

## Research Article

# Strain-Sensing Characteristics of Carbon Nanotube Yarns Embedded in Three-Dimensional Braided Composites under Cyclic Loading

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Carbon nanotube yarns are embedded in three-dimensional (3D) braided composites with five-axis yarns, which are used as strain sensors to monitor the damage of 3D braided composites. In the cyclic mechanical loading experiment, the strain-sensing characteristics of 3D braided composites were studied by in situ measuring the resistance change of the embedded carbon nanotube yarn. The 3D five-directional braided composite prefabricated part based on carbon nanotube yarns was developed, and the progressive damage accumulation experiments were carried out on carbon nanotube yarns and specimens embedded in carbon nanotube yarns. The research results show that there is a good correlation between the change of relative resistance of the carbon nanotube yarn and the strain of the composite specimen during cyclic loading and unloading. When the tensile degree of the specimen increases beyond a certain range, the carbon nanotube yarn sensor embedded in the specimen shows resistance hysteresis and produces residual resistance. Therefore, the fiber can better monitor the progressive damage accumulation of 3D five-direction braided composites.

## 1. Introduction

As an advanced structural load-bearing material, three-dimensional (3D) braided composite materials, due to their excellent properties such as nonlayered structure, good overall performance, one-time braiding, and flexible design of special-shaped parts, have a growing share in engineering applications that pay great attention to strength and light characteristics, especially in the field of aerospace [1]. Although the strength of composite materials is superior, invisible damage such as fatigue and even impact may accumulate and cannot be identified due to external load during use. The monitoring ability of composite materials has become the biggest weakness restricting their development. Therefore, it is very important to monitor the local damage and development status of the composite structure in real time for its safe application [2, 3]. So, in situ structural

health monitoring (SHM) of 3D braided composites is a very important research topic.

In recent years, researchers have proposed a variety of composite monitoring and sensing technologies. However, some of these technologies, such as ultrasonic technology, cannot be applied in the mechanical operation of composite materials, while other technologies, such as active piezoelectric sensors, optical fiber sensors, acoustic emission sensors, and other embedded sensing technologies, can monitor the composite structure in real time [4–6]. For the manufacturing methods, identifiability and damage types of composite materials, each different monitoring technology, have their own advantages and disadvantages.

Literature research [7, 8] provides us with a simple monitoring technology based on resistance change, that is, the monitoring method based on the piezoresistive effect. In these studies, piezoresistive effect monitoring technology

was successfully applied to conductive carbon fiber-reinforced polymer. The conductivity of the carbon fiber can be used to monitor the damage indexes in the polymer, such as fiber fracture, delamination, and matrix cracking, which may be related to the damage mechanism in composites. Muto et al. [9] studied the application of the piezoresistive effect monitoring method in nonconductive composites. The research showed that the mechanical load exerted on the composite can be monitored by inserting carbon fiber into glass fiber-reinforced polymer during the manufacturing process and by the electrical response of the carbon fiber. However, due to different elastic moduli between the two materials and the limitation of carbon fiber conductivity, in fact, the carbon fiber sensor does not monitor the progressive cumulative damage of the composite, but only predicts the final fracture of the composite. Therefore, it is necessary to find a kind of conductive fiber with strong conductive ability, which can monitor the damage of low tensile axial strain through the change of resistance, so as to realize the damage monitoring of the conductive fiber for nonconductive composites.

Carbon nanotube (CNT) has a unique seamless tube structure. In 1991, Iijima [10] discovered CNT for the first time, which caused extensive research. CNT is regarded as the best new material for real-time structural health monitoring because of its lightweight, good mechanical properties, high conductivity, and easy to build the sensor network [11–13]. Compared with traditional strain sensors, CNT sensors can overcome many limitations of existing conventional sensors, such as limited monitoring space and small weight. Therefore, the additional impact of CNTs in the monitoring process is relatively small, which has the potential to embed in situ monitoring in the composite structure. CNT fiber is composed of single CNT, and then CNT fiber tape is twisted together to make carbon nanotube yarns. Carbon nanotube yarns have an orderly fiber stable structure, so they have good repeatability and stable resistance strain behavior [14]. Previous studies have also shown that [15–17] the embedded CNT fiber sensor can be used to monitor the generation and expansion of damage in composite structures in real time.

Therefore, the composite material samples of the carbon nanotube yarn sensor are prepared by a 3D four-step braiding process. Through cyclic loading and unloading experiments, the strain-sensing performance of the carbon nanotube yarn sensor for composite materials was analyzed. By observing the change of the resistance of the embedded carbon nanotube yarns with the tensile loading of the composites, the occurrence and progressive damage accumulation of the composites are monitored, which provides the basis for the application of 3D braided composite in situ sensors based on carbon nanotube yarns.

## 2. Research on the Embedding Method of the Carbon Nanotube Yarn Sensor

Carbon nanotube yarns were embedded into 3D braided composites by the 3D five-direction four-step braiding process. The 3D braiding steps are shown in Figure 1 [18].

Taking 3D four-step  $1 \times 1$  square braiding as an example, the main yarn carriers are arranged around the main body with the number of rows  $m$  and columns  $n$ , expressed as  $ab$ . The yarn carrier moves through four steps to realize one braiding cycle, which is called four-step method. Step 1: the yarn carrier moves along the adjacent row direction for one braiding motion; that is, the center distance between two adjacent yarn carriers is listed; Step 2: the yarn carrier moves along the adjacent column direction for one braiding motion, that is, the center distance between two adjacent yarn carriers; Step 3: the motion direction of the yarn carrier in Step 1 is changed to the opposite direction; Step 4: the motion direction of the yarn carrier in Step 2 is changed to the opposite direction. After a cycle of braiding, after the above four steps, the arrangement of yarn carriers returns to the original state, as shown in Figure 2.

Carbon nanotube yarn is braided with the carbon fiber in the form of an axial yarn. When the prefabricated part is braided, a carbon nanotube yarn sensor is braided into every 5 carbon fibers. The spatial structure of the composite prefabricated part is shown in Figure 3.

## 3. Design of the Strain-Sensing Experimental System for the Carbon Nanotube Yarn Sensor

*3.1. Strain-Sensing Mechanism of the Carbon Nanotube Yarn.* When analyzing the piezoresistive effect of the carbon nanotube yarn sensor, firstly, based on Ohm's law,

$$R_0 = \frac{\rho L}{A}. \quad (1)$$

In the formula,  $R_0$  is the original resistance of the yarn;  $\rho$  is the resistivity of the yarn;  $L$  is the length of the yarn;  $A$  is the cross-sectional area of the yarn. The change rate of resistance is

$$\frac{\Delta R}{R_0} = \frac{\Delta \rho}{\rho} + \frac{\Delta L}{L} - \frac{\Delta A}{A}. \quad (2)$$

In the formula,  $\Delta R$  is the change of resistance of the yarn;  $\Delta \rho$  is the change of yarn resistivity;  $\Delta L$  is the change of yarn length;  $\Delta A$  is the change of yarn cross-sectional area.

The change in yarn length can be expressed as

$$\frac{\Delta L}{L} = \varepsilon_{11} - \frac{\varepsilon_{11}^2}{2}. \quad (3)$$

In the formula,  $\varepsilon_{11}$  is the strain coefficient.

The latter part of formula (3) can be neglected when the strain is small. The sensor cross section can be expressed as

$$A' = A(1 - 2\vartheta_{12}\varepsilon_{11}). \quad (4)$$

In the formula,  $\vartheta_{12}$  is Poisson's ratio of carbon nanotube yarns; therefore,

$$\frac{\Delta A}{A} = -2\vartheta_{12}\varepsilon_{11}. \quad (5)$$

$$\frac{\Delta R}{R_0} = \frac{\Delta \rho}{\rho} + \varepsilon_{11} + 2\vartheta_{12}\varepsilon_{11} = \frac{\Delta \rho}{\rho} + \varepsilon_{11}(1 + 2\vartheta_{12}). \quad (6)$$

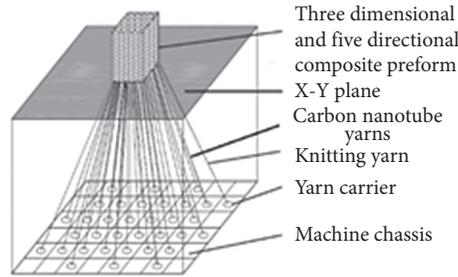


FIGURE 1: Schematic of four-step 3D braiding.

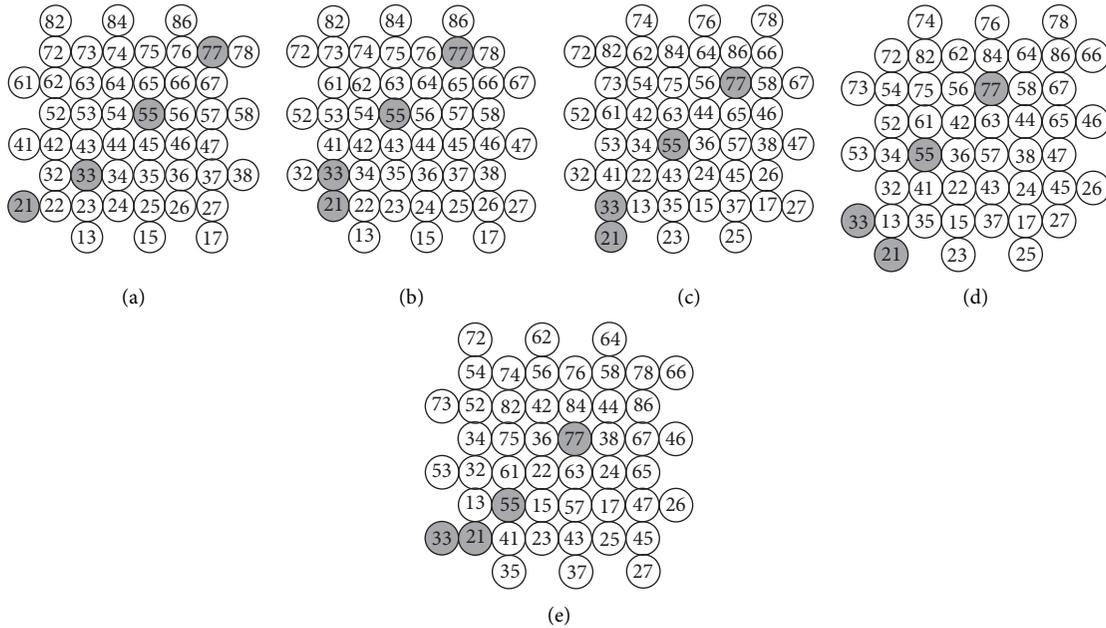


FIGURE 2: Diagram of the 3D braided composite prefabricated part braiding process. (a) Original state. (b) First steps. (c) Second steps. (d) Third steps. (e) Fourth steps.

It can be seen from equation (6) that the resistance change of the carbon nanotube yarn sensor is caused by the change of strain and resistivity. Because of the symmetry between the resistance change rate and the load, the resistance change rate is linear in the load range [19].

**3.2. Strain-Sensing Experimental System of the Carbon Nanotube Yarn.** The experimental system consists of an AG-250KNE Shimadzu universal material experimental machine (produced by Shimadzu company of Japan), 50 mm extensometer, resistance strain gauge, 10 V DC power supply, analog-to-digital converter, computer, and other relevant connecting equipment. It is used to measure tension and displacement data, longitudinal strain data, in situ resistance of the specimen during mechanical loading and data acquisition and processing. The strain-sensing experimental system based on the carbon nanotube yarn sensor is shown in Figure 4. The tensile speed is 2 mm/min. The experiments in this paper are carried out at room temperature.

**3.3. Verification of the Strain-Sensing Mechanism of the Carbon Nanotube Yarn.** The relationship between strain and resistance change rate of the carbon nanotube yarn under tension is analyzed to verify the feasibility of the above strain-sensing technology theory.

Under monotonic tension, the relationship between the strain of the carbon nanotube yarn and the change rate of relative resistance is shown in Figure 5. It can be seen from the figure that there is a good linear relationship between strain and resistance change rate in the elastic range, and the experimental results are consistent with the theory of strain sensor technology. Detailed analysis is carried out in the results and discussion.

## 4. Experimental Study

**4.1. Experimental Materials and Preparation.** Experimental materials: T300B-3K carbon fiber, epoxy resin TDE-86 matrix material, 70 anhydride curing agent, and carbon nanotube yarns which are HQCNTs-014 (prepared by the

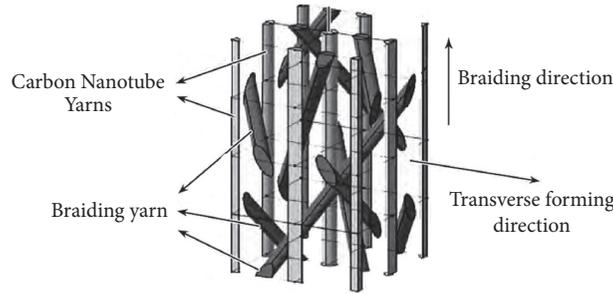


FIGURE 3: Prefabricated part structure of the 3D five-directional braided composite.

carbon nanotube array dry spinning method, belonging to the multiwall carbon nanotube fiber) developed by Suzhou Hengqiu Graphene Technology Co., Ltd. The main technical parameters of carbon nanotube yarns are shown in Table 1.

The experimental specimens were prepared by a  $180 \times 120$  rectangular braiding machine (developed by Tiangong University) in the Institute of Composite Materials, Tiangong University. The 3D five-direction braiding process and vacuum-assisted resin transfer molding curing process (VARTM) were used. The specification of the 3D braided composite specimen is  $250 \text{ mm} \times 25 \text{ mm}$ . Wipe both ends of the carbon nanotube yarns in the specimen and apply silver glue. The two ends of the carbon nanotube yarns in the specimen are connected with copper wires, as shown in Figure 6.

The schematic diagram of the tensile test of the experimental specimen is shown in Figure 7; that is, longitudinal tensile stress is applied at both ends of the specimen and connected to the strain-sensing experimental system to test its strain-sensing characteristics.

## 4.2. Results and Discussion

**4.2.1. Strain-Sensing Characteristics of the Carbon Nanotube Yarn under Monotonic Tension.** The monotonic tensile test of the carbon nanotube yarn was carried out to analyze the relationship between stress and strain, strain, and resistance change rate of the carbon nanotube yarn.

Under monotonic tension, the typical stress-strain curve of the carbon nanotube yarn under monotonic tension is shown in Figure 8. It can be seen from the figure that the stress and strain of the carbon nanotube yarn have a good linear correlation in the strain range of 1%. When the strain exceeds about 1.9%, the linear relationship between stress and strain becomes smaller and smaller; that is, the slope decreases obviously. Under monotonic tension, the stress and strain of the carbon nanotube yarn show obvious two-stage behavior. In the first stage, the strain increases linearly with the stress, which is mainly due to the tensile deformation, untwisting, and diameter reduction of the carbon nanotube yarn under certain tensile stress. In the second stage, the strain decreases obviously with the change of stress, mainly because when the tensile stress continues to increase, the further torsion of the carbon nanotube yarn leads to the separation or splitting in the carbon nanotube layer in the yarn, until the possible local damage or fracture.

This yield behavior can also be attributed to the weak van der Waals force interaction and the slip phenomenon of carbon nanotubes, which is consistent with the existing research results [20, 21].

Under monotonic tension, the typical curve of strain and relative resistance change rate of the carbon nanotube yarn is shown in Figure 9. It can be seen from the figure that the strain of the carbon nanotube yarn has a good linear relationship with the resistance change rate. Contrary to the mechanical behavior, even if the second stage yield behavior leads to a significant reduction of strain with stress, the linear correlation between resistance change rate and strain is still good; that is, the resistance change rate and strain of the selected carbon nanotube yarn have a highly linear behavior under large strain. The linear relationship between carbon nanotube yarn resistance and strain can be attributed to the relative slip deformation of the carbon nanotube in the tensile state. This relative slip reduces the contact between carbon nanotube bundles, increases the strain, and increases the yarn resistance until the carbon nanotube bundles are completely separated from each other.

In conclusion, it is feasible to apply the theory of strain-sensing technology to carbon nanotube yarn strain sensing. At the same time, the resistance change rate of the carbon nanotube yarn maintains a linear correlation with the strain under large strain, so it can be embedded in 3D braided composites to monitor the progressive damage and accumulation of fabrics.

**4.2.2. Strain-Sensing Characteristics of the Carbon Nanotube Yarn under Cyclic Loading.** Progressive damage accumulation experiment was carried out on carbon nanotube yarns; that is, 10 progressive tensile cycles were loaded until fracture. The typical real-time resistance and mechanical loading curves of the carbon nanotube yarn sensor are shown in Figure 10.

It can be seen from Figure 10 that, with the gradual increase of the loading stress of the progressive tensile cycle, the initial resistance of the carbon nanotube yarn sensor also increases; that is, the resistance lag occurs with the continuous loading time. At the same time, it is also found that the resistance of the carbon nanotube yarn sensor always shows a consistent correlation with the bearing stress, which indicates that it has good repeatability, stable resistance strain behavior, and reliable strain-sensing performance.

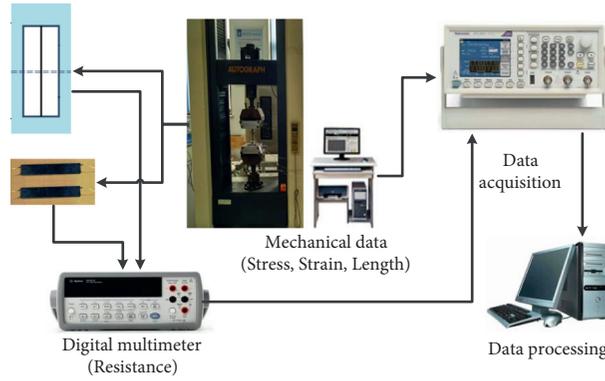


FIGURE 4: Schematic diagram of the strain-sensing experimental system of the carbon nanotube yarn sensor.

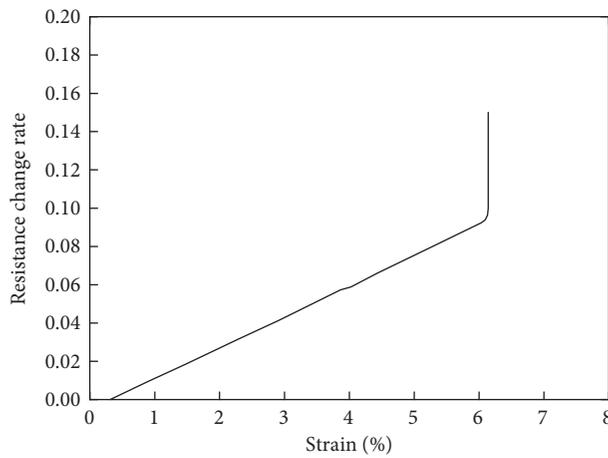


FIGURE 5: Relationship between strain and change rate of carbon nanotube yarns.

TABLE 1: Main technical parameters of carbon nanotube yarns.

Model	Diameter ( $\mu\text{m}$ )	Strength (MPa)	Modulus (GPa)	Density ( $\text{g}/\text{cm}^3$ )	Electrical conductivity (S/m)
HQCNTs-014	20–30	270–800	4–6	0.3–0.5	$7 \times 10^4 \sim 1 \times 10^5$



FIGURE 6: 3D braided composite sample.

In addition, at the end of each progressive tensile cycle, the initial resistance and length of the yarn were measured under free loading, and the relationship between the resistance change of the carbon nanotube yarn sensor and the yarn length was plotted. The results are shown in Figure 11.

It can be seen from Figure 11 that there is a good linear correlation between the initial resistance of the carbon nanotube yarn sensor, that is, the change of relative resistance and the instantaneous length of the yarn. The reason is that, with the gradual increase of stress and strain, the

permanent deformation of the yarn is caused, resulting in the linear growth behavior of the two. The delay of resistance change during the first load may be related to the accuracy of the measuring instrument or the degree of pretensile, and the sensitivity of the sensor needs to be further studied. On the contrary, the mechanical and electrical properties of the yarn always show linear resistance strain behavior before breaking. The resistance variation of carbon nanotube yarns and the instantaneous length of the yarn show a linear relationship independent of the load level, so the strain can be sensed by the resistance variation.

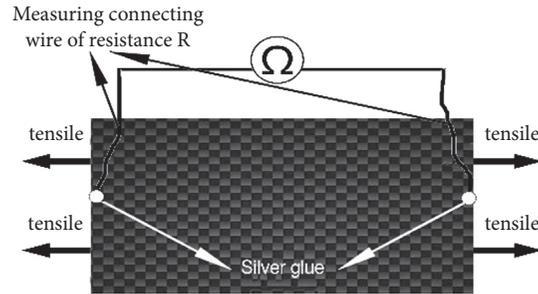


FIGURE 7: Schematic diagram of the longitudinal tensile test.

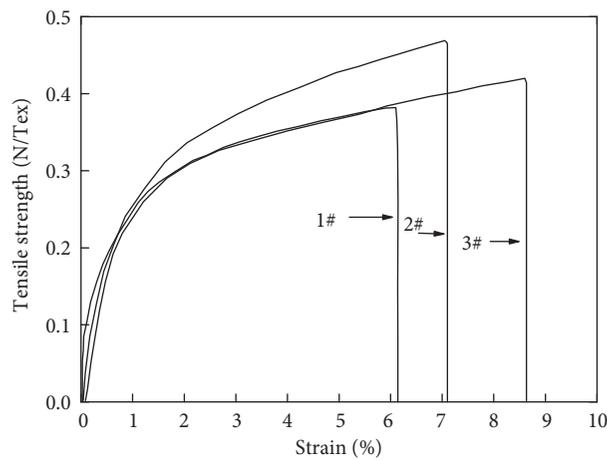


FIGURE 8: Curve of stress-strain of the carbon nanotube yarn.

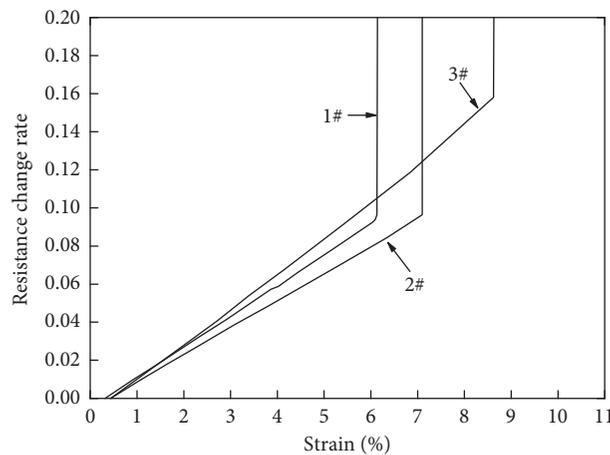


FIGURE 9: Curve of strain and resistance change rate of the carbon nanotube yarn.

In conclusion, the strain-sensing characteristics of the carbon nanotube yarn show good consistency under monotonic tension and cyclic loading, especially when the mechanical behavior shows a certain softening stage; that is, the slope of the stress-strain curve decreases obviously. On the contrary, the resistance change rate and strain of the carbon nanotube yarn can maintain a highly linear behavior under large strain. Therefore, the carbon nanotube yarn can be used to monitor the damage of its embedded braid based on the mechanism of strain-sensing technology.

*4.2.3. Strain-Sensing Characteristics of Composite Specimens under Cyclic Loading.* Progressive damage accumulation experiments were carried out on 3D five-direction braided composite specimens, that is, 10 progressive cyclic loading and unloading until fracture. The electromechanical properties of composites under a wide range of mechanical loading are analyzed.

Under cyclic loading and unloading, the stress-strain curve of the 3D five-direction braided composite specimen is shown in Figure 12. It can be seen from the figure that the

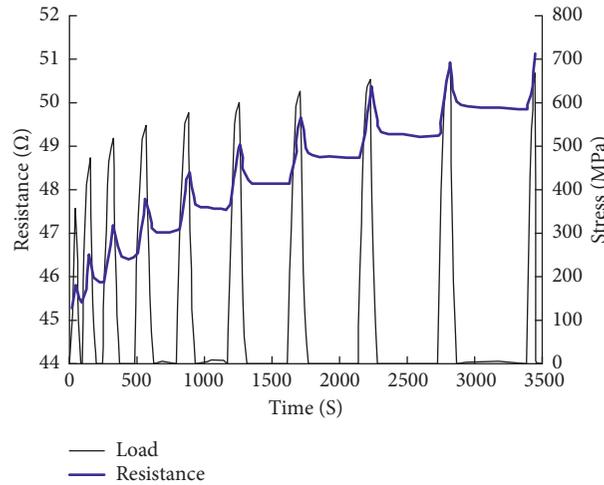


FIGURE 10: Curve of resistance and tensile stress of the carbon nanotube yarn.

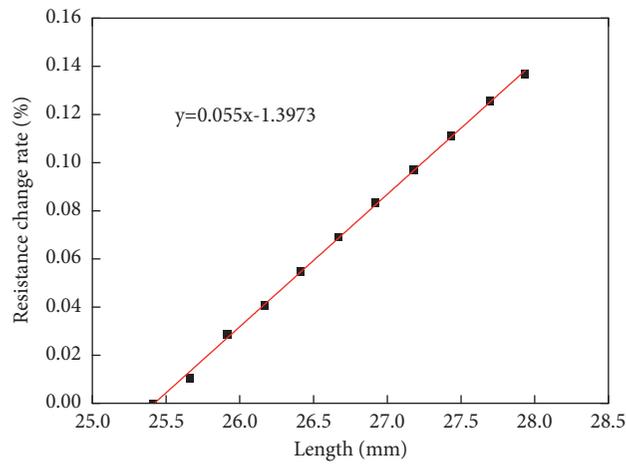


FIGURE 11: Curve of length and resistance change rate of the carbon nanotube yarn.

axial mechanical strain and stress of the 3D braided composite specimen show good monotonic consistency. That is, they increase monotonically with the increase of mechanical loading and decrease monotonically with unloading. At the same time, it is also found that when the tensile stress increases to a certain extent, the specimen does not return to absolute zero strain under zero mechanical load. That is, the residual strain is produced, which indicates that the progressive cyclic loading and unloading cause the residual damage of the specimen. As shown in the figure, the strain of the specimen seems to recover to about 0.1% after the fourth cycle and about 0.15% after the ninth cycle. Residual damage is caused by matrix cracks or fiber separation in the fabric due to the continuous increase of tensile stress.

Under cyclic loading and unloading, the curve between resistance change rate and specimen strain of the embedded 3D five-direction braided composite carbon nanotube yarn sensor is shown in Figure 13. It can be seen from the figure that the resistance change rate of the carbon nanotube yarn sensor shows good monotonic consistency with the strain. At the same time, it is also found that, with the continuous

increase of cyclic loading and unloading stress, the electrical properties of the specimen show characteristics similar to the mechanical properties. For example, after the strain exceeds about 1.0% in the fourth cycle (about 35% of the fracture stress), the residual resistance is observed after unloading, and the change value of resistance will not return to zero. With the continuous increase of bearing stress, the residual resistance of the carbon nanotube yarn sensor also increases accordingly. At the same time, when the strain exceeds about 1%, the residual resistance is generated after the specific point. With the increase of stress in progressive cyclic loading and unloading, the resistance gradually increases in an approximately linear manner. In the experiment, all embedded sensors show similar characteristics. This specific point represents the strain threshold of the material and is actually the damage monitoring threshold of the specimen. Previous studies have shown that when the 3D braided composites exceed this strain threshold, matrix cracks or fiber separation may occur [22].

In conclusion, when the internal damage of the 3D braided composite specimen occurs, the resistance of the

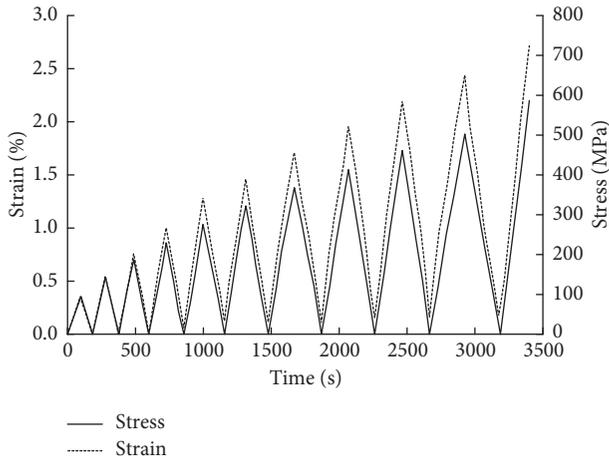


FIGURE 12: Curve of stress-strain of the composite specimen.

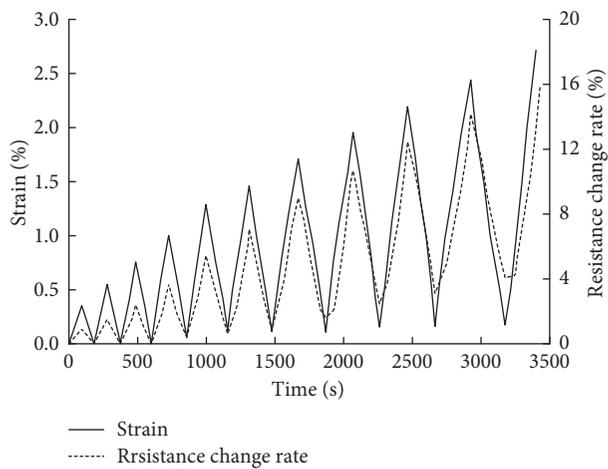


FIGURE 13: Curve of resistance change rate of the carbon nanotube yarn sensor and specimen strain.

embedded carbon nanotube yarn sensor will change, but with the continuous increase of load until fracture, the resistance change rate and strain of the carbon nanotube yarn sensor still have a good linear relationship. At the same time, the residual resistance can well detect the occurrence and accumulation of induced damage in composites. Therefore, carbon nanotube yarn can be used to monitor the progressive cumulative damage of 3D braided composites.

## 5. Conclusion

The experimental results of progressive damage accumulation of the carbon nanotube yarn show that the resistance and stress of the carbon nanotube yarn show good monotonic consistency and show a linear increase behavior with the change of yarn length. In contrast to the mechanical properties, the resistance change rate of the carbon nanotube yarn is linearly proportional to the instantaneous length of the yarn and independent of the load. Therefore, based on the piezoresistive effect, the structural strain can be monitored by the resistance change of the carbon nanotube yarn.

The experimental results of progressive damage accumulation of 3D braided composites show that when the mechanical load of progressive tensile cycle exceeds about 35% of the fracture stress of the composites, the carbon nanotube yarn sensor shows a large resistance measurement value and forms a hysteresis loop, so it can better monitor the strain of 3D braided composites and realize better monitoring of progressive damage accumulation in 3D braided composites. Therefore, the results of this study provide useful guidance for the application of carbon nanotube yarns embedded in 3D braided composite in situ sensors.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

## Acknowledgments

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## References

- [1] Z. Wan, Z. Zhang, M. Jia, W. Bao, and Q. Dong, "Internal damage detection of three-dimensional four-step six-directional braided composites based on carbon nanotube thread sensor," *Insight-Non-Destructive Testing and Condition Monitoring*, vol. 59, no. 10, pp. 537–543, 2017.
- [2] F. Romano, M. Ciminello, A. Sorrentino, and U. Mercurio, "Application of structural health monitoring techniques to composite wing panels," *Journal of Composite Materials*, vol. 53, no. 25, pp. 3515–3533, 2019.
- [3] M. Naebe, M. M. Abolhasani, H. Khayyam, A. Amini, and B. Fox, "Crack damage in polymers and composites: a review," *Polymer Reviews*, vol. 56, pp. 31–69, 2016.
- [4] C. Tuloup, W. Harizi, Z. Aboura, Y. Meyer, K. Khellil, and R. Lachat, "On the use of in-situ piezoelectric sensors for the manufacturing and structural health monitoring of polymer-matrix composites: a literature review," *Composite Structures*, vol. 215, pp. 127–149, 2019.
- [5] J. P. Berro Ramirez, D. Halm, and J.-C. Grandidier, "Assessment of a damage model for wound composite structures by acoustic emission," *Composite Structures*, vol. 214, no. 106, pp. 414–421, 2019.
- [6] S. Jothibas, S. Anandan, G. S. Dhaliwal et al., "Spatially continuous strain monitoring using distributed fiber optic sensors embedded in carbon fiber composites," *Optical Engineering*, vol. 58, no. 7, Article ID 072004, 2019.
- [7] R. Nobile and A. Saponaro, "Real-time monitoring of fatigue damage by electrical resistance change method," *International Journal of Fatigue*, vol. 151, Article ID 106404, 2021.
- [8] J. P. Goulmy, G. Camus, and F. Rebillat, "Monitoring damage evolution of ceramic matrix composites during tensile tests using electrical resistivity: crack density-based

- electromechanical model,” *Journal of the European Ceramic Society*, vol. 41, no. 1, pp. 121–129, 2021.
- [9] N. Muto, Y. Arai, S. G. Shin et al., “Hybrid composites with self-diagnosing function for preventing fatal fracture,” *Composites Science and Technology*, vol. 61, no. 6, pp. 875–883, 2001.
- [10] S. Iijima, “Helical microtubules of graphitic carbon,” *Nature*, vol. 354, no. 6348, pp. 56–58, 1991.
- [11] M. Wang, N. Li, G. D. Wang, S. W. Lu, Q. D. Zhao, and X. L. Liu, “High-sensitive flexural sensors for health monitoring of composite materials using embedded carbon nanotube (CNT) buck paper,” *Composite Structures*, vol. 261, p. 113280, 2021.
- [12] S. Jung, H. W. Choi, F. C. Mocanu et al., “Modelling electrical percolation to optimize the electromechanical properties of CNT/polymer composites in highly stretchable fiber strain sensors,” *Scientific Reports*, vol. 9, p. 20376, 2019.
- [13] K. Ke, Y. Wang, Y. Li, J. Yang, P. Pötschke, and B. Voit, “Nuomici-inspired universal strategy for boosting piezoresistive sensitivity and elasticity of polymer nanocomposite-based strain sensors,” *ACS Applied Materials & Interfaces*, vol. 11, no. 38, pp. 35362–35370, 2019.
- [14] M. Scholz, Y. Hayashi, V. Eckert et al., “Systematic investigations of annealing and functionalization of carbon nanotube yarns,” *Molecules*, vol. 25, no. 5, p. 1144, 2020.
- [15] Z. J. Yang, G. Yan, and C. M. Wang, “Detection of impact damage for composite structure by electrical impedance tomography,” *Lecture Notes in Civil Engineering*, vol. 37, pp. 519–527, 2020.
- [16] S. Lu, K. Du, X. Wang, C. Tian, and D. Chen, “Health monitoring of composite structures subjected to low-velocity impact with surfacebonded CNT buckypaper sensor arrays,” *Insight - Non-Destructive Testing and Condition Monitoring*, vol. 61, no. 6, pp. 324–330, 2019.
- [17] S. J. Park and Y. H. Kim, “CNT/epoxy interleaves for strengthening performance of filament wound composite structures,” *International Journal of Modern Physics B*, vol. 35, no. 14, p. 2140001, 2021.
- [18] M. Chen, W. Zhang, Y. F. Zhu et al., “Alignment and dispersion of functionalized carbon nanotubes in polymer composites induced by an electric field,” *Carbon*, vol. 46, pp. 706–720, 2008.
- [19] P. Li and Z. K. Wan, “Parameter analysis of CNT yarns in smart 3-D braiding composites,” *Journal of Testing and Evaluation*, vol. 48, no. 1, pp. 557–567, 2020.
- [20] J. Reiner, T. Feser, D. Schueler, M. Waimer, and R. Vaziri, “Comparison of two progressive damage models for studying the notched behavior of composite laminates under tension,” *Composite Structures*, vol. 207, pp. 385–396, 2019.
- [21] S. N. Rocker, N. Shirodkar, T. A. McCoy, and G. D. Seidel, “Electro-mechanical response of polymer bonded surrogate energetic materials with carbon nanotube sensing networks for structural health monitoring applications,” *Mechanics of Composite, Hybrid and Multifunctional Materials*, vol. 5, pp. 185–193, 2019.
- [22] Z. K. Wan, P. Li, and M. R. Jia, “Parameter design and variation characteristics of carbon nanotube yarns in intelligent composites,” *Textile Research Journal*, vol. 39, no. 6, pp. 58–63, 2018.