염해환경하의 콘크리트 구조물의 잔존수명 예측

Remaining Service Life Prediction of Concrete Structures under Chloride-induced Loads

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ABSTRACT

In order to predict the remaining life of marine concrete structures under climatic loads, it is necessary to develop an analytical approach to predict the time and space dependent deterioration of concrete structures due to mainly chloride attack up to corrosion initiation and additional deterioration like cracking of cover concrete. This study aims to introduce FEM model for life-time simulation of concrete structures subjected to chloride attack. In order to consider uncertainties in materials as well as environmental parameters for the prediction, Monte Carlo Simulation is integrated in that FEM modeling for reliability-based remaining service life prediction. The paper is organized as follows: firstly general scheme for reliability-based remaining service life of concrete structures is introduced, then the FEM models for chloride penetration, corrosion product expansion and cover cracking are briefly explained, finally an example is demonstrated and the effects of localization of chloride concentration and corrosion product expansion on service life using above model are discussed.

요　약

해양 환경에 노출된 구조물의 잔존수명을 예측하기 위해서는 부식 개시기까지의 염화물 침투와 콘크리트 피복 균열과 같은 콘크리트 구조물의 열화현상에 대하여 시간과 공간적 요소를 고려한 분석적 접근 방법의 개발이 필요하다. 이를 위하여 본 연구에서는 유한요소해석 기법을 이용하여 염해에 노출되어 있는 콘크리트 구조물의 생애주기를 시뮬레이션하는 것을 목표로 한다. 내구성 예측을 위한 환경적 변수와 재료의 불확실성을 고려하기 위하여 신뢰성에 기반한 잔존수명의 예측을 위한 유한요소해석 모델링에 Monte Carlo Simulation 기법을 도입하였다. 본 논문에서는 콘크리트 구조물의 신뢰성에 기반한 잔존 내구수명에 대한 일반적 개념과 염화물 이온 침투, 부식 생성물의 팽창, 피복 균열 등에 대한 유한요소 모델에 대해 설명하고, 마지막으로 예제를 통하여 염화물 이온의 집중, 부식 생성물의 팽창등이 콘크리트 구조물의 잔존수명에 미치는 영향에 대해 논의하였다.

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1. Reliability-based remaining service life model

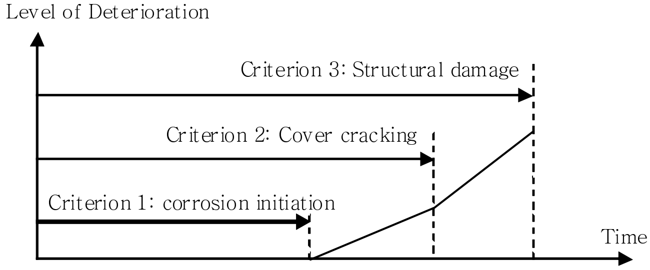

Fig 1 Deterioration level versus time of concrete structures under chloride attack

Fig. 1 shows the relationship between level of deterioration and time of concrete structures under chloride attack. In this paper, it's tentatively to define three deterioration levels corresponding to three criteria for ending of service life: corrosion initiation criterion, cover cracking, and structural damage. Most of current reliability-based stops at the first criterion. In this paper, we try to move forward to consider second criterion as the ending of service life.

1.1. General scheme for reliability-based service life modeling

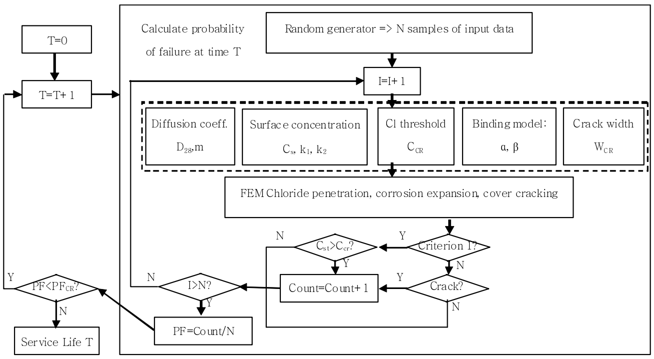

Fig 2 Reliability-based scheme for service life prediction

Remaining service life can be predicted by the scheme in Fig. 2. Thescheme starts at time T=0 and increases one year at each step. At each time T, the probability of failure is calculated and compared with critical failure probability. In this model, the value of 0.1 is used for critical failure probability. To calculate the probability of failure at time T, the random generator is used to create N samples of input data. Input variables for the model include diffusion coefficient at 28 days, time dependent constant of diffusion coefficient m; surface concentration and constants k_1, k_2 for time dependent surface concentration; chloride threshold; constants of Freudlich binding isotherm; crack width. Each sample of input data is inserted in FEM models for chloride penetration, corrosion expansion and cover cracking to get chloride concentration at reinforcement surface and time to cover crack. The above values are then put in limited state function to decide whether they sastify. Finally the probability of failure is calculated by the ratio of the number of samples that violate limit state function to the total number of samples.

1.2. Chloride penetration model

Chloride ingress in concrete structures is governed by following differential equation:

$$\frac{dC_f}{dt} - div(D\nabla C_f) + \frac{dC_b}{dt} = 0 \tag{1}$$

where, C_f is free chloride, C_b: bound chloride, D: diffusion coefficient. In this paper, the Freudlich binding isotherm is chosen to relate binding chloride with free chloride:

$$\frac{dC_b}{dt} = \frac{dC_b}{dC_f}.\frac{dC_f}{dt} = \frac{d(\alpha C_f^{\beta})}{dC_f}.\frac{dC_f}{dt} = \alpha\beta C_f^{\beta-1}.\frac{dC_f}{dt}$$

Eq.(1) can be solved by two steps of discretization. First discretization is carried out over the whole space using Galerkin method. Crank-Nicolson method is then used to discrete over time for each time step. The iteration is necessary for Crank-Nicolson method.

1.3. Corrosion product expansion model

Update the diameter at time T: D2=D3

Calculate volume loss: $V1 = 2.95.10^{-11}\pi.D2.i_{CORR}\Delta t$

Calculate accumulated volume loss from starting: $V2 = V2 + V1$

Calculate residual steel diameter at this step: $D3 = \sqrt{D2^2 - \frac{V1.4}{\pi}}$

Calculate the total volume of rust: $V3 = V2.2$

Calculate the volume of rust that causes the stress: $V4 = V3 - V2$

Calculate the expansion diameter: $D4 = \sqrt{D1^2 + \frac{V4.4}{3.1416}}$

Fig 3 Corrosion induced rust expansion model

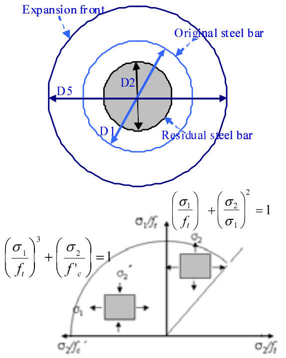

Fig 4 Stress criteria for cracking

Immediately after corrosion initiation, the corrosion products expansion model showed in Fig. 3 is introduced. The expansion exerts radial displacement on concrete cover that causes cracking and spalling.

1.4. Cover cracking model

The relation of equivalent stress and strain model is used for uncracked concrete. The detailed description of the model can be found elsewhere[1)]. The crack happens when stress condition meet stress criteria shown in Fig. 4. The smeared crack approach is utilized in this work. Compressive model parallel to crack has the same shape as uniaxial uncracked compressive stress-strain curve with the reduction of strength. Tension softening curve $\sigma = f_t.(\varepsilon_{tu}/\varepsilon)^c$ is used for the direction perpendicular to crack. The element-size sensitivity can be avoided by adjusting the softening curve, according to the element size, such that the strain energy released after localization of cracks in an integration point is equal to the fracture energy of concrete, according to the crack band theory.

2. Illustration example and the effect of localization of corrosion product expansion on service life

2.1. Illustration example:

Considering RC slab under chloride attack and geometry of simulation section as in Fig. 5. The boundary condition for chloride ingress model and cover cracking model are in Fig. 6.

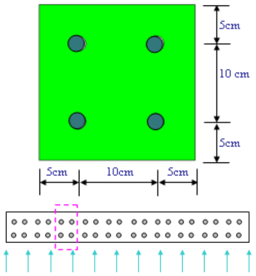

Fig 5 Concrete slab and geometry

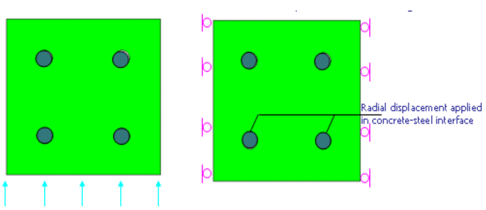

Fig 6 B.C. for chloride penetration and cover cracking model

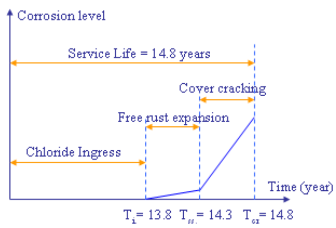

Fig 7 Results from deterministic model

The input data for reliability based model are as follows: diffusion coefficient: D=(1,0.1)x10^{-12} m/s^2 surface concentration: C_s=(5,0.5) kg/m^3,chloride threshold value: C_{lim}=(1.2,0.12) kg/m^3 ,concrete compressive strength: 400kgf/cm^2,concrete tensile strength: 35kgf/cm^2. Mean and standard deviation are the first and second value in the bracket. The deterministic model takes the mean value of about data as its input. The results from deterministic and reliability based model are shown in Fig. 7 and Fig. 8. Fig. 7 gives the service life of 13.8 and 14.8 years corresponding to the first and second criterion. From Fig. 8, if critical probability of failure is chosen as 0.1, the service life are 12.7 and 13.7 years corresponding to first and second criterion. The service life calculated by reliability based model is smaller that of deterministic model.

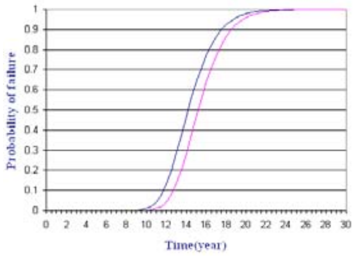

Fig 8 Results from reliability-based model

2.2. Effect of localization of chloride concentration and corrosion product expansion on service life:
Most of current reliability-based service life model using analytical solution of Fick's second law that cannot consider the effect of reinforcement. Using the proposed model, it shows that the chloride concentration is highest at nearest depth and significant lower elsewhere. The assumption of uniform corrosion expansion is often used in current cover cracking model. This is contrast to the fact that the localization of chloride concentration leads to localization of corrosion product expansion. The analysis results from presented model show that both of the above localization have significant effects on service life of concrete structures.

3. Conclusions

In this paper, a reliability-based service life model of concrete structures considering cover cracking as service life ending criterion is proposed. Its application is shown through an example. The effect of localization of chloride concentration and corrosion product expansion on service life is also discussed. The need to develop more accurate model that considering effect of localization and expand the model to include the third criterion is important for reliable service life prediction.

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