrosion[J].Concrete, **(2014)**,(9):1-4.

## Authors



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