報告番号	甲　第 11181 号

主 論 文 の 要 旨

論文題目　**EXPERIMENTAL AND NUMERICAL STUDY ON CORROSION-INDUCED DAMAGES ON REINFORCED CONCRETE STRUCTURES (鉄筋腐食により生じるコンクリート構造物の損傷に関する実験的及び数値解析的研究)**

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論 文 内 容 の 要 旨

In recent years, deterioration of reinforced concrete (RC) structures caused by chloride-induced corrosion of reinforcing steel bars has been a growing concern for durability of structures. Rebar corrosion may result in several types of damages on RC structures: loss of effective concrete section due to concrete cracking and cover spalling, loss of rebar tensile performance due to a reduced cross section and reduced bond strength between corroded rebars and the concrete. These damages can compromise the load bearing capacity of an RC structure. In addition to these effects on structural safety, corrosion may also lead to falling concrete, which increases the risk to human safety. Therefore, it is of great importance to fully understand the influences of corrosion on RC structures. Meantime, a reliable means to assess the residual strength and crack development is essential. Such a method could contribute to optimized and efficient maintenance work that would extend the service life of RC structures in corrosive environments.

This study clarified the corrosion-caused damages in three-dimensional level, where crack propagation and cover spalling as well as tensile performance of corroded rebars influenced by various corrosion distributions around or along the rebar were focused. On the other hand, a time-dependent electro-mechanical model based on Rigid Body

Spring Method (RBSM) was developed for the evaluation of both concrete cracking and tensile degradation of rebars due to corrosion. The dissertation contents consist of 8 chapters.

Chapter 1

This chapter is the introduction part, including a general background of the study, a review of related references, and the study objectives.

Chapter 2

This chapter introduces an electric corrosion method using a salt-water pool on the concrete cover, which can approximate the natural corrosion state of a rebar due to chloride attack. The electric corrosion process implemented by this method was investigated as a basic study, in which corrosion degree and corrosion profile that is represented by radius losses along the rebar were examined. The test results demonstrated that the circumference of rebar facing the concrete cover was more corroded, confirming the applicability of the proposed test method to the study of structural behavior of RC members exposed to chloride-induced corrosion. In addition the interaction between electric corrosion and cracks was explained. It was found that the cracks generated in the concrete cover might enlarge the difference of corrosion rates between various positions around the rebar. A simple test method was also proposed for simulating various corrosion profiles in which bare rebar specimens and different cathode arrangements were used. The measured corrosion profiles confirm that the use of a small cathode can concentrate the resulting corrosion at the rebar part close to the cathode to a certain extent.

Chapter 3

This chapter presents an investigation of 2D cracking behavior in the plane of rebar which was studied both experimentally and analytically. In the experiments, the single-rebar specimens with different cover thicknesses were tested using the proposed electric corrosion method and the crack patterns were observed. The test results showed that the internal crack patterns for the specimens with 30 and 10mm concrete cover both consisted of parallel cracks to the concrete surface, which was different from the theoretical crack model. In the analysis, the corrosion-expansion model was used to simulate the cracking behavior in comparison to the test results, where a non-uniform corrosion model was assumed. It was identified that the corrosion-expansion model can simulate accurately internal crack pattern if the corrosion distribution around the rebar is properly assumed. The parametric study concerning the effect of corrosion distribution demonstrated that internal crack pattern was highly dependent upon the corrosion distribution around the rebar rather than cover thickness as suggested by the theoretical crack model. Additionally the parametric study with regard to the effect of concrete material properties was carried out. It was found that surface crack initiation is determined by concrete tensile strength, while tensile fracture energy has a great influence on the propagation of surface and internal cracks.

Chapter 4

This chapter shows a study of the 3D crack propagation caused by local corrosion along the rebar length, which was compared with the 2D cracking behavior. The local corrosion state, i.e. corrosion concentrates at the center part of the rebar, was simulated using salt-water pools of various sizes in the experiments. The resulting crack patterns and the relation to the cover spalling were examined. In addition, the corrosion-expansion model was applied to simulate the crack propagation and to predict spalling area by assuming similar distributions of corrosion amounts along the rebar to the test results. Both experimental and analytical studies demonstrated that the internal crack pattern varied along the rebar length. At the center part with high corrosion level the inclined lateral cracks appeared instead of the parallel cracks as shown by 2D cracking behavior, which might lead to cover spalling. On the other hand, at the area with less corrosion only vertical cracks were obvious.

Chapter 5

This chapter shows an experimental study on the tensile behavior of rebars corroded with various corrosion profiles. Both bare rebar specimens and those corroded in concrete were considered. A digital image processing method was employed to obtain the strain distribution along a test specimen when the tensile load was applied. It yields satisfactory accuracy for recording the development of local strains, offering an available method for measurement of large strain in other loading tests. The tensile test results demonstrated that with an increase of corrosion level the ultimate load of a tested rebar decreased more than yield load and elongation was most degraded. The residual tensile performance was largely related to radius loss variability along the rebar length. The applicability of some empirical equations was checked with the test results, which suggested that these equations can only work well with more uniform corrosion along the rebar length.

Chapter 6

This chapter presents a quantitative evaluation method for the tensile performance of corroded rebars considering corrosion profile. This model was implemented using the RBSM incorporated with a truss network and verified with the test results of bare rebar specimens. With truss network model, Laplace equation and Faraday's law were used to evaluate the corrosion profile. Good agreement with the measurements shows that the proposed model can be applied to model the corrosion process due to a micro-cell corrosion circuit. The simulation of tensile performance of the corroded specimens is also in agreement with test data, suggesting that the residual tensile capacity can be accurately predicted when corrosion profile is taken into account.

Chapter 7

This chapter presents an electro-mechanical model that was developed by integrating the model proposed in Chapter 6 for evaluating the tensile behavior of corroded rebars into the corrosion-expansion model. The time-dependent electro-mechanical model is on the basis of radius loss, with which both concrete cracking and rebar tensile degradation can be analyzed. The model takes into consideration the effect of cracks on the corrosion process with an assumption of the relationship between current efficiency for Faraday's law and crack width near the rebar. The applicability of the newly developed model was verified by comparing the simulated corrosion degrees, corrosion profiles, concrete crack patterns and residual rebar tensile performance to the test results of the basic experimental study presented in Chapter 2. The simulation agrees well with the test data, confirming that the proposed model is capable of assessing the corrosion-caused damages for a targeted corrosion level, if corrosion distributes consistently along the rebar length. It was also found that, under electric corrosion, when a crack with a width greater than 0.1mm is generated, the adjacent rebar may be highly corroded. In addition the model was applied to the local corrosion cases discussed in Chapter 4. The corrosion distributions along the rebar and the corresponding cracking behavior were analyzed. The analysis indicates that the corrosion process implemented in the test by using a short salt-water pool may be affected by other factors except the electric field applied.

Chapter 8

This chapter includes the conclusions derived from the study and recommendations for future research.

This study is contributable to a better understanding of the factors affecting the development of corrosion-induced cracks. The behavior of cracking and cover spalling resulting from local corrosion is clarified. On the other hand, the relation between corrosion profile and rebar tensile performance is elucidated. A numerical method based on RBSM is proposed to accurately estimate the residual tensile capacity of corroded rebars. It is integrated into the electro-mechanical model, which also offers good prediction of the electric corrosion process of rebars and associated crack development in the case of continuous corrosion along the rebar length. Although the newly developed model needs to be improved by accounting for other factors of corrosion process, such as transport of chloride ions, oxygen and water as well as consumption of oxygen, it makes a solid step towards a reliable means of assessing corrosion-caused damages of RC structures.