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<th>Enhancing the electrical sensing properties of long gauge carbon fiber sensors for health monitoring of structures</th>
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Structural Health Monitoring (SHM) aims to give, a full life cycle behavior of a structure, a diagnosis of the state of the constituent materials, of the different parts, and of the full assembly of these parts constituting the whole structure”. Or, alternatively, SHM is defined as “the use of in-situ, nondestructive sensing and analysis of structural characteristics, including the structural response, for detecting changes that may indicate damage or degradation”. In fact, SHM can improve understanding, characterization, and prediction of effects associated with damage that threatens the structural safety. The SHM process involves the observation of a system over time using continuous static and periodically sampled dynamic measurements from an array of sensors, the extraction of damage-sensitive features from these measurements, and the statistical analysis of these features to determine the current state of system health. Strain is one of the most sensitive parameter to referrer some structural damage information.

Carbon fiber reinforced plastics CFRPs exhibit excellent mechanical properties such as high strength, low density, long-term durability and high resistance to chemical corrosion, as a result the application of CFRPs as a structural material become increasingly attractive in civil engineering. Moreover, Carbon fibers are electrically conductive in which its electrical resistance changes with the changing in the applied stresses gaining it some distinctive characteristics in strain sensing.

In earlier studies, carbon fiber long-gauge CFRP sensors were developed to measure the strain changes in structures. The CF strip sensor showed a good stability in measuring strains. The continuous CF tow consists of numerous continuous micro carbon fibers. Each fiber can be considered as a sensing cell, such that the CF sensor’s output signal is the integrated response from all of the sensing cells. Under ideal conditions, a CF tow can be considered a parallel circuit that is composed of large numbers of micro-CFs. However, under actual conditions, the microfibers are not completely straightened or arranged in parallel due to the fabricating defects such as misalignment and breakage of carbon fibers. Because of these defects, the change of resistance (ΔR) of a CF sensor is influenced by the contribution between fibers in the transverse direction which affecting on the linearity of CF output signals.

The main objectives of this research is to develop a smart CF sensor that has a small cross sectional area in order to push forward the sensor’s potential applicability and overcomes the problem of skewed fibers through a pre-tensioning approach to enhance the electrical sensing properties of the sensors. Moreover, this research discusses the static and dynamic measuring errors in low and high strain levels and the methods to increase the confidence of the measuring data from the sensors. Lastly the ability of the developed sensor in providing accurate macro strain measurements to detect the structural damages was also discussed. This thesis consists of seven chapters, here the brief description about the content of each one:

In chapter 1: Research introduction and the objectives of this research are addressed. The aims of this research are, (1) produce a slim high-strength sensor (CFL) basis of self-strain-sensing with a diameter less than 1.4 mm using HS carbon tow of 6 mm width, (2) Studying the effect of micro fibers arrangement on the effective error compensation system, (3) The feasibility of enhancing the stability and linearity of carbon sensors from low to high-level strains through post-tensioning approach, (4) Stabilization of the electrical sensing properties in static and dynamic measurements of carbon fiber sensors via double-tensioning technique, (5) Developing
In chapter 2: this chapter addressed a perspective review of the (SHM) process utilizing strain sensing techniques. In addition a brief discussion about point and long gauge sensors was also presented. Furthermore, the CFRP-based sensing techniques are introduced. Especially the sensor performance and low sensitivity of previous developed continuous CFRP-based strain measurement are discussed. A hybrid-CFRP (HCFRP), which consists of different types of carbon fibers, is introduced.

In chapter 3: a new approach of self-sensing strain measurements based on smart CFL sensors was firstly illustrated, a theoretical background about the principle behind sensing operation of CFL sensor has been clarified afterwards. The fiber distribution in this transverse connection introduces variability, the initial electrical resistance and the gauge factor of CFL sensors will not exactly the same, therefore the effect of fiber arrangements on the change of the electrical resistance of the sensor in low and high strain levels as well as the long term monitoring were studied. A series of experiments were implemented to study the effective error compensation for long term monitoring based on CFL sensors. It has been demonstrated that, the fiber arrangement affects the successful compensation method. By using two convergent CFL sensors signal measurements on long term monitoring showed good stability, and the ΔR/R error was reduced from 0.022% to 0.007%, a reduction percentage of 68.2%. On the other hand, in case of connect two sensors with divergent gauge factors, the ΔR/R error was reduced by a small value: from 0.022% to 0.015%, a reduction percentage of 31.8%. The CFL sensor signal demonstrates good linearity with the applied strain under low strain levels; however, some curvature appeared and increased under higher strain levels. The signal fluctuation errors increased with increased applied strain levels up to 3000 microstrains, and then the signal fluctuation error appears to remain constant.

In chapter 4: The main objective is to enhance the linearity and the performance of the CFL sensors for strain measurements via double-tensioning the fibers during and after completely hardening of the epoxy resin to straightening the fibers and removing the initial resin creep. Polymer matrix resins in CF sensors are viscoelastic and exhibit to loss of stress under high strain which called relaxation, this factor affecting on the linearity and the confidence of the sensor in measuring strains. The elimination of creep deformation in the resin would allow stress to be uniformly transferred through the resin. The resin in the CFL sensor continues to undergo creep deformation when it is subjected to a sustained load, allowing the possibility that the fibers could interact in the resin, therefore, three different tension methods were applied to the sensor during the fabrication process which are during resin hardening, after completely hardening of the resin, and a double tension which is a combination between during and after hardening of the resin with different tensile stresses (30%, 60%, 80%) of the ultimate strength (fu) of composite. The following conclusion can be drawn out, (1) by tensioning the sensor during hardening, the fibers stretch during the tensile stress but after releasing the stress the fibers lose some of its stretching resulting in some curvature remains in the measured signals especially in the first stages of the tensioning process, (2) The post-tensioned CFL sensor exhibits a good cyclic ability and stable gauge factor up to 6000 microstrains, and can reduce the fluctuation errors in the ΔR/R from ±0.031% to ±0.007%. Beyond 6000 microstrains, the sensor exhibits poor linearity relative to the reference strain. (3) when the sensor was double tensioned by 60% fu during and after hardening, the fibers were sufficiently straighten with removing the initial creep, as a result the change of resistance has a linear relationship with the applied strain from the beginning to the micro-fractures stag, (4) both sensors Post60 and D60P60 have a great effect on the linearity than Dur60; the R-square value was improved from 0.862 for Norm to 0.989 and 0.998 for Post60 and D60P60 respectively. (5) the accuracy of the double tensioned CFL sensors in low strain measurements was verified by an impact dynamic test. The sensor showed a stable signal with an accurate strain measurements values regarding to the reference strain and the fluctuation errors vary in between of ±3.5 με. (6) the distribution of the measured signal’s fluctuation distribution through the 10 loading-unloading cycles of gauge lengths from 500 to 100 mm were found to be from ±10 to ±12 micro strains respectively, although for 50 mm was found to be ±17 micro strains.
In chapter 5: In this chapter, a damage identification method for reinforcement concrete (RC) structures was developed based on the separated static strain response of distributed long-gauge sensors mounted on concrete surface under different moving loads with different speeds. Two different approaches were proposed in this chapter to remove the dynamic effects from the measured dynamic strain response of distributed sensors. The first approach is to use Wavelet Transform (WT) to remove the stochastic noise influences from the measured dynamic signals. The WT is a recently developed signal decomposing technique that it has been recognized as suitable to shrink normally distributed noise. Using the “mother” function of the WT, the original continuous signal can be decomposed into two series of “baby” wavelet coefficients. The second approach is Moving Average (MA) method. The MA is a calculation to analyze data points by creating series of averages of different subsets of the full data set which commonly used with time series data to smooth out short-term fluctuations and highlight longer-term trends or cycles. Based on the numerical results it was found the follows: (1) The dynamic strains distribution along the simulated beam were symmetrically about the center line of the beam in the intact case but after damage only the sensor covers the damage location increased at the time in which when the acting moving load was on the sensor location. (2) By using the two proposed approaches MA and WT to separate the static signals, the dynamic vibrations effects can be removed effectively from the total dynamic response before and after damage and the resulted signals can be considered mainly due to the effect of the static weights of the moving loads. (3) The damage location can be found obviously using WT, MA and NU methods calculated using the numerical simulation of ANSYS program by applying the same loads at each the same location. (4) The errors in β values found on the other locations without damaging decreased through the use of WT approach than the other approach MA. (5) The damage index β in the damage location determined using WT has a good agreement with the corresponding calculated using actual static (NU) strains at the same location.

In chapter 6: In this chapter, A damage identification method was developed based on the separating the static strain distributions from the dynamic strain response of distributed sensors to different moving loads with different speeds. The proposed method was validated using the long-gauge sensors damage identification of an existed bridge in Japan under normal traffic operations. Firstly the response of the CFL sensors to the dynamic vibration was compared with different long and short gauge sensors. The ability of the sensors to capture the natural frequencies and measuring the applying strain accurately was verified. Finally the measured response due to more than 35 different moving loads was used to assess the ability of the WT static strain ratio damage identification method to localizing the damage of the monitored structure. The proposed method verified that it can be used for instant damage inspection of the existed structures. Main conclusions can be drawn as follows: (1) The ratios between WT static strain values of a target location and the reference of different moving loads with different speeds lie on the same trend line for one time monitoring data. (2) The WT static strains of distributed sensors under daily traffic loads can be used to identify damages of bridge effectively by selecting a suitable reference sensor. (3) Static analysis can give a relative good simulation for moving loading under speed 40km/h. (4) Proposed substructure method on the basis of interaction between vehicle and bridge can give a good simulation in dynamic response of structure under moving load. It is applicable for actual survey of the old under-use bridge. (5) The distributed long-gage FBG sensing system has good accuracy in old bridge monitoring.

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

構造ヘルスモニタリング（Structural Health Monitoring, SHM と略す）とは、構造物のフルライフサイクル健全性を検出し、あるいはその構造物の構成材料、各部材および全体の状況を評価したりとする技術を目指す。一方、SHMは現場でのモニター、また非破壊検査技術など構造システムのセンシング手法を用いて、構造物の物理特性（挙動）を分析し、損傷劣化や構造変化の検出および診断評価行為を定義してよい。そこで、SHMにおいて、構造物のひずみ変化や振動応答による損傷同定が可能となるスマート材料を用いたセンシング手法は注目されている。とりわけ、優れた力学的特性と導電性の両方を同時に保有するカーボンファイバー（炭素繊維）が大いに期待されている。カーボンファイバーは軽量・高強度・化学性安定など優れた特性を持ち、ひずみの発生に伴い電気抵抗変化率が変化する特性も併せ持つ。本研究は、今まで研究されてきたカーボンファイバーのセンシング手法と問題点を踏まえて、高度化されたカーボンファイバー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、本研究の背景や目的、概要について取り纏められている。
第2章では、カーボンファイバーセンサーを用いたひずみ計測技術に関する検討を行い、カーボンファイバーセンサーに関する開発の意義及び問題点を述べた。
第3章では、カーボンファイバーセンサーに対するひずみ測定やノイズの影響を検討し、最適なセンサー形状を提案するとともに、従来のロングゲージパッケージ手法の改良を行い、ロングゲージカーボンファイバーを構築した。
第4章では、カーボンファイバーの樹脂含浸による初期クリープの2段階制御技術を提案し、センサーの高度化手法を開発した。また、各種要因に対する実験的検証を行い、センサーの最適化手法の提案に成功した。
第5章では、橋梁などの交通荷重による応答を利用し、開発されたロングゲージカーボンファイバーセンサーによる構造物の変形型損傷同定手法を開発した。また、構造モデルの静的と動的計測実験や実構造物の計測実験を行い、構造物のひび割れに関する損傷同定手法の有効性を検証できた。
第6章では、ロングゲージカーボンファイバーセンサーによる損傷同定手法に関する各種構造物の適用性を検証し、カーボンファイバーセンサーの分布モニタリングの標準化手法を纏めた。
第7章では、以上の研究により得られた成果を示し、本研究での開発技術に関する将来の展望をも含めて取り纏めた。

本研究の新規性の一つは、高精度化と高範囲化計測に難ある従来のカーボンファイバーの樹脂含浸による初期クリーブの2段階制御技術を提案することによって、光ファイバーセンサー並みのセンシング性能を有するカーボンファイバーの開発に成功したことにある。また、高度化されたカーボンファイバーの形状、引張量、引張方式等に関する検討を行い、その有効性を検証した。そして、カーボンファイバーを使用した分布型ロングゲージセンシングシステムを構築し、静的・動的センシングの適用性を検証した上で、損傷同定手法を開発した。以上により、開発されたカーボンファイバーの有効性や優位性をよく検証しており、新規・独創性と有効・実用性とともに富んでいる。本研究は高性能化されたカーボンファイバーの開発検討により、より高度な構造ヘルスモニタリング手法の創出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のため、災害・リスク管理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足し、合格であると判定する。