EFFECT OF TENSILE STRESS AFTER CRACKING IN COVERING CONCRETE ON MASS LOSS OF CORRODED STEEL BAR

Kochi University of Technology (student member) Songkram PIYAMAHANT
Kochi University of Technology (JSCE member) Hiroshi SHIMA

1. Introduction

Mass loss of steel causing crack in the covering concrete due to the corrosion of steel bars, so called corrosion crack, was simply estimated by the tensile strength of covering concrete [1]. However, tension-softening is known as necessary behavior regarding to the fracture mechanics. Therefore, some researches dealing with the corrosion problem already considered this tension-softening behavior in the cracked concrete model [2] [3]. Even though the tension-softening was considered in previous research, the mass loss of steel bar due to the corrosion does not satisfy the confinement condition. To satisfy this confinement condition, the pressure and displacement relationship in concrete is necessary. In this research, the effect of tension-softening on the radial pressure and crack width in concrete at the steel bar position as well as mass loss of steel bar is demonstrated.

2. Cases of Tensile Behavior of Concrete in Calculation

As the objective, the types of tensile stress after cracking are the main parameter governing on the pressure and crack width in concrete at the steel position. **Fig.1** shows the cases of tensile stress used in calculation. The tension-softening curve after cracking used in the calculation was purposed by Uchida [4]. Following Okamura [5], the plastic flow behavior before the occurrence of tensile crack in the covering concrete is postulated until two times of cracking strains.

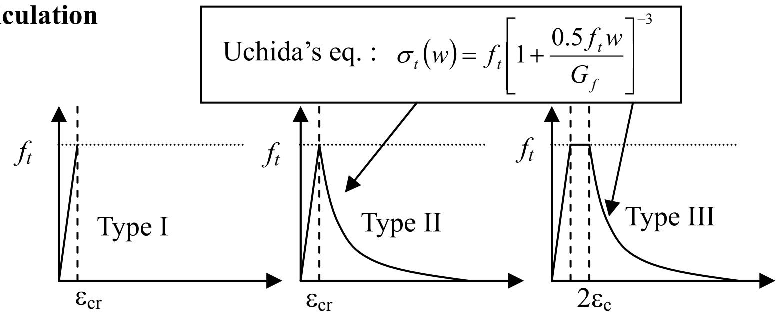


Fig.1 Models of tensile stress of concrete using in calculation

3. Calculation of Pressure, Crack width, and Displacement of Concrete

Referring to thick-walled cylindrical theory, the steel bar and covering concrete was assumed as cylindrical specimen which is actually a part of general concrete structures. In analysis, single crack was postulated based on the fact that the crack generally takes place in the thinnest covering concrete first. The dimension of cylinder specimen using in analysis is covering concrete 50 mm and steel diameter 32 mm. The compressive strength of the cylindrical specimen is 30 MPa. The figure of specimen using in analysis are shown in **Fig.2**. The calculation method, so called pseudo boundary integral method [6], was used in determining crack width of concrete around the steel bar position.

$$u_{crack} = \frac{p\,\phi/2}{E_c\left((c+\phi/2)^2 - (\phi/2)^2\right)}\left[(1-\nu_c)(\phi/2)^2 + (1+\nu_c)(c+\phi/2)^2\right] \qquad \textbf{Eq.1}$$

Displacement of concrete around the steel bar at first cracking was calculated by thick-walled cylinder theory, **Eq.1**. After cracking appeared at the concrete surface, the displacement of concrete around the steel bar was calculated by summing the displacement from **Eq.1** with the crack width at the steel bar position as shown in **Eq.2**.

$$u_{total} = u_{crack} + \frac{w}{2\pi} \qquad \textbf{Eq.2}$$

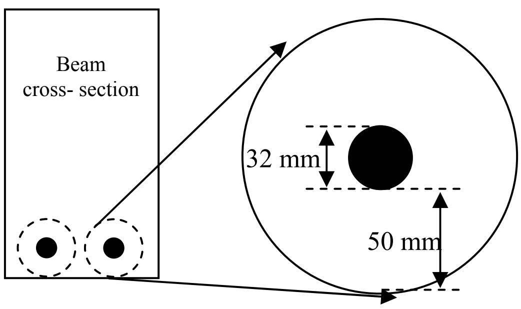
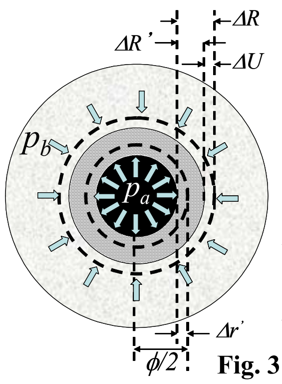


Fig.2 Cylindrical specimen using in analysis



$\Delta r'$: radius loss due to corrosion
ΔR : free expansion radius of rust
$\Delta R'$: confined expansion radius of rust
ΔU : displacement due to confining pressure

$$a = \frac{\phi}{2} - \Delta r' \qquad b = \frac{\phi}{2} - \Delta r' + \Delta R$$

$$\Delta U = \frac{(1+\nu_{rust})a^2b^2}{E_{rust}(b^2-a^2)}\left[\frac{(p_a-p_b)}{b} + (1-2\nu_{rust})\frac{(p_a a^2 - p_b b^2)}{a^2b^2}b\right]$$

$$u_{total} = \Delta R - \Delta U - \Delta r'$$

Fig. 3 Displacement involving in calculation

By using **Eq.2**, the displacement of concrete around steel bar is assumed to solely depend on crack width and regardless of the displacement due to the radial pressure incremented after first cracking.

4. Effect of Confinement

As aforementioned, to determination of weight loss of steel bar is necessary to consider the effect of confining pressure from the covering concrete on rust layer. In **Fig.3**, the displacement involved in calculating the mass loss of steel bar under

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Contact Address: 〒782-8502 Kochi Tosayamada Miyanokuchi 185, TEL 0887-57-2000

confinement condition is shown. The procedures for achieving the mass loss of steel under the confinement condition is explained hereafter. First, the mass loss of steel and free expansion radius of rust was sequently calculated by assuming the radius loss due to corrosion and expansive volume ratio of rust. Second, the radial pressure and displacement in concrete around the steel bar is determined by the method described in **3**. It is noted that the position of crack tips have to be assigned before calculating pressur e and displacment in concrete. Next, the radial pressure in concrete at the position of steel was also applied on the rust layer in order to achieve the confined rust layer. Finally, the rust layer expanding thicker than the original diameter of steel is checked with the displacement in concrete around the steel bar for the displacment compatibility. Therefore, the radius loss of steel bar have to be iterative until this compatible condition is satisfied in each state of crack propagation.

5. Calculation Results

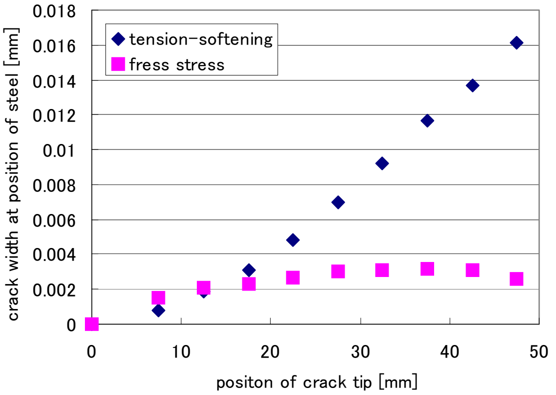

Fig.4 Crack width at steel propagation and crack propagation

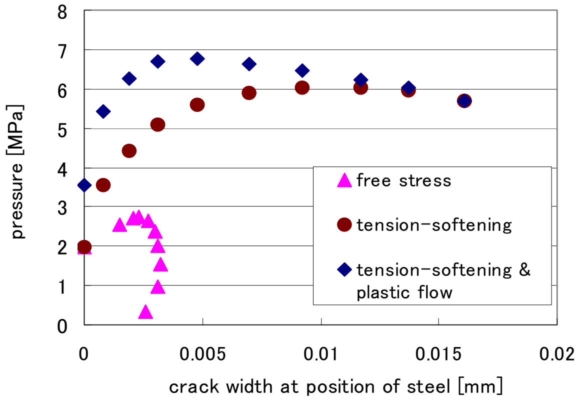

Fig.5 Pressure and crack width at steel position

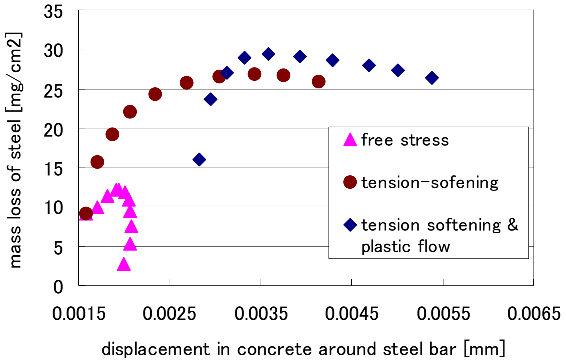

Fig.6 Mass loss of steel and displacement

Based on above calculation method, the crack width in concrete at the position of steel bar is plotted against the position of crack tip as shown in **Fig.4**. Since the crack width in concrete is governed by the tension-softening curve, the difference in plastic flow behavior between Type 2 and Type 3 is not the case here. It is clearly seen from the figure that the larger crack width is needed for driving the crack tip whereas very small crack width is enough for driving the crack tip through the covering concrete. From **Fig.5**, three relationships between radial pressure and crack width in concrete around steel bar are shown according to their tensile stress behavior after cracking. The case without tension-softening curve, Type 1, showed the lowest pressure and smallest crack width when the crack propagated from the position of steel bar to the concrete surface. Type 2 and Type 3 showed the same crack width when the crack propagated from steel bar to the concrete surface because the tension-softening curve is the same. However, Type 2 and Type 3 showed the different radial pressure because the postulated plastic flow behavior before tension-softening behavior. This plastic flow created high radial pressure when crack width was small where the crack propagation was far from the concrete surface but the effect of plastic flow behavior cannot be observed when crack propagated nearby the concrete surface. In **Fig.6**, the mass loss of steel bar when the crack started to propagate from the steel bar position to the concrete surface is plotted against the displacement in concrete around steel bar. It can be clearly seen that the tension-softening curve largely affected the maximum mass loss of steel and maximum displacement in concrete. The different in the mass loss of steel bar is about three times if the case of free stress is compared with the case of tension-softening curve.

6. Conclusion

Mass loss of steel bar when the corrosion crack took place at the concrete surface was determined from the radial pressure and displacement relationships in concrete. It is found that the existing of tension-softening curve increased mass loss of steel bar about three times regarding to the dimensions of simulated specimen.

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