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Author(s)	Nariman Fouad Anwar Atwa
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氏　　　名	Nariman Fouad Anwar Atwa
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学位論文題目	Corrosion monitoring of steel reinforcements of reinforced concrete structures with long-gauge carbon fiber sensors (ロングゲージカーボンセンサを用いたコンクリート構造物の鉄筋腐食モニタリングに関する研究)
審査会	委員長　呉　智深　　委員　原田　隆郎　委員　沼尾　達弥 委員　　車谷　麻緒

論 文 内 容 の 要 旨

Steel corrosion is the irreversible deterioration and destruction of the steel material and its vital properties due to the electrochemical or chemical reaction of its surface to environmental factors such as chloride ions, acids, moisture and oxygen. The corrosion distribution of the corroded bars varied significantly in both the transversal ross-section and longitudinal surface. Corrosion causes expansion of reinforcing steel owing to the corrosion products (rust) which exerts pressure on the surrounding concrete and cracks start occurring on the surfaces of concrete as well as a reduction on the effective diameter of the steel bar which leads to a reduction of the structural stiffness. Cracking results in delamination and subsequent spalling of concrete cover. This phenomenon keeps on increasing with the higher levels of corrosion.
The study of these cracks is very important to assess durability and service life of reinforced concrete (RC) structures. Many previous research show the behavior of RC beams when the main longitudinal reinforcement and transverse (shear) reinforcement, such as stirrup are corroded simultaneously. There is a considerable loss in ultimate strength and maximum deflection when both the reinforcement is simultaneously corroded

Corrosion monitoring of steel reinforcements is a tough task. At present, electrochemical methods are the main means of assessing the corrosion state of steel reinforcements without removing the concrete cover. In general, the corrosion of steel reinforcement is detected in terms of three measurement parameters, namely (i) half-cell potential (ii) concrete resistivity, and (iii) corrosion current density. These methods may give some information about corrosion localization however it cannot provide quantitative evaluation of the corrosion especially for large-scale concrete structures.

Many studies on monitoring corrosion based on sensing techniques are emerging in recent years, by measuring the wavelength shift of the Fiber Bragg Grating (FBG) sensors with the rust-induced increase diameter of steel reinforcement due to corrosion deposits. The limitations of using the FBG methods in corrosion monitoring are; (i) can only conduct localized inspection of steel corrosion, (ii) it has a direct contact with the surface of the steel rebar, which leads to the fact that fiber optic is vulnerable when corrosion rust accumulates,(iii) although FBG sensors itself are non-corrosive material but the corrosion rust can affect the fixation between steel and the sensor so a suitable bonded material with covering need to be chosen. (iv) a temperature compensation sensor also needed for accurate measurements.

In earlier studies in our lab, it was realized that, carbon tows are capable of being used as active elements by influence of their piezoresistivity and conductivity as well as long-term durability. It was found that, the strain response and electrical properties of the long-gauge carbon fiber reinforced polymers (CFRP) strip sensor exhibited a good linear relationship with the applied strain. In addition, the proposed sensors maintain a stable linearity through the long-term cyclic performance. The change of resistance of CFRP sensors are affected by the change in temperature because of the negative temperature resistivity of micro-fibers. The effect of fiber arrangement on the effective temperature compensation method of the smart type carbon fiber line (CFL) sensors was recently studied. Moreover, in their study a posttensioning method was developed to straighten the skewness fibers and control the initial creep of CFL sensor to enhance the linearity and repeatability of sensor from low to highlevel strains.

The use of CFL sensors in the field of corrosion monitoring of steel reinforcements in RC structures offers the following advantages, (1) The CFL sensor is a long gauge sensor, which is suitable for macrostrain measurements of large-scale structures; this is in contrast to shortgauge sensors, which are too local to detect the corrosion damages. (2) Carbon fiber is a durable and rustproof material that is unaffected by the corrosion of the main steel reinforcement. (3) Carbon fiber is a high-strength material that can function for a long time without deterioration.

The main objective of this study is to evaluate and localize the presence of corrosion of main steel reinforcement of concrete structures through monitoring the strain changes due to the reduction of the effective diameter of the steel bars and conduct a relation that reflects the damage severity.

In order to understand the fundamentals of the proposed system, this thesis consisted of seven chapters

In chapter 1: At first, a background about the corrosion process and deterioration was addressed.The aims and scopes were also included in this chapter which are: (1) studding the effect of different erosion environments on the sensitivity performance of CFL sensors, (2) produce a suitable packaging system with self-compensation for sensor protection for long-term monitoring, (4) identify different corrosion locations and monitor the progress of corrosion in terms of the decrease in the cross-sectional area of steel rebar, (5) applying the proposed packaging system for on-line monitoring of corrosion damages inside flexural reinforced concrete structures.

In chapter 2: a review on the non-distractive testing (NDT) methods for corrosion monitoring, classifications and the advantages and disadvantages of each methods were presented.

In addition, the researches focused on corrosion monitoring of steel rebar using strain measurements using FBG sensors and the limitations faced these methods were discussed. Finally, the development of strain sensing technique based on carbon fiber sensors was presented.

In Chapter 3: this chapter introduces development of packaged system of long-gage CFL sensors, which deal with temperature compensation, environmental effects of erosion, and easy to construct distributed monitoring system. The effect of different corrosion solutions on the sensitivity characteristics of CFL sensors with and without packaging system by impressed the sensors in the corrosion solution for 12 weeks and tested them every 2 weeks.

It can be concluded that, the corrosion solution does not affect the behavior of the CFL sensors even without packaging, the average errors of the measured signals changed from 7 to 10 micro-strains within 12 weeks. As the CFL sensor is an electrical sensor, when some fibers came into direct contact with the steel bar connected with the electrical current, the fibers transferring the electrical current through the sensor caused instability in the measuring circuit however the proposed packaging system can effectively protect CFL sensors against electric effects.

Chapter 4: This chapter proposes an approach for early corrosion monitoring of steel reinforcements by using strain measurements of long-gauge packaged carbon fiber line (PCFL) sensors. An accelerated corrosion method utilizing a salt solution and constant current was used to achieve the required corrosion levels. Thereafter, the effect of the change in temperature during the corrosion process on the signals of the proposed packaged sensors was studied. A PCFL with temperature compensation and a protective cover was installed on a steel bar and tested under accelerated corrosion and a constant tensile load. Monitored measurements of the PCFL sensors during the corrosion progress were compared with a laboratory-scale model and measurements of packaged fiber Bragg grating (PFBG) sensors.

The results confirmed that, (1) through the use of the working and compensation sensors as one package, the effects of temperatures variation on the sensors itself can be effectively eliminated, in addition by using two different specimens of steel bars—one stressed and the other in a stress-free state were corroded at the same time the effects of thermal deformations of the steel bar can be neglected. (2) Comparison of the weight loss ratios calculated from the PCFL sensors, PFBG sensors, and Faraday’s law revealed that the errors of the estimated weight loss ratios for both the PCFL and the PFBG sensors relative to the corresponding theoretical values vary in the range of ±0.8%, which can be acceptable for real applications.

Finally, the proposed (PCFL) sensors were verified of its ability in evaluating and localizing different corrosion severities of steel by mounting a series of sensors on the surface of the steel bar under axial tensile loading. It is found experimentally that the distributed strain monitored with PCFL sensors achieved high-confidence signals in identifying and localizing corrosion damages of reinforcement steel bars.

In chapter 5: The evolution of the structural behavior of RC beams subjected to reinforcement corrosion based on strain distribution measurements is studied numerically using a nonlinear finite element analysis. The main objective of the study presented in this chapter was to create and execute a detailed three dimensional (3D) finite element (FE) model evaluating and monitoring steel reinforcement corrosion inside reinforced concrete (RC) structures under sustained loads using distributed long- gauge strain measurements. The available finite element software package, ANSYS program (ANSYS, Release 15) was used for this purpose. The effect of corrosion is modeled by reducing the cross sectional area of one of two tensile bars in a certain location at the maximum moment region of a simply supported RC beams. The stage studied here in this chapter, when the corrosion occurs inside concrete beams under Low level of sustained load before cracks initiation. Three different approaches, continuous-strain ratio (CSR), distributed-strain ratio (DSR), and section fiber model (SFM), were proposed to evaluate corrosion levels using strain long gauge measurements. The different groups of distributed strain measurements sensors on the tension and compression fibers of concrete surface and steel reinforcements of RC beam were used to determine different corrosion levels using the three different approaches in the cases under consideration.

In chapter 6: In this chapter, the monitoring of corrosion damages of flexural reinforced concrete members under service loads before and after cracks initiation using distributed longgauge carbon fiber sensors were studied. The different groups of distributed PCFL sensors installed on the tension and compression fibers of concrete surface and steel reinforcements of RC beam. Based on corrosion monitoring experimental results of the corrosion monitoring test under sustained load, the following main points can be addressed; (1) The proposed packaging system can effectively protect the CFL sensors inside the concrete beam without affecting their stability.

(2)The presence of corrosion didn't affect the fixation between the PCFL sensors and steel bar with the use of the epoxy resin as a pasting material.(3) In case of corrosion occurrence inside concrete before cracks occurrence, the first approach CSR will be suitable to evaluate the corrosion degrees because the changes on steel strains in a certain location will be mainly related to the decrease in bar diameter.(4) In case of early corrosion levels after cracks initiation which is often found in nature, the second method DSR will be most suitable than FSM because at this stage, there is no significant variations of the compression strains affecting the reliability of the results.

(5) In case of high levels of corrosion with cracks propagations along the beam, the most suitable approach to evaluate the area loss of steel is by using FSM because in that case the probability of damages everywhere along the beam in addition, the strains of the compression zones will changes obviously with the progress of corrosion.(6) The calculated corrosion levels based on DSR have convergent values with the actual As calculated from FSM and weight loss of the external model.

Finally, the concluding remarks of this work are summarized in ***chapter 7*** some research significance and future recommendations are given.

論文審査の結果の要旨

構造システムの維持管理や防災・リスク管理の高度化を実現させるため、構造物の実時間的な健全性の監視を目指した「構造ヘルスモニタリング（Structural Health Monitoring, SHMと略す）」に関する関心が高まっており、各種インテリジェントマテリアルを用いたセンシング技術や情報科学を活用したSHMシステムの開発が国内外で盛んに行われるようになっている。本研究は，今まで研究されてきた炭素繊維（カーボンファイバ）のセンシング効果と問題点を踏まえて，高度化された線型カーボンファイバセンサの開発を行ったものであり，以下に示す７章から構成される.

第１章では，SHMに関する研究現状と問題点を概観し，本論文の目的と工学的な意義ならびにその概要について述べている.

第２章では，非破壊検査やSHMシステムの計測技術に関する最新動向を取り纏め，現状で示されている重要課題を明確にした.

第３章では，具体的には，カーボンファイバセンサのロングゲージパッケージ手法を検討し，様々な腐食環境の影響に関するシミュレーションを行った結果，カーボンファイバセンサの高度化手法を提案した.

第４章では，ロングゲージカーボンファイバセンサの表面接着による鉄筋腐食を定量的にモニタリングする手法を開発し、鉄筋腐食の加速試験などにより、その有効性を検証した。

第５章では，鉄筋コンクリート構造部材における鉄筋腐食をモニタリングするためのロングゲージカーボンファイバセンサの配置手法を開発した。そして、センサのひずみ変化を分布的に測定し，腐食前の過去のある時点の測定値に対する各センサ領域のひずみ変化比，無損傷の構造領域のセンサひずみに対する各センサ領域のひずみ比，ファイバーモデルを用いた逆解析による鉄筋腐食箇所と腐食量の同定手法をそれぞれ提案した。実験的な検討により、各種同定手法の優位性と適用範囲を究明した。

第６章では，非線形有限要素法シミュレーションにより提案された各種腐食損傷同定方法の有意性と汎用性を確認した.

第７章では，本研究で得られた結果を要約し，今後の発展の方向について述べた.

本研究では、鉄筋腐食をモニタリングするためのカーボンファイバセンサのロングゲージパッケージ手法と性能向上手法を開発するとともに、鉄筋コンクリート構造物における鉄筋腐食を長期かつ分布的にモニタリングするための損傷同定法を提案しており，新規性，独創性ともに富んでいる．また，鉄筋コンクリート構造部材実験を実施して，開発手法の優位性と実用性が検討される一方、非線形有限要素解析による汎用性も確認されている．本研究は都市インフラ構造物の本格的なSHMの構築に大きく貢献するものであり、今後の発展により実用化されていくと考えられる．本研究は構造システムの維持管理や防災・リスク管理の高度化に大きく貢献するものであり，今後の発展により実用化されていくと考えられる．また，本研究に関して，学術論文2編および国際会議論文1編の公表が行われ，あるいは公表が確定している.

以上を総合して，当審査会は，本論文を茨城大学大学院理工学研究科博士後期課程における博士（学術）の学位審査基準を充たし，合格であると判定する.