Smart Structures and Systems, Vol. 3, No. 2 (2007) 133-146
DOI: http://dx.doi.org/10.12989/sss.2007.3.2.133

Broad and stage-based sensing function of HCFRP sensors

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(Received September 22, 2004, Accepted June 22 2006)

Abstract. This paper addresses a new type of broad and stage-based hybrid carbon fiber reinforced polymer (HCFRP) sensor that is suitable for the sensing of infrastructures. The HCFRP sensors, a type of composite sensor, are fabricated with three types of carbon tows of different strength and moduli. For all of the specimens, the active materials are carbon tows by virtue of their electrical conductivity and piezoresistivity. The measurement principles are based on the micro- and macro-fractures of different types of carbon tows. A series of experiments are carried out to investigate the sensing performances of the HCFRP sensors. The main variables include the stack order and volume fractions of different types of carbon tows. It is shown that the change in electrical resistance is in direct proportion to the strain/load in low strain ranges. However, the fractional change in electrical resistance ($\Delta R/R_0$) is smaller than 2% prior to the macro-fractures of carbon tows. In order to improve the resistance changes, measures are taken that can enhance the values of $\Delta R/R_0$ by more than 2 times during low strain ranges. In high strain ranges, the electrical resistance changes markedly with strain/load in a step-wise manner due to the gradual ruptures of different types of carbon tows at different strain amplitudes. The values of $\Delta R/R_0$ due to the fracture of high modulus carbon tows are larger than 36%. Thus, it is demonstrated that the HCFRP sensors have a broad and stage-based sensing capability.

Keywords: structural health monitoring; HCFRP sensors; broad and stage-based sensing.

1. Introduction

With rapid development of new materials, structural sensing and control, and data acquisition and processing technologies, a new generation of structural systems is expected to be generated. This new phase will be characterized by self-sensing, diagnosis, and curing functions. However, maintenance, inspection, and health monitoring for civil engineering structures are difficult and challenging, mainly due to the following reasons: 1) The infrastructures are inherently spatial and distributed, and the areas to be inspected are typically large. 2) The inspection and monitoring should be performed onsite. Moreover, the sites to be inspected are inconveniently located, hidden, dangerous or even impossible to access in some cases.

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Consequently, sensors and sensing systems of large infrastructures should have the following characteristics:

(1) The sensors are selected and distributed for measurement of key parameters that influence the performance and health of the structural system.

(2) In addition to point sensing, global structural health monitoring and integrity assessment with long-gauge or broad-based sensors are necessary, particularly in the cases of a major earthquake, a hurricane or other unpredictable disasters. The safety of the structure can be assessed in this manner with potentially large time & cost savings.

(3) Due to the fact that practical infrastructures are structurally complicated and consist of different materials, sub-structures, and/or joints, the failure of such components (such structures) can generally be divided into several stages, i.e., concrete cracking, yielding of steel reinforcements, rupture of PC tendons, impending of final failure, etc. Consequently, a stage-based sensing for practical infrastructures is necessary. The stage-based sensing can reflect the characteristics of different damage stages and provide necessary warnings of impending final failure.

(4) Most sensors should be embedded into the structures so as to provide self-health monitoring and diagnosis functions during the whole life cycle. For this reason, sensing systems in infrastructures also require long-term sensing abilities including stability, durability, serviceability, reliability, and calibration over the whole structure life cycle, i.e., generally more than 50 years.

(5) The health monitoring of key infrastructures also requires prompt response. In addition, the sensing system should be cost effective and easily installed.

Due to these reasons, traditional non-destructive techniques such as acoustic emission, ultrasonic detection, X-ray radiography, infrared thermograph, and eddy current are not appropriate for the structural health monitoring of infrastructures.

It is therefore necessary to develop new types of sensors and sensing systems for monitoring structural health and assessing the global integrity of key infrastructures at low cost. The sensors and sensing systems should be characterized by broad and stage-based sensing function, long-term durability, reliability, and simplicity in technique and installation.

It has been observed that carbon fiber-reinforced polymer (CFRP) composites intrinsically possess potential damage detection and health monitoring functions by virtue of their electrical conductivity and piezoresistivity. Generally, under tension or compression, the resistivity of carbon fibers will increase or decrease in proportion to the applied stress or strain prior to the rupture of carbon fibers; this phenomenon is known as the piezoresistivity of carbon fibers, and it affords CFRP composite with a strain/stress sensing capability. Both d.c. and a.c. electrical resistance measurements (Abry and Choi 2001, Ceysson and Salvia 1996, Kupke and Schutle 2001, Muto and Araki 2001) may be used to measure the strain and monitor the health of CFRP structures in real time. Kupke, *et al.* (2001), who investigated the non-destructive testing of FRP by d.c. and a.c. electrical methods, pointed out that electrical resistance measurement is a promising method in structural health monitoring. Compared with other damage detection methods, this approach, which relies on the piezoresistivity and electrical conductivity of carbon fibers, has major advantages of simplicity, low cost, and long-term durability.

CFRP is suitable for use as a sensing material in civil infrastructures owing to the good electrical properties of carbon fibers as well as their excellent mechanical properties, low cost, and high resistance to chemical corrosion. Nevertheless, CFRP that is comprised of only one type of carbon fiber offers electrical and mechanical behaviors that are not sufficiently stable due to the inherent crispness of CFRP composites (Wu and Yang 2004a). This characteristic greatly impairs the effectiveness of

CFRP composites, either as sensing or structural materials. To overcome this weakness, the authors (Wu and Yang, 2003, 2004b, 2005, 2006) have carried out a series of experimental studies on the self-sensing and mechanical performances of HCFRP (hybrid carbon fiber reinforced polymer) composites and HCFRP-strengthened concrete structures. The active materials are carbon fiber sheets that act both as structural and sensing materials. The results reveal that the electrical behaviors of the HCFRP composites and as-strengthened structures are correlated to their mechanical behaviors, thus demonstrating self-health monitoring functions. This sensing capacity is inherently characterized by broad and distributed sensing capability since the whole area of the HCFRP sheet can function as a sensing material. Moreover, the inherent crispness of CFRP composites is effectively overcome and a stage-based sensing function is obtained through hybridization.

The aim of the present work is to address a new class of HCFRP sensor composed of several types of carbon tows, such as high strength (HS), high modulus (HM), and middle modulus (MM) carbon tows, for civil engineering applications. Some measures are taken to improve the change in electrical resistance in low strain ranges and enlarge the strain sensing range. The results indicate that the electrical resistance of HCFRP sensors varies with strain in a step-wise manner due to gradual fractures of different types of carbon tows at different strain amplitudes. Thus, stage and broad-based sensing feasibility for real infrastructures is demonstrated. It is also revealed that the proposed measures can markedly improve the change in electrical resistance by more than 2 times, especially in low strain ranges. It is also demonstrated that the stack order employed in the fabrication of the HCFRP sensors influences the sensing performance of the sensors.

2. Experimental details

2.1. Fabrication of HCFRP sensors

All the specimens were fabricated with three types of pitch-based carbon tows: C1 used as HS carbon tows, C5 as MM carbon tows, and C7 as HM carbon tows. The mechanical properties of the carbon tows are listed in Table 1 according to the manufacturers' specifications. FR-E3P standard epoxy resins and hardeners with a mix ratio by weight of 2:1 were used to impregnate the carbon tows. The tensile strength and Young's modulus of the used epoxy resins are 50 MPa and 245 MPa, respectively. In general, two types of specimens were fabricated and tested. For the first type, the HCFRP sensors were tensioned directly under a hydraulic universal material testing machine (UH-500KNI) under a load control. For the second type, the HCFRP sensors were adhered to a layer of Dyneema fiber sheet. The impregnated Dyneema layer has a dimension of 700 mm × 40 mm. The HCFRP sensors with a dimension of 200 mm × 1 mm were adhesively bonded to the surface of the Dyneema layer, as schematically shown in Fig. 1. After impregnation, the specimens were cured at room temperature in open air for one day and subsequently at a temperature of 60 °C for approximately two days.

Table 1 Properties of applied carbon tows

Type of tows	Tensile strength (GPa)	Young's modulus (GPa)	Tex	Density (g/cm^3)
C1	4.90	230	800	1.80
C5	2.750	392	728	1.81
C7	3.73	490	900	2.10

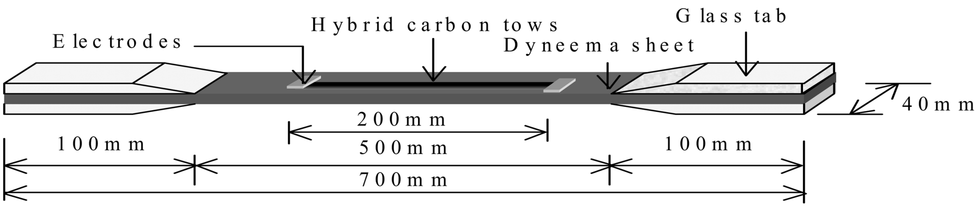

Fig. 1 Schematic dimension of the HCFRP sensor adhere on a layer of Dyneema sheet

2.2. Measures to enhance the change in electrical resistance

Generally, the value of $\Delta R/R_0$ is smaller than 2%, and in some cases the measurement uncertainty due to ambient changes approximates this value. It is thus necessary to improve the values of $\Delta R/R_0$ in order to enhance the sensitivity of the HCFRP sensors in low strain ranges. In the present investigation, two types of measures are taken to improve the increase in electrical resistance. One type isthrough pretension. After impregnation and curing, the HCFRP sensors are pre-tensioned to the point of HM and MM carbon tow micro-fracturing. The other is to bend the HM and MM carbon tows repeatedly until the initiation of micro-fractures. After the bending treatment, the carbon tows are impregnated with epoxy resins and cured. Both measures are termed pretreatment. In the present study, the first measure is termed pretreatment type I (PT-I) while the second is called pretreatment type II (PT-II). For both types of treatments, some micro-fractures are preset in the HM and MM carbon tows. The difference between the two measures is that for PT-I the HM and MM carbon tows are pretreated after impregnation with epoxy resins whereas for PT-II they are pretreated before impregnation. As a result, a small strain/stress can open the micro-fractures preset in the HM and MM carbon tows, causing the resistance of the sensors to increase markedly. Thus, the sensitivity is enhanced greatly in low strain/ stress ranges. As the micro-fractures will close after the strain/stress is removed, the resistance returns to its original state. The enhancement of sensitivity within low strain ranges is due to the reversible opening and closing of micro-fractures preset in the HM and MM carbon tows of the HCFRP sensors.

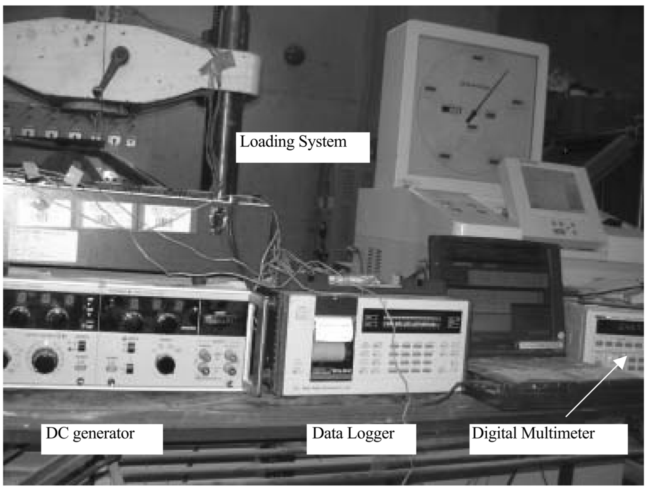

Fig. 2 Schematic illustration of experimental system

2.3. Loading and electrical resistance measuring systems

Fig. 2 schematically shows the loading and electrical resistance measuring systems. Glass tabs shown in figure 1 are attached to both ends of the specimen in order to prevent slipping and damage between the specimens and the testing machine. The specimens were loaded and unloaded at a loading rate of 1 kN/min. The loading speed was lowered when the specimens approached fracturing of the carbon tows. The strain was measured with strain gauges and a Data logger 302. During the experiments, load, strain and direct voltage were recorded simultaneously. The electrical resistance along the stress axis was measured by means of the four-probe method. Four thin copper foils were used as electrical electrodes and silver paste was applied in order to ensure good electrical contact between the specimen surfaces and the copper electrodes, as shown in Fig. 1. Both cut ends of the specimens were filled with conductive resins so as to improve the electrical contact with all conductive fibers in the cross-section of the specimens. A small direct current (DC) of 5 mA was introduced into the specimens from the electrodes, and the voltage was measured using a digital voltmeter with an accuracy of 0.001 mV. According to Ohm's law, the axial resistance can be easily obtained.

3. Results and discussion

3.1. Electrical behavior of C1 and hybrid C1C7 subjected to cyclic tension

The electrical behavior of C1 (HS carbon tows) subjected to cyclic tension is shown in Fig. 3. It is shown that the electrical resistance changes with strain linearly in a low strain range before fracture of the carbon tows. However, the values of $\Delta R/R_0$ are relatively small; the $\Delta R/R_0$ is only about 0.65% at a strain of about 5,800 $\mu\varepsilon$. For the last loading cycle, when the specimen is loaded to a strain of about 10,000 $\mu\varepsilon$, the $\Delta R/R_0$ increases nonlinearly to approximately 2.4%. These results indicate that the electrical behavior of the HS carbon tows is characterized by good recoverability and linearity in the low strain range prior to the rupture of carbon tows. The gradual rupture of carbon tows can result in a

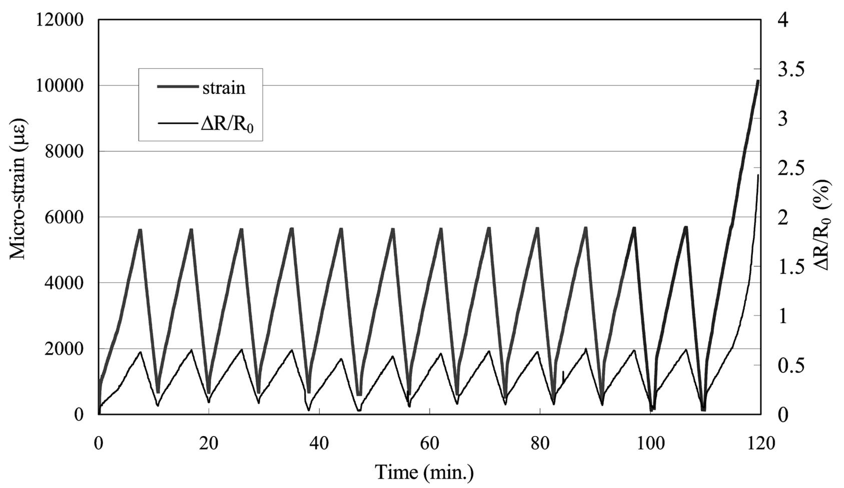

Fig. 3 Cyclic tension result of epoxy resin-impregnated C1 carbon tows

quick but nonlinear increase in electrical resistance.

The cyclic tension of C1 demonstrates the sensing feasibility of the carbon tows. Previous investigations (Wu and Yang 2004a) indicated that for CFRP composites with only one kind of carbon fiber as an active material the increase in electrical resistance was fairly small before the fracture of carbon fibers. The marked increase in electrical resistance generally associated with the crisp rupture of CFRP composites, greatly impairs their serviceability and effectiveness as sensing materials. Therefore, the present study mainly focuses on the hybridization of several types of carbon tows of different strength and moduli. The HCFRP sensors are designed to provide practical concrete structures with a stage-based monitoring function, where sudden resistance jumps at different strain amplitudes correspond with concrete cracking, yielding of steel reinforcements, rupture of PC tendons, etc. In the following sections, the symbol mCpnCq denotes that the specimen consists of carbon tows of Cp and Cq in a ratio of m:n. If m and n are 1, they are generally omitted. For example, the symbol C1C7 denotes that the specimen contains HS (C1) and HM (C7) carbon tows in a ratio of 1:1.

During the experiment, it is observed that after unloading it takes several hours for the specimen to return to its original state. For this reason, the hybrid C1C7 was loaded and unloaded for only one cycle per day. Hence, the hybrid composite has sufficient time to return to its original state. Another reason for employing this loading cycle is to study the influence of loading history on the electrical behavior. The electrical and mechanical behaviors of the hybrid C1C7 with load for the first five loading cycles are shown in Fig. 4. It is revealed that the values of $\Delta R/R_0$ are small in the low strain ranges prior to the rupture of carbon tows, i.e., generally smaller than 2%. There exists a certain dispersion of initial electrical resistance for different loading cycles, mainly due to micro-fractures of carbon tows during the first several loading cycles, change in contact electrical resistance, measurement uncertainty, and ambient changes. For the first five loading cycles, the mechanical behavior is stable and recoverable whereas the electrical behavior is relatively dispersive due to the reasons addressed above as well as a possible change in the interface. The results demonstrate that the electrical behavior of the HCFRP sensors is more sensitive than the mechanical behavior to ambient variations such as change in temperature,

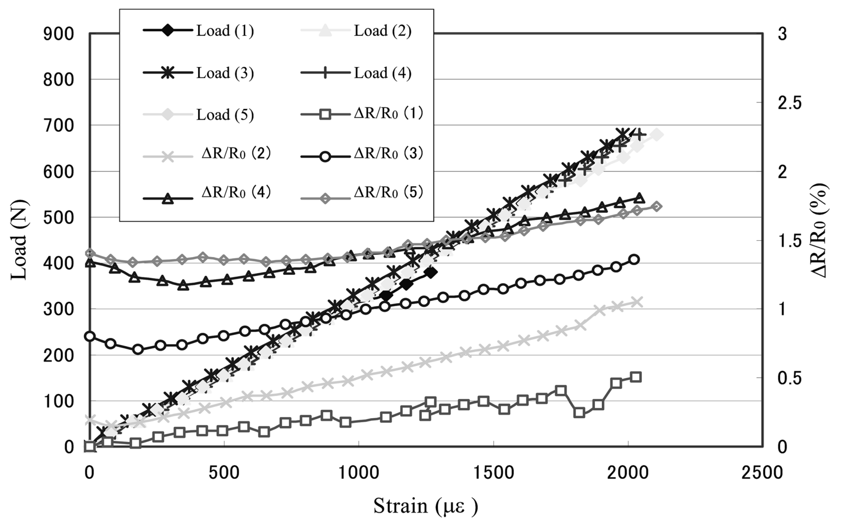

Fig. 4 Cyclic tension result of the C1C7 HCFRP sensor for the first five loading cycles before the micro-ruptures of carbon tows

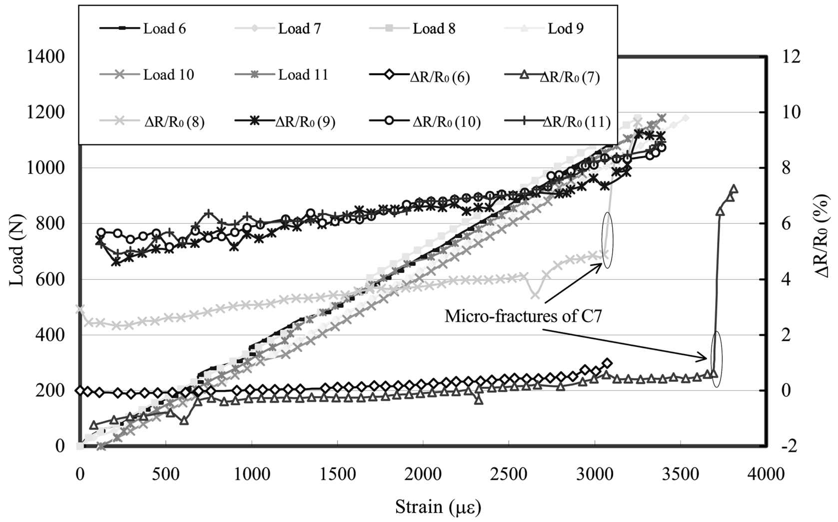

Fig. 5 Cyclic tension result of the C1C7 HCFRP sensor for the 6th-11th loading cycles around the micro-fractures of carbon tows

moisture, and/or contact conditions. Consequently, the HCFRP sensors should be tensioned in advance for several cycles so as to stabilize the interface before experiments.

In order to obtain good agreement between the electrical and mechanical behaviors, the first measure (PT-I) is taken to improve the values of $\Delta R/R_0$, recoverability, and stability of the electrical behavior of hybrid C1C7. After the first five loading cycles in the low strain range, the specimen of hybrid C1C7 was loaded and unloaded immediately subsequent to micro-fracturing of the HM and MM carbon tows for the following 6th-11th loading cycles. The experimental results are shown in Fig. 5. After the micro-fracturing of the HM and MM carbon tows, there are some jumps in the electrical resistance. When unloaded, there are residual increases in the electrical resistance due to micro-fracturing of the HM carbon tows. From Fig. 5, it is revealed that after micro-rupturing of the carbon tows the corresponding values of $\Delta R/R_0$ become much larger. If there were no new fractures in the carbon tows, the electrical behavior was relatively stable. For example, the electrical behaviors of the 8th-11th loading cycles are similar, as shown in Fig. 5.

After the above loading cycles, the specimen of hybrid C1C7 was strained with a weight of 40 kg for 8 hours in order to obtain good sensitivity and stability of the electrical behavior by stabilizing the interface between the carbon tows and matrix. The specimen was then loaded and unloaded continuously for 38 cycles. It is shown that the sensitivity and stability of the electrical behavior improves as the cyclic tension progresses. The 46th-49th loading cycles are taken as examples to illustrate the electrical and mechanical behaviors. Fig. 6 shows the evolution of $\Delta R/R_0$ and load of the 46th-49th loading cycles as a function of micro-strain. The electrical and mechanical behaviors are characterized by good repetition and stability, meaning that the interface between the carbon tows and matrix becomes increasingly stable as the cyclic tension progresses. After micro-fractures appear in the HM and MM carbon tows, the value of $\Delta R/R_0$ (about 8.8%) at a strain of about 1,450 $\mu\varepsilon$ is much larger than that (about 0.5%) at a strain of 2,000 $\mu\varepsilon$ before the macro-fracture of the carbon tows, as shown in Figs 6 and 3, respectively. This indicates that the first measure can enhance the values of $\Delta R/R_0$ by more than 9 times within the low strain range. The residual $\Delta R/R_0$ of approximately 25% (Fig. 6) is due to the permanent fracturing

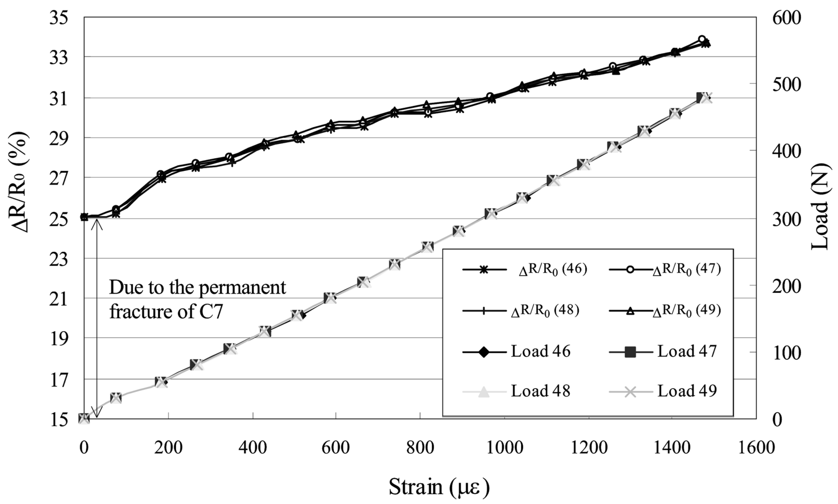

Fig. 6 Cyclic tension result of the C1C7 HCFRP sensor for the 46th-49th loading cycles after the micro-fractures of carbon tows

of HM and MM carbon tows during pretreatment of the 6th-11th loading cycles. Such phenomena imply that the first measure, PT-I, is a promising and effective method to improve the sensitivity and values of $\Delta R/R_0$ within low strain ranges.

3.2. Influence of the volume fraction of C1 (HS carbon tows) on the electrical and mechanical behaviors of HCFRP sensors with three types of carbon tows

The above section mainly focuses on HS carbon tows and HCFRP sensors with two types of carbon tows (HS and HM) within a relatively low strain range. This subsection focuses on the characterization of the electrical and mechanical behaviors of HCFRP sensors consisting of three types of carbon tows (HS, HM, and MM). The main parameter among these HCFRP sensors is the volume fraction of the HS (C1) carbon tows.

The influence of the volume fraction of the HS carbon tows (C1) on the electrical and mechanical behaviors is shown in Fig. 7. The HCFRP sensor of C1C5C7 consisting of C1, C5, and C7 in a ratio of 1:1:1 fails suddenly at a strain of about 4,200 $\mu\varepsilon$, and the final value of $\Delta R/R_0$ (about 50%) is relatively small compared with that of the other specimens. The electrical behavior of hybrid C1C5C7 does not demonstrate a step-wise increasing behavior, because the volume fraction of HS carbon tows (C1) is small. After the rupture of C7 and C5, the HS carbon tows (C1) cannot sustain the load transferred from the fractured MM and HM carbon tows. As a result, the specimen suddenly fails at a strain approximating the ultimate strain of the HM carbon tows, and the electrical resistance changes in a manner corresponding well to that of the mechanical behavior. In the case where the ratio of C1, C5, and C7 is enhanced to 2:1:1, the ultimate strain and value of $\Delta R/R_0$ are enhanced, accordingly, as shown in Fig. 7. However, in a high strain range of 5,000-13,000 $\mu\varepsilon$, the electrical and mechanical behaviors of hybrid 2C1C5C7 are sparse, and only about ten items of data are obtained. The measurement system registers data every 2 seconds, and the time from the rupture of the HM carbon tows to the final rupture is short due to structural instability after gradual fracturing of the HM and MM carbon tows. As a result, the data are sparse for hybrid 2C1C5C7 after the fracturing of HM and MM carbon tows.

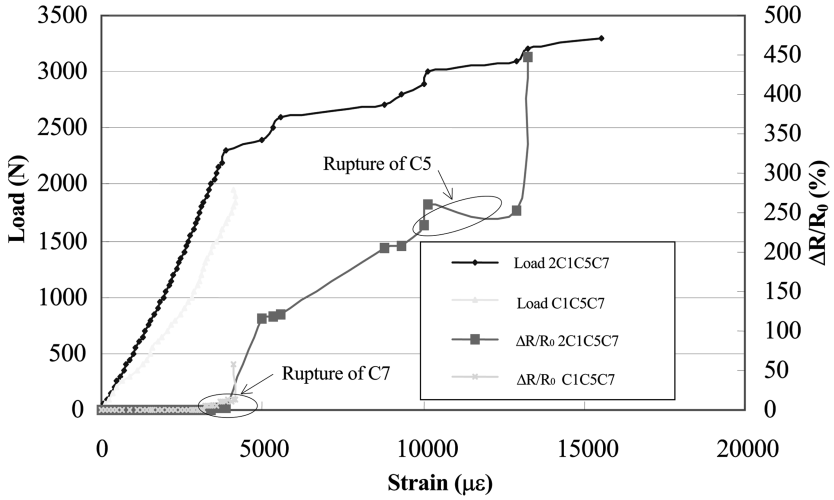

Fig. 7 Volume fractions of HS carbon tows on the electrical and mechanical behaviors of HCFRP sensors with three types of carbon tows

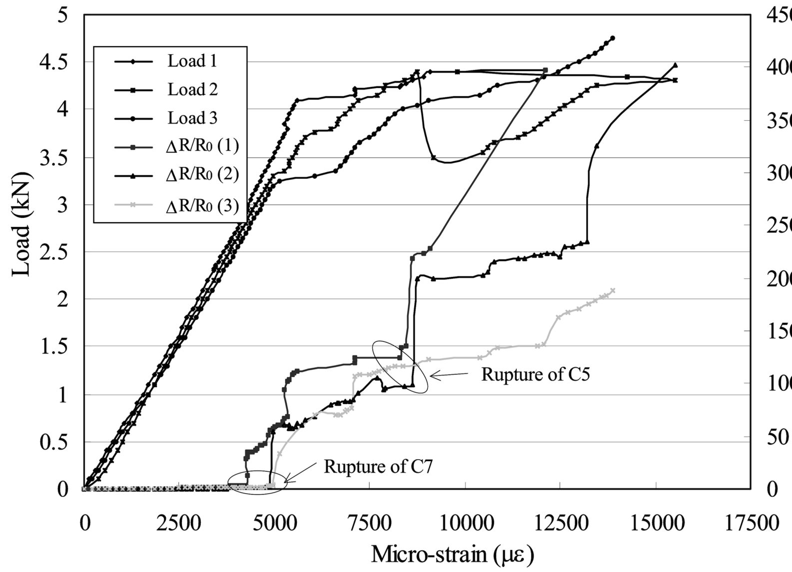

Fig. 8 Experimental results of specimens 1-3 with C1, C5 and C7 in a ratio of 3:1:1

In order to improve the stability of the electrical and mechanical behaviors in the high strain ranges, it is necessary to further improve the volume fraction of the HS carbon tows in the HCFRP sensors. For this reason, three specimens of 3C1C5C7 HCFRP sensors consisting of C1, C5, and C7 in a ratio of 3:1:1 were designed and tested; these are denoted as specimen 1, 2, and 3, respectively. The evolutions of load and $\Delta R/R_0$ with strain are shown in Fig. 8. It is revealed that the electrical and mechanical behaviors of the hybrid 3C1C5C7 are relatively stable. The rupturing of HM and MM carbon tows lead to sudden jumps in the electrical resistance. The jumps due to the fracture of HM and MM carbon tows are larger than 36 and 80%, respectively. After the fracture of one type of carbon tow, the electrical resistance increases with strain with a larger slope. Thus, stage-based sensing for practical structures is realized. However, during the high strain range, the electrical behaviors are slightly dispersive among the three specimens, partly due to the dispersion of mechanical properties, as shown in Fig. 8. In order to obtain stable electrical behavior, some measures should be taken to ensure the uniformity and stability of the mechanical properties of the hybrid composite.

It is revealed that, through enhancing the volume fraction of the HS carbon tows, the method of hybridization of several kinds of carbon tows of different moduli and strength is a simple, economical, and promising method to fabricate smart materials and structures with self-health monitoring and damage detection functions. In addition, hybrid CFRP can be used as a new type of composite sensor to provide practical structures with a broad and stage-based sensing.

3.3. Sensing properties of HCFRP sensors adhered on a layer Dyneema sheet

The HCFRP sensors in the above sections are tested directly, that is, they are used both as sensing and structural materials to sustain the loads. In such cases, the volume fraction of HS carbon tows in the hybrid should exceed a critical value to ensure the structural stability of the hybrid after macro-fracturing of the HM and MM carbon tows. When the sensors are used only as sensing materials, the volume fraction of the HS carbon tows should be lowered to an appropriate level so as to improve their sensitivity and enhance their sensing range. In this subsection, the sensing properties of HCFRP sensors bonded to an epoxy resin impregnated Dyneema sheet are investigated. The tensile strength and ultimate strain of the Dyneema sheet are 1,850 MPa and 2.6 4%, respectively. Three HCFRP sensors, indicated as specimens 4-6, are designed and tested. The compositions of the specimens are identical: they consist of three types of carbon tows: HS C1, MM C5 and HM C7 in a ratio of 1:1:1. The variables among these three specimens are the stack order and with/without pretreatment of HM and MM carbon tows during fabrication. For specimens 4 and 6, the carbon tows were adhered to the surface of the Dyneema sheet with epoxy resin in a stack order of C7, C5, and C1 whereas for specimen 5, they were adhered to the surface of the Dyneema sheet in a stack order of C1, C5, and C7. The above investigation reveals that the values of $\Delta R/R_0$ are relatively small in a strain range prior to macro-rupturing of the carbon tows, which impairs the sensitivity in low strain ranges. The measurement principles of the HCFRP sensors are based on gradual macro-rupturing of different types of carbon tows. However, the ultimate strain of the HM carbon tows is beyond 4,000 $\mu\varepsilon$, which means that the measuring sensitivity is poor within a large strain range prior to macro-fracturing of the HM carbon tows. In order to advance the rupture of the HM carbon tows and enhance the change in electrical resistance in low strain ranges, the HM and MM carbon tows of specimen 6 were pretreated via the second measure (PT-II), that is, they were bended repeatedly until the occurrence of some micro-fractures. Fig. 9 shows the evolutions of load and $\Delta R/R_0$ with strain for the three specimens. The strains where the first macro-fracture of HM carbon tows takes place are 5077, 6835 and 3889 $\mu\varepsilon$ for specimens 4-6, respectively. That of specimen 5 is much larger than those for the other two specimens due to the different stack order of the hybrid carbon tows, as shown in Fig. 9(a). It is implied that the stack order has a major influence on the sensing performance in a high strain range. This is attributed to the strain/stress loss between the Dyneema layer and the HCFRP sensors.

In this study, the fracture sensing range is defined as the strain/load range from the strain/load where the first jump in electrical resistance takes place to the strain/load where the electrical resistance measuring method becomes ineffective due to rupture of the HS carbon tows. The first jump in electrical resistance

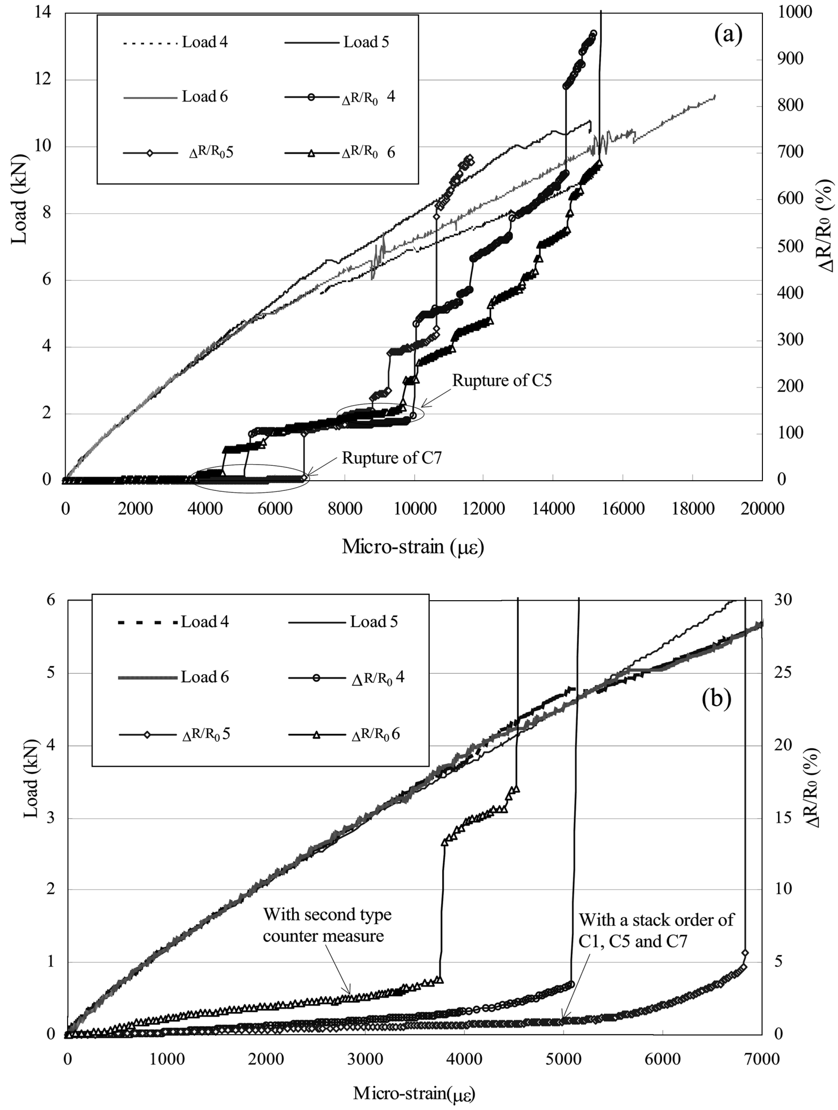

Fig. 9 Evolutions of load and $\Delta R/R_0$ with micro-strain for specimens 4-6 with C1,C5 and C7 in a ration of 1:1:1 adhesively bonded on the surface of Dyneema sheet during whole strain range (a); during the low strain range (b).

is due to the rupture of the HM carbon tows. The fracture sensing range of specimen 5 with a stack order of C1, C5, and C7 is much smaller than that of the other two specimens with a stack order of C7, C5, and C1. Moreover, the stack order also influences the electrical behavior in low strain ranges. The corresponding values of $\Delta R/R_0$ are smaller for specimen 5 than those for the other two specimens, as shown in Fig. 9(b). Fig. 9(b) also shows that before the macro-fracturing of the HM and MM carbon tows, the electrical resistance increases in direct proportion to the strain for all of the specimens.

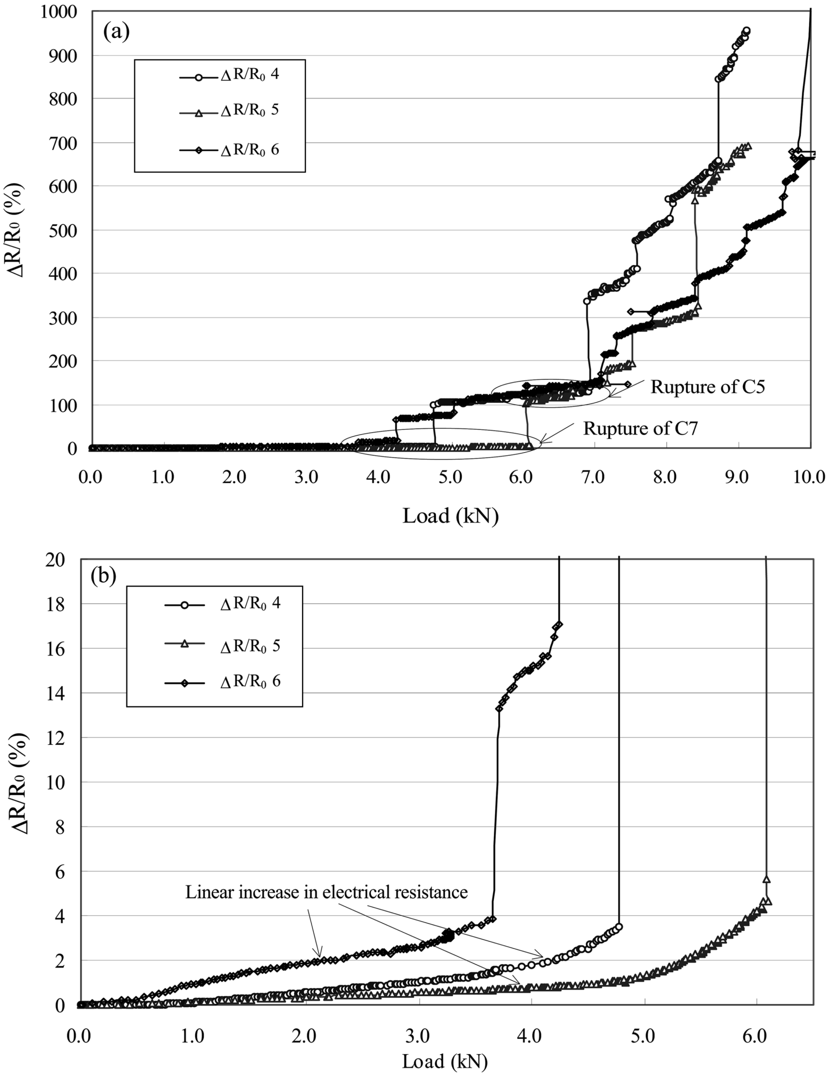

Fig. 10 Evolutions of $\Delta R/R_0$ as s function of load for specimens 4-6 with C1, C5 and C7 in a ration of 1:1:1 adhesively bonded on the surface of Dyneema sheet during whole load range (a); during the low load range (b).

It is shown in Fig. 9 that the second measure (PT-II) has some important influences on the sensing performance of the HCFRP sensors. Compared with the first sudden jumps in electrical resistance of specimens 4 and 5 without any pretreatment, the first jump in electrical resistance of specimen 6 with pretreatment is advanced by about 1,188 $\mu\varepsilon$ and 2,946 $\mu\varepsilon$, respectively. In addition to advancing the first jump in electrical resistance, the corresponding values of $\Delta R/R_0$ in the low strain ranges are enhanced markedly. For example, the values of $\Delta R/R_0$ are 3.86%, 1.42%, and 0.66% for specimens 4-6, respectively. The results demonstrate that the second measure (PT-II) can improve the change in electrical resistance by more than 2.7 times in low strain ranges.

The relationships between $\Delta R/R_0$ and load for specimens 4-6 are shown in Fig. 10. The loads where the first jump in electrical resistance takes place for specimens 4, 5, and 6 are, respectively, 4.7 kN, 6.1 kN and 3.6 kN. This means that the stack order also influences the load sensing range, as shown in Fig. 10(a). Additionally, the stack order also affects the electrical behavior and values of $\Delta R/R_0$ in low load ranges, as shown in Fig. 10(b).

The experimental results from Fig. 10 also reveal that PT-II is an effective measure for improving the load sensing range. In comparison with the first resistance jumps of specimens 4 and 5, the first resistance jump of specimen 6 with pretreatment is advanced by about 1.1 kN and 2.5 kN, respectively. The values of $\Delta R/R_0$ are also improved markedly, as demonstrated in Fig. 10(b). From Fig. 10 (a), it can also be seen that pretreatment of HM and MM carbon tows can also enhance the number of jumps in electrical resistance.

4. Conclusions

Based on the experimental study, the following conclusions have been drawn:

1. Carbon tows can be used as sensing materials by virtue of their electrical conductivity and piezoresistivity. The hybridization of several types of carbon tows with different moduli and strength is confirmed to be an effective means of providing a broad and stage-based structural sensing function.

2. The electrical resistance of the HCFRP sensors changes with strain/load linearly in low strain/load ranges, but is smaller than 2%. Within high strain ranges, the resistance changes with strain/load in a step-wise manner. The values of $\Delta R/R_0$ due to the fracturing of HM carbon tows are larger than 36%.

3. Both measures (PT-I and PT-II) have important influences on the sensing performance of the HCFRP sensors, especially in low strain/load ranges. PT-I and PT-II can enhance the values of $\Delta R/R_0$ by more than 10 and 2.7 times, respectively, in low strain ranges. In addition, PT-II can advance the first jump in electrical resistance by more than 1,100 $\mu\varepsilon$ and it enhances the jumps in electrical resistance in high strain ranges.

4. The stack order of the carbon tows affects the electrical behavior of the HCFRP sensors. In order to enhance the sensing range and improve sensitivity in a low stain range, the HM and MM carbon tows should be adhered directly to the surface of the structure.

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