Experimental investigation on strain-resistance characteristics of carbon nanotube fibers and their multi-ply wires

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ABSTRACT

CNT fibres is composed of millions of highly aligned carbon nanotubes along the axial direction, the CNT wires that have more remarkable properties are twisted together by several fibres. In this paper, the strain-resistance characteristics of CNT fibre monofilaments and their multi-ply wires are investigated. The experimental results show that the gauge factor (the relative change in resistance per unit strain) of the CNT fibers is about 1.50, which is lower than the uniaxial gauge factor of the commonly-used electric resistances strain gauges. As the CNT fiber is elongated, the change of the resistance is determined by the change of both the geometric length of the fiber and the electrical resistivity. However, the geometric length is the main reason. In addition, the change of electrical resistance of CNT wires made of two-ply and three-ply CNT fibers with uniaxial strain are also investigated. The results show that the gauge factor of CNT wires is lower than that of CNT fibers. Specifically, the change of electrical resistance of the CNT fibers and wires under uniaxial tensile loading and cyclic loadings are analyzed. The results indicate that the change of electrical resistance of the CNT fibers and wires are synchronous with the cyclic strain, demonstrating good stability.

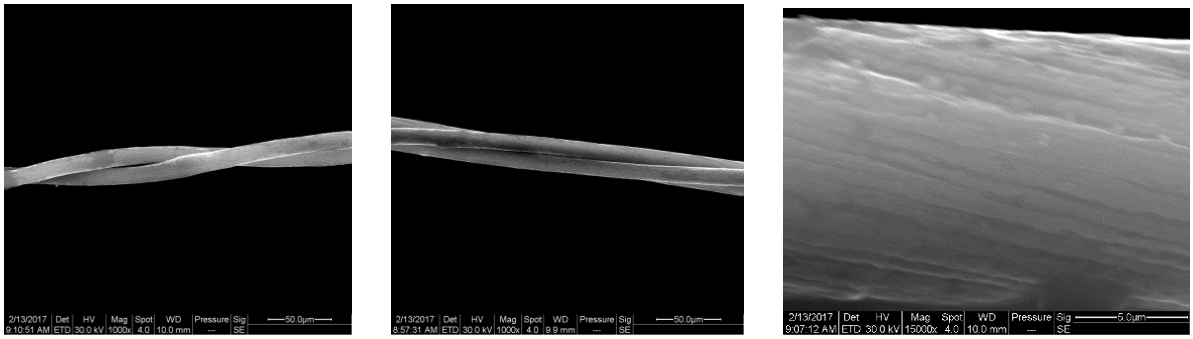
1 INTRODUCTION

Carbon nanotube fibres have been extensively studied as a functional material with high strength, high modulus, thermostability, corrosion-resistance, fatigue resistance, electric-conduction, heat conduction and light specific weight. A single CNT has a high electrical resistivity of 5.1×10^{-8} at room temperature, which is comparable to the resistivity of silver [1]. CAO [2] have carried out a systematic investigation of the electromechanical properties of various types of SWNTs under tensile strain, the result suggests that quasi-metallic SWNTs (GF up to 600–1000) are potentially useful for highly sensitive electro-mechanical sensors and could present a new type of strain gauge material. In order to improve their practical applications, great effort has been made to assemble CNTs into macrostructures, such as continuous fibres. Amanda [3] first demonstrates their potential to serve as sensors in high rate applications by the dynamic tensile behavior of CNT fibers. The mechanical and electrical properties of Highly twisted double-helix carbon nanotube yarns were investigated[4]. Introducing stretch ability and elasticity into carbon nanotube (CNT) yarns could extend their applications to areas such as stretchable and deformable fiber-based devices and strain sensors[5]. CNT thread can provide reliable and robust strain measurements for composite and metallic structures. the strain sensor performance meets or exceeds other strain sensors in performance [6]. A behavior consisting of a negative piezoresistive response was encountered during most of the deformation range of the CNT yarn in [7]. However, carbon nanotube yarns exhibit positive piezoimpedance in Obaid's experiment [8].Strain-resistance characteristics of CNT-Fs have been studied by different scholars, but different results were obtained. Furthermore, experimental study on strain-resistance characteristics of CNT-wires is rarely reported. In order to provide a new perspective for guiding the design of sensors and wearable electronic devices based on CNT wires. We conduct in-depth studies on the strain-

resistance characteristics of CNT fiber and CNT wires consisting of two or three CNT fibers (denoted as two-ply and three-ply CNT wire, respectively).

2 EXPERIMENTAL SETUP AND SPECIMEN PREPARATION

The parameters of CNT fiber are listed as follows. The density is 0.8-1.0 g/cm3, the strength is 1200-1500 MPa, the modulus is 50-100 GPa and the elongation at break is 2-3.5%. The CNT fiber was prepared using the array spinning method, SEM photos as shown in Fig. 1.



(a) two-ply CNT wire (b) three-ply CNT wire (c) surface topography of CNT fiber

Fig 1: SEM photos of CNT wires

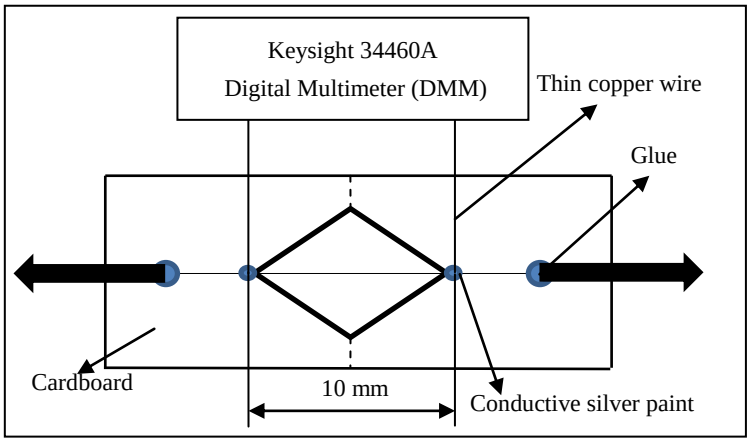


Fig 2: Schematic diagram of the specimen preparation and electrical resistance testing

Fig 3: Agilent UTM T150 nano-tensile tester

Fig. 2 illustrates the specimen preparation method and the electrical resistance testing setup. The specimens with a length of 10 mm are prepared by fixing the fiber segment on a cardboard with glue. Besides, thin copper wires are bonded to the fibers ends using conductive silver paint. The tensile strain data of the CNT fibers is collected by using a nano-tensile tester (Agilent UTM T150, see Fig. 3) which has a maximum force of 450 mN. What's more, the resistance data are collected by Keysight 34460A. The data acquisition rates of both devices are set to 1 Hz.

3 RESULTS AND DISCUSSION

3.1 Stress-strain behavior under tensile loading

The CNT fibers tested in this experiment has higher tensile strength and lower elongation at break. The potential of excellent properties of CNT fibres have been widely concerned as a composite reinforcement. As displayed in Fig. 4, the stress–strain curves can be divided into three stages, namely, the elastic stage (stage I), the plastic stage (stage II) and the damage-fracture stage (stage III), which

has been reported in a previous work [9]. There are a lot of loose and entangled bundles and threads inside a fibre, In the stage I, most of the curved bundles in the fiber become tightened and straightened under the tensile loading, with the increase of the applied load, almost all of the bundles begin to carry loading, leading to a slow increase in slope of the stress–strain curve of the fiber. However, most of the threads can only carry a small part of the load. As the load increases, some of the bundles are straightened and stretched. Meanwhile, the fibres are stretched elastically. In stage II, the slope of the stress–strain curve increases gradually with the development of the plastic deformation. Besides, compared to stage I, some of the CNT threads become the load-bearing elements, Most of threads among bundles damage and parts of bundles break caused by intra-bundles slipping, which contributes to the plastic deformation of the fibre. The diameter of bundles decreases due to the intra-bundle slipping. For the fracture stage III, accumulation of the CNT slipping within the bundles leads to the crack of bundles, which lead to the final failure of the CNT fiber.

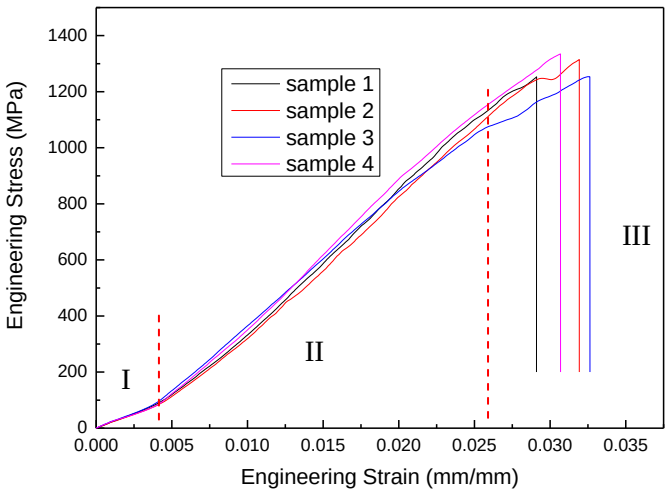


Fig 4: Stress-strain curves of CNT fibres under tensile loading

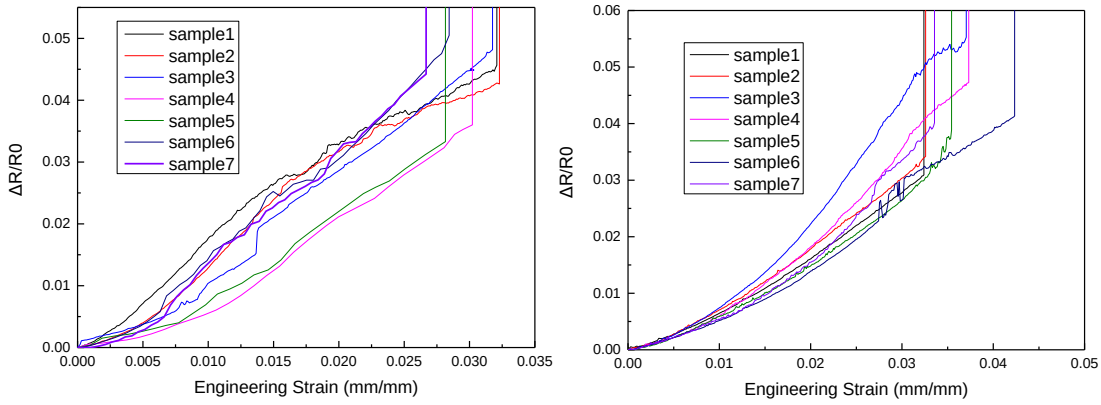
3.2 Strain-electrical resistance characteristics

The gauge factor is introduced as:

$$GF=\frac{\Delta R/R_0}{\varepsilon} \tag{1}$$

Where $\Delta R/R_0$ is the relative resistance change.

The gauge factor of the CNT fibres is about 1.50, which is lower than the uniaxial gauge factor of the commonly-used electric resistances strain gauges. However, the average gauge factor of three-ply CNT wires is about 1.20. We can draw a conclusion that the gauge factor of CNT wires is lower than that of CNT fibres. Three-ply CNT wire is preferable to CNT fibre monofilament in stability (see Fig. 5). We can explain the positive piezoresistive response of CNT fibres from the perspective of changes in the microstructure of the CNT fibres. There are a lot of loose and intertwined bundles and threads inside a fibre, in the initial stage of fibre tensile test, the vast majority of the fibre bundles and threads will experience a process from a state of relaxation to stretch. with the increase of load applied on the fibre, some bundle's cross-sectional area decreases as it is stretched, At the same time, the threads intertwined around the bundles is broken, which blocks the transmission of electrons ,these change is the main reason for the increase of resistance in the initial stage. In the continuous plastic deformation stage, the length of the CNT fibre is elongated. With the increase of the loading, fibres are stretched to fracture where the resistance becomes infinite. As the CNT fibres elongated, the nanotubes that comprise the threads are separated further increasing the resistance. The progressive deformation mechanisms of multi scale structures of CNT fibre is shown in Fig. 6.



(a) CNT fiber (b) three-ply CNT wire

Fig 5: Relative rate of change in the electrical resistance versus strain at strain rate of 5×10^{-4} /s.

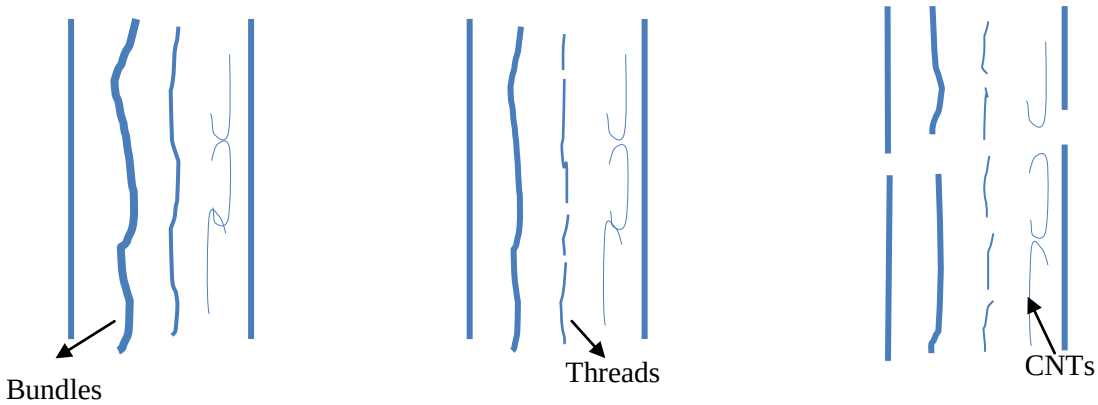


Fig 6: Progressive deformation mechanisms of multi scale structures of CNT fibres under tensile force

3.3 Progressive cyclic loading-unloading test

Fig. 7 shows typical real-time relative change in the electrical resistance and strain for single CNT fibre. A typical tensile progressive cyclic loading curve of CNT fibre is shown in Fig. 8. It can be seen that the residual deformation of the fiber increases as the applied strain increases (Figure. 8). It is obvious that the change in the resistance shows a linear increase with the total length of the fibre after each cycle (Figure. 9). Due to the existence of residual strain, the resistance cannot reversibly return to the initial value after each loading-unloading cycle. Clearly, the length of the fibres exhibits a permanent increase as the loading-unloading cycles increase. This also reveals the changes in the microstructure within fibres. Furthermore, increased resistance of the fibres implies that average distances between the individual CNTs increase and a progressive breakage of CNT-CNT interconnects as the applied loading increases (see Fig. 6). Fig. 10 shows the strain variation and the corresponding resistance variations of two-ply and three-ply CNT wires with time, respectively. We see that, after 11 cycles of loading-unloading tests, whether it is two-ply wires or three-ply wires, the resistance increase is always consistent with strain. This further proves that the CNT wires also possess sensitive strain-resistance response, which can be used for strain sensing, for instance, structural health monitoring.

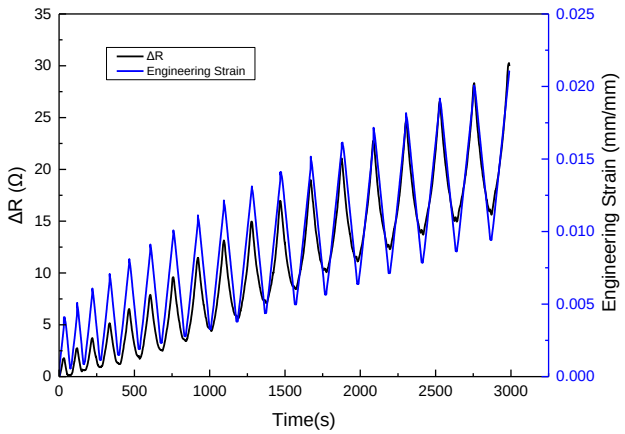


Fig 7: Relative change in the electrical resistance and strain versus time for single CNT fibre, respectively.

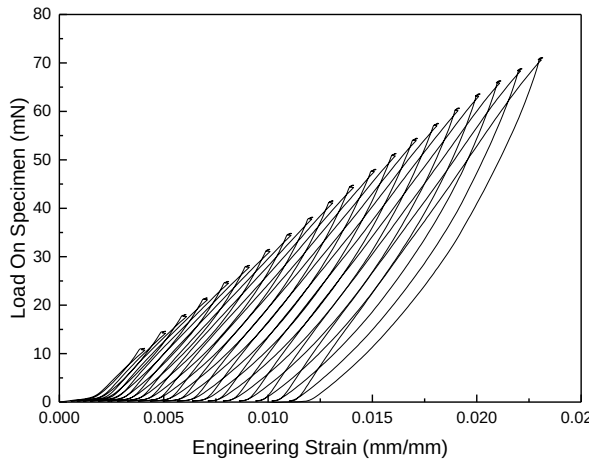


Fig 8: Stress-strain curves for cyclic loading with strain increment of 0.01 in each cycle at strain rate of 2×10^{-5}/s

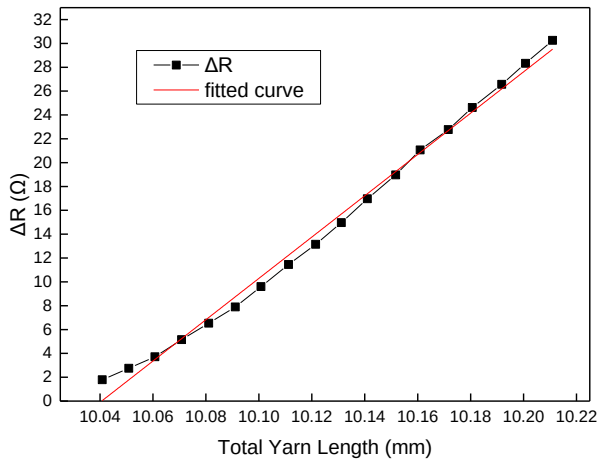


Fig 9: Change in the resistance versus total length of fiber after each cycle
Modified equation Y=173.26356X-1739.67156

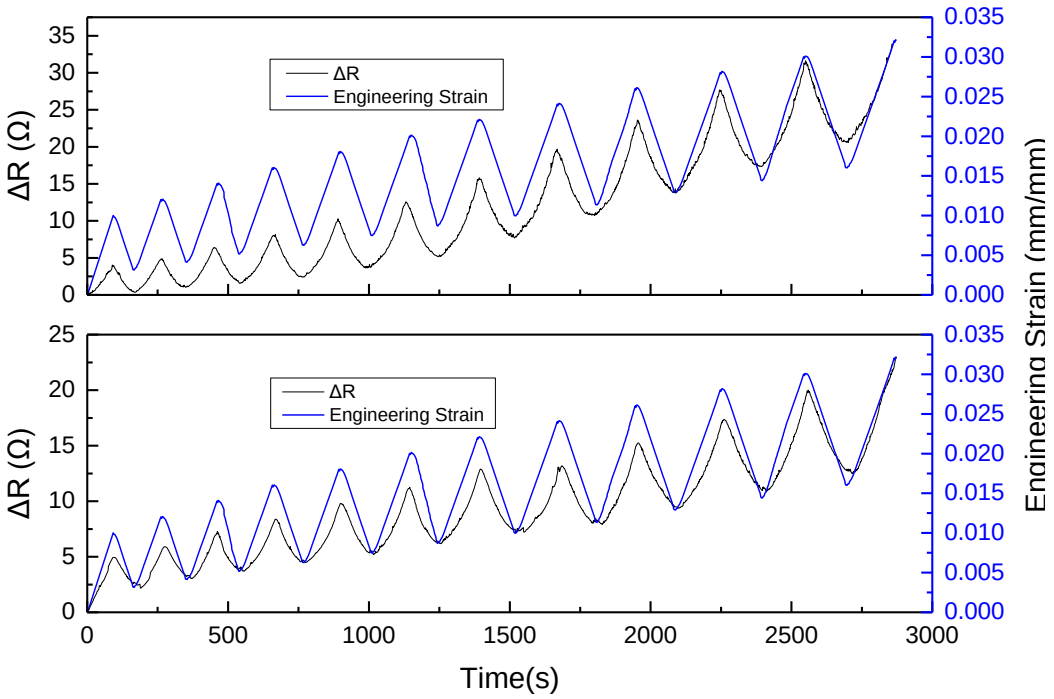


Fig 10: Real-time resistance change of CNT wires (two-ply, three-ply respectively) under incremental displacement.

3.4 Cyclic loading-unloading test

In order to use CNT fiber as a sensing element, the stability of fatigue performance after long-term work should be fully considered, so this paper carried out repeated loading-unloading cycles to verify the stability of strain-resistance performance of the CNT wires (see Figure. 11). The resistance of CNT wires increases with the increase of tensile strain and returns to the initial value with the decrease of tensile strain when unloaded. After 200 times of loading-unloading cycles, the change of electrical-resistance of the CNT wires are synchronous with the cyclic strain, demonstrating good stability, excellent repeatability. Due to the existence of residual strain, the tensile strain of wires can't return to zero. The residual strain gradually increases and tends to stabilize at a fixed value with cycle times increase. Therefore, the wires should be pre loaded-unloaded several times before selecting it as a strain sensing element.

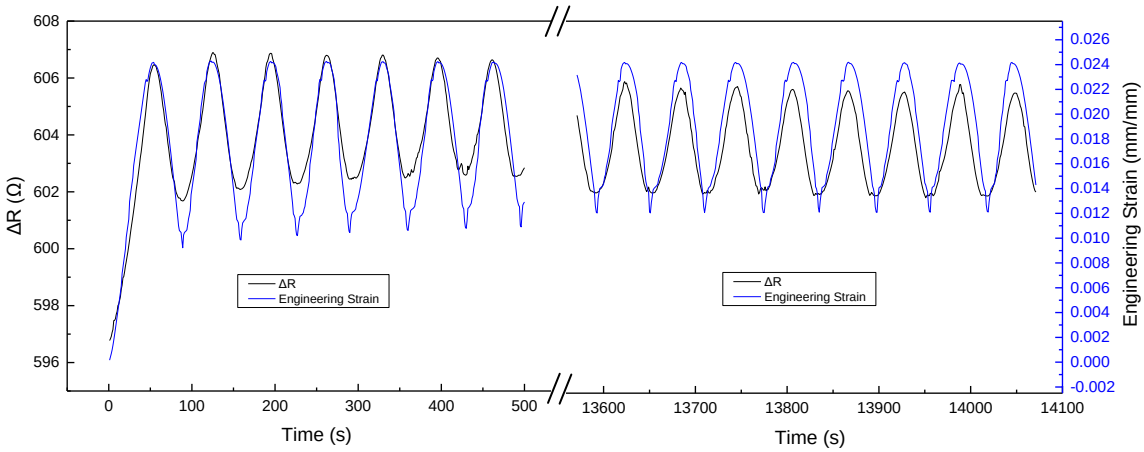


Fig 11: Real time resistance change of three-ply CNT wires under cyclic loading at strain rate of 5×10^{-4}/s .

3.5 Stress relaxation test

Taking two-ply CNT-wires as an example, the creep effect is tested. When the strain remains constant, the stress of the wires decreases obviously, while the resistance remains almost unchanged (see Fig. 12).Which further proves that the main reason for the change of the resistance is the change of the axial length of the wires.

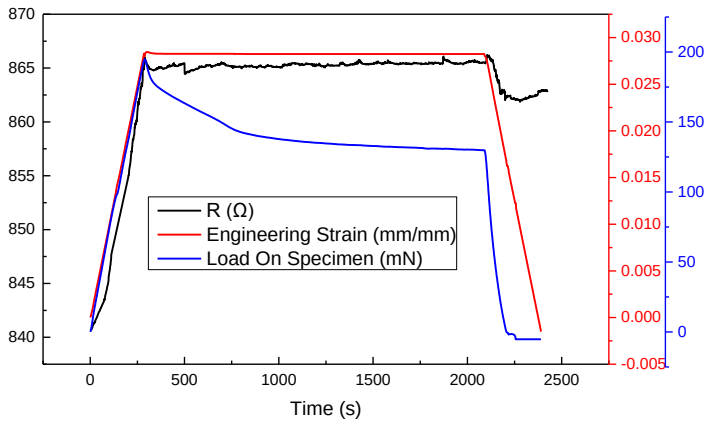


Fig 12: Creep test of CNT-wires

4 CONCLUSIONS

CNT wires formed by twisting together CNT fibers have reduced resistance-strain sensitivity. However, both the elastic and plastic deformation phases are prolonged and the stability is improved. As the CNT fibre is elongated, the change of the resistance is mainly determined by the change of the geometric length of the fibre. Both CNT fibres and wires exhibit excellent Strain-resistance characteristics, which enable them to have potential application in sensing technology.

ACKNOWLEDGEMENTS

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