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AN INVESTIGATION ON THE USE OF CARBON NANOTUBE FIBER SENSORS FOR STRAIN MONITORING IN ALUMINUM PLATES

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Abstract. *Structure Health Monitoring (SHM) systems are vital for aircraft operation, and it is becoming a promising technology, being considered for reference certification authorities as FAA (Federal Aviation Administration). Novel techniques for Non-Destructive Inspection (NDI) tasks could be implemented, opening new possibilities for future implementation of in-flight systems to monitor aircraft structures. In order to seek for this possibility, the development and evaluation of new, non-intrusive and lightweight sensors are of capital importance. In this context, carbon nanotube fibers have demonstrated to be highly sensitive to strain and are virtually non-intrusive, being then good candidates to be used as SHM sensors. Therefore, the present work is devoted to the experimental assessment of a sensor based on a single carbon nanotube thread, applied to monitor strains in metallic specimens. The study includes the sensor description, the lamination process and the experimental procedure. The results presented show that the sensor shows high sensitivity and provides good qualitative measurements. However, difficulties are engendered by the occurrence of nonlinear behavior.*
Keywords: *strain sensor, carbon nanotube yarn, structural health monitoring.*

1. INTRODUCTION

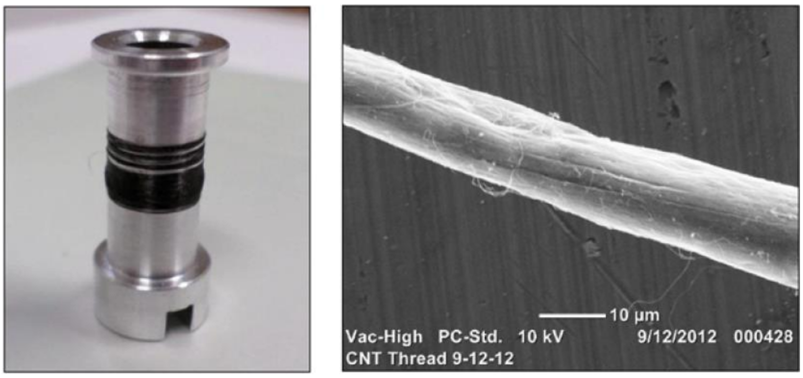
At the beginning of the development of the first aeronautical structures, these were designed to have infinite life. Such strategy invariably led to oversizing in favor of safety and sacrificed the aircraft performance. As a result of the better understanding of fatigue mechanisms and adoption of new materials, besides the multiplication of challenging scenarios in civil aircraft market, the adoption of the damage-tolerant concept design was a natural process in the evolution of the aircraft technologies. Therefore, more optimized aircraft structures have begun to gain space. However, to follow this design philosophy, it becomes necessary to develop new technologies for damage detection in such a way to provide adequate inspection routines.

Farrar and Lieven (2006) define SHM as the process of identifying the presence of damage and quantifying its extent in a structure based on information extracted by means of a response measurement system. Since size, type and location of damage are known, it is possible to determine the best action to be undertaken for that particular type of damage in the component or structure (Inman and Grisso, 2007). Ideally, the sensors used for non-destructive inspections should be smaller than the microstructure of the host material, low in cost, easy to integrate, highly sensitive to strain, insensitive to temperature variations, and not require complex or expensive measuring equipment (Abot *et al.*, 2018).

The philosophy of damage tolerance is based on the use of Non-Destructive Inspections (NDI), applying Non-Destructive Evaluation (NDE) methods during the aircraft scheduled maintenance stops. These operations are programmed to impact minimally the dispatchability of the fleet. In this way, crack detection techniques and inspection methods that provide faster results and generate shorter stopping time of the aircraft are incessantly requested by the operators.

The development of nanotechnology has enabled to conceive novel types of sensors used for NDE operations. Winchesky and a group of researchers from Langley Research Center, in Virginia, are using a method based on electron-beam lithography, leading to very flexible, powerful and small carbon nanotube (CNT) sensors, creating a smart skin which is capable of detecting and monitoring crack growth in metallic sheets (Wincheski *et al*., 2011). Loh *et al*. (2007) makes a similar proposition, with the development of a nanotube skin that can be applied to metallic surfaces to monitor the strain response of the structure and the evolution of cracks employing a multilayered single-wall carbon nanotube-polyelectrolyte composite thin film. Ashrafi *et al*. (2012) focus on the application of epoxy nano-composite thin film sensors for continuous monitoring of crack evolution in metallic structures.

Abot *et al*. (2010) investigated the use of a novel piezoresistive strain sensor consisting of a yarn made of carbon nanotubes and applied it to epoxy resin and carbon-epoxy composite specimens. The underlying principle of this sensor is that its electrical resistance varies as function of the strain it is subjected to in its lengthwise direction. The same category of sensor, which is presented in Fig. 1, is considered in the present study, as applied to measure strains in metallic specimens.



(a) (b)

Figure 1: (a) Illustration of a CNT fiber in a spool; (b) scanning electron microscopy of the CNT fiber (Abot *et al.*, 2014).

2. FIBER LAMINATION

In order to enable the installation of the CNT sensor to surface of the specimen to be monitored, the fiber was laminated with the commercial epoxy resin Araldite® Professional, manufactured by Tek-Bond®, as illustrated in Fig. 2. One of the objectives of the present study is to evaluate the process of lamination and its influence on the sensor performance, since the CNT yarn and the resin will be mechanically coupled. It should be noticed, however, that a single type of resin is considered here; the evaluation of different types of resins and their interactions with the CNT yarns are not in the scope of the research presented here.

This particular type of resin was chosen since it has a slow curing process, thus facilitating eventual adjustments during the fiber placement over the specimen. Table 1 presents the physical-chemical properties of the resin.

Table 1: Araldite® Professional specifications

Specifications	Resin	Hardener
Viscosity at 25ºC	30.000 to 50.000 cps	20.000 to 35.000 cps
Mixture relation in volume	100:100	
Mixture relation in weight	100:80	
Time for handling	60 minutes	
Time for initial curing process	90 minutes	
Time for complete cure	24 hours	
Application temperature	+5 to 35 ℃	
Work temperature	-30 to +80 ℃	
Shear strength	120 kgf/cm²	

Figure 2(a) illustrates the specimen, consisting of a plate made of Aluminum 2024 – T761 of 2.3 mm of thickness and dimensions of 127 mm of length by 381 mm of height, on which the CNT fiber sensors have been attached. Figure 2(b) shows two fibers laminated on the plate: one fiber was installed in the center of the plate (between two holes at 190mm from the corner of the plate) and the other was installed in a remote position on the plate, at 127mm from the middle of the plate. The process of lamination is manual and the length of the fiber for sensor was adopted as 20 mm ± 5 mm. All the connectors and wirings have been assembled during the lamination process. Table 2 describes the phases followed for the surface preparation and sensor installation over the plate.

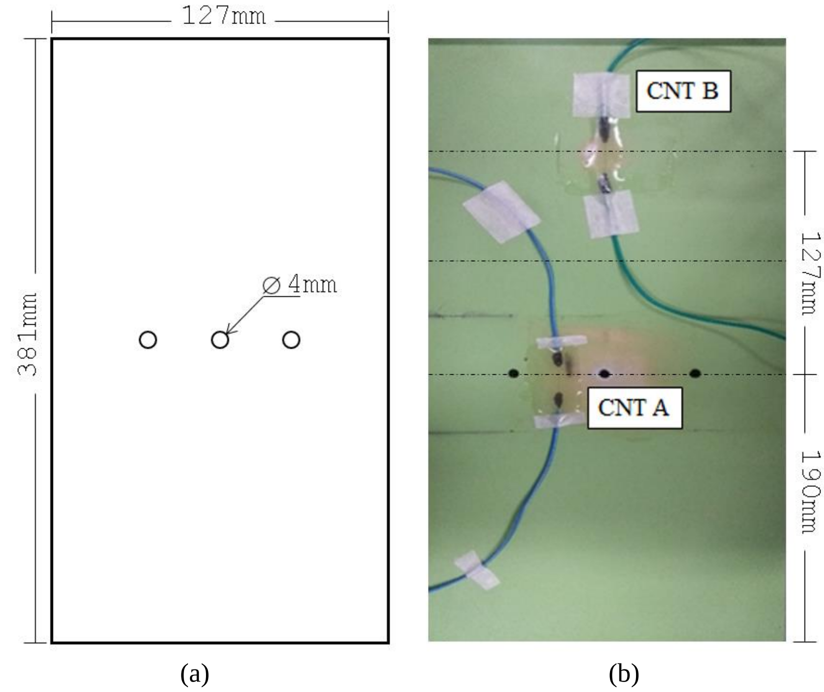


Figure 2: (a) – Illustration and dimensions of Al 2024 T761 plate- thickness of 2.3mm; (b) CNT fibers laminated on an Al 2024-T761 plate.

Table 2: Resin epoxy sensor manufacturing steps

Steps	Process	Comments
Step 01	Surface preparation	With a sandpaper with roughness between 200 and 300, remove the protective layer from metallic sheet until the exposition of the metallic surface. Clear the region with a fabric and alcohol.
Step 02	Protective layer application	Apply a thin layer of resin over the region already cleaned and let dry until complete cure as specified in Table 1.
Step 03	Application of CNTs	Apply the fiber over the structure, gluing the tips with cyanoacrylate (or another fast curing glue) to maintain the CNT fiber in place during the process. Make sure the fiber is installed with a small pre-load[1].
Step 04	Connector and wiring installation	The connection between CNT fiber and wires for acquisition system is done with silver glue. Apply the silver glue on fiber and wire tips, and put both together until complete cure of silver glue[2], which takes about 24 hours. Use a scotch tape to hold the wires in position during curing process.
Step 05	Final layer application	After all curing processes, both protective layer and connection wiring are completely fixed to the surface. The last layer, responsible to fix the CNT fiber to the surface should be applied. This layer will protect the connector ends, since silver glue has limited strength.

[1] This pre-load was not controlled since installation is manual and, because of that, it is impossible to apply always same load.
[2] The silver glue has no mechanical strength, providing only electrical connection.

3. TEST SETUP

Quasi-static tests were carried-out using a MTS testing machine with load control on six plates (main dimensions shown in Fig. 2(a)), with two points of fiber lamination showed in Fig. 2(b), one in a remote position named “CNT B” and another in the middle of the plate , between holes, called “CNT A”. The steps and details of the tests are given in Table 3. These steps were repeated four times for each specimen. Figure 3(a) depicts a sample mounted on the testing machine.

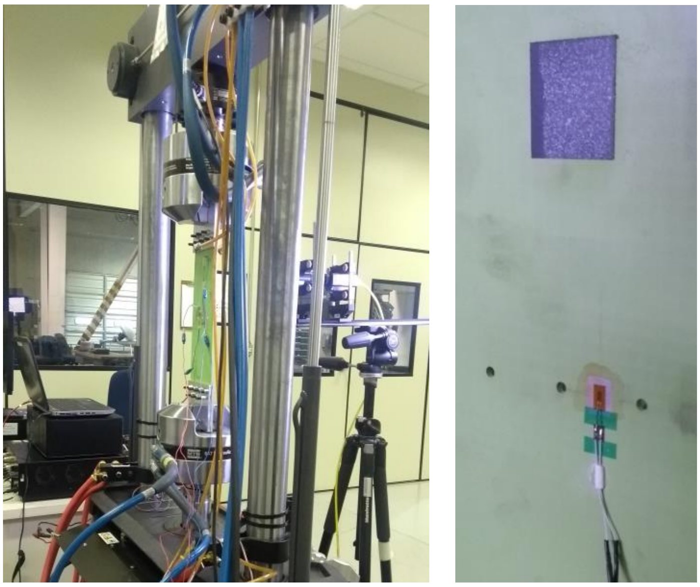
Table 3 - Steps and details of static tests

Samples:	6	
Number of repetitions:	4	
Period between repetitions:	Approx. 2 minutes	
Step	**Load value [kN]**	**Time**
Loading	0 to 20	2 minutes
Hold	20	15 seconds
Unloading	20 to 0	2 minutes

Two other techniques of strain measurement methods were used for comparison with the measurements provided by the carbon nanotube fiber sensors, as shown in Fig. 3(b). A 6mm × 2.7 mm Y-type electrical resistance metallic foil strain-gauge was placed in the middle of the plate, positioned at same location as CNT A, but on the opposite side of the plate, and a video gauge was directed to a remote region, on the opposite side of the position of CNT B, as it was not feasible to focus the video gauge on the same region where the two other sensors were installed. The video gauge measured the displacement of the pixels with respect to a baseline image of a region prepared with special painting.

A National Instruments acquisition board and a Labview routine were used as the acquisition/signal processing system. The NI9219 board is a four-channel module designed for multipurpose testing in any NI CompactDAQ or CompactRIO chassis. The modulation chosen for the carbon nanotube fiber measuring was the half-bridge, with pin-out showed in Fig. 4, where the connections are numbered 3 and 5.

Since the resistance values of the CNT fiber are typically very high, high resolution measurements are necessary to enable to capture the variations of the fiber resistance. The acquisition rate was setup to 2 Hz, which provides the resolution necessary to capture the variations in CNT fiber resistance.



(a) (b)

Figure 3 - (a) Illustration of experimental setup; (b) Details of the metallic foil strain-gauge and video gauge sensors

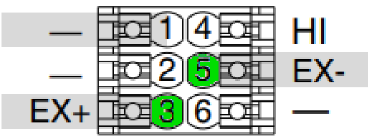
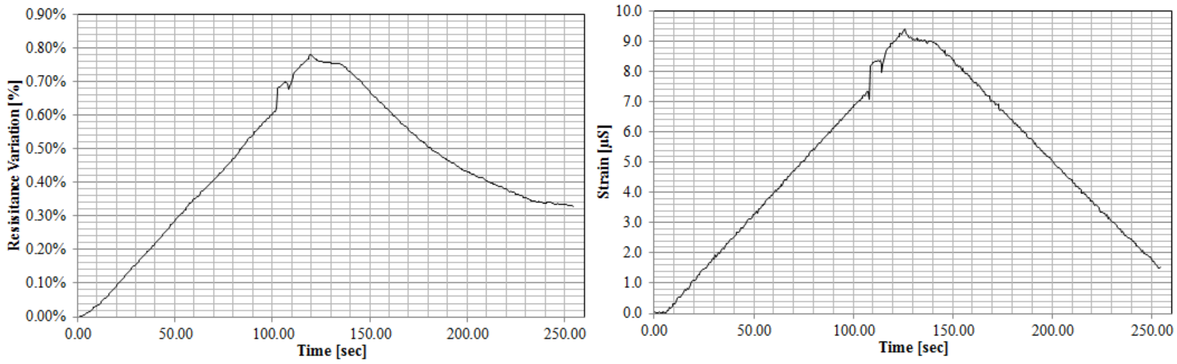


Figure 4 – Half-bridge pin-out

4. RESULTS

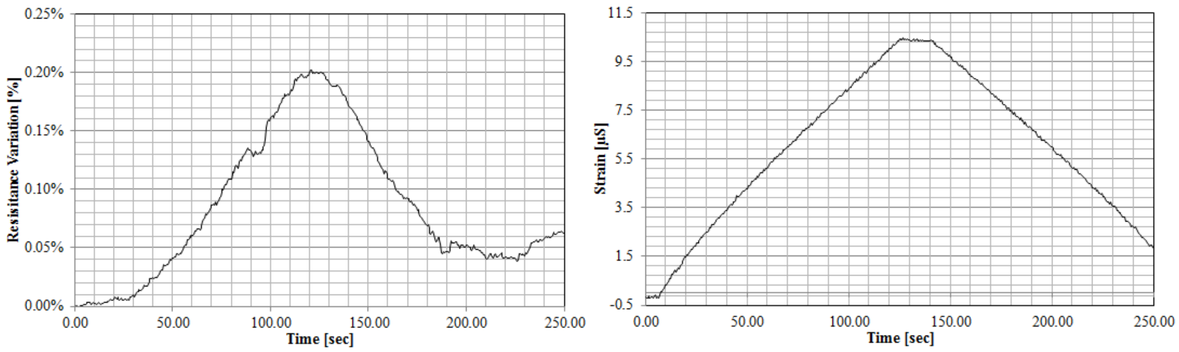
Figure 5 shows the measurement results obtained with CNT A fiber sensor and the metallic foil strain-gauge, after processing of the raw acquired data, for one of the tested specimens, identified as #3. It can be seen that measurement results is very similar to each other, demonstrating good sensitivity of the CNT fiber sensor. Both results show abnormal measurement variations at the end of the load phase, which are due to slippage of specimen with respect to the machine grips.



(a) (b)

Figure 5 – Measurement results for specimen #3: (a) CNT A; (b) metallic foil strain-gauge.

It should be noticed, however, that the behavior of the CNT fiber sensor is highly dependent on the lamination and installation process. Figure 6 shows a comparison, similar to that presented in Fig. 5, obtained for other tested specimen, identified as #2, demonstrating the variability of the measurements obtained from CNT A.



(a) (b)

Figure 6 – Measurement results for specimen #2: (a) CNT A; (b) metallic foil strain-gauge.

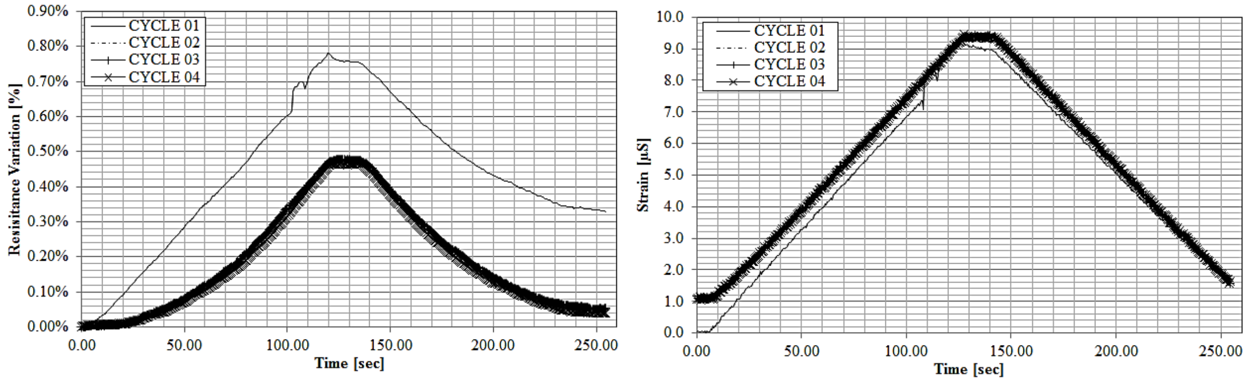
Since the most stable and coherent results were obtained from specimen #3, all discussions that follow will be based on tests performed on this specimen.

In order to evaluate the stability of the measurements, specimen #3 was subjected to four successive loading-unloading cycles. The idle time between two consecutive cycles is about 2 minutes, used to save the data and restart the machine for the next cycle.

Figure 7 illustrates the results obtained from CNT A, together with those obtained from the metallic foil strain-gauge, while Fig 8 enables to compare the results obtained from CNT B and those provided by the video gauge. Both results are displayed considering relative values of resistance variations, which means that, for each loading cycle, the variations are computed with respect to the value of the resistance at the beginning of the respective cycle.

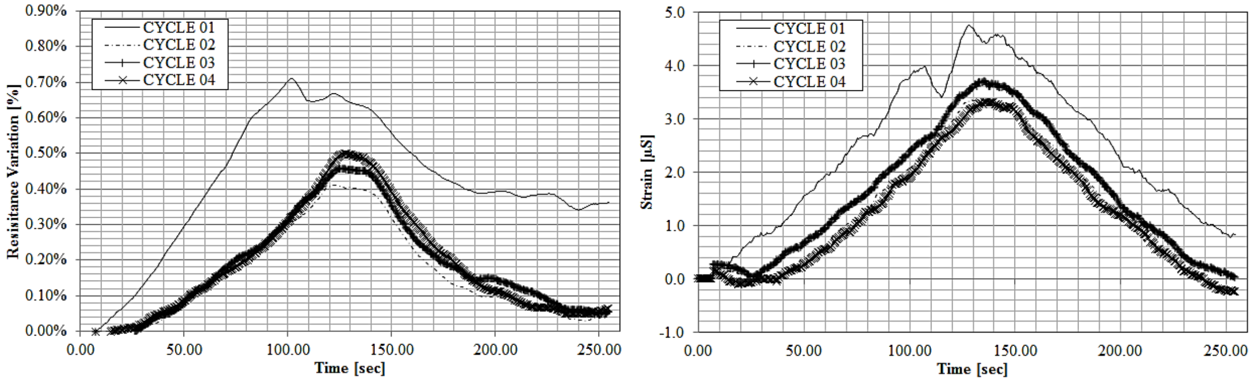
It should be noticed that, since the results obtained from the video gauge measurements were shown to be strongly affected by measurement noise, a noise-cleaning numerical process had to be applied to them before plotting.

The results presented in Figs. 7 and 8 show that: a) the behavior of CNT fiber sensors indicates the occurrence of accommodation, as the measurements associated to the first loading cycle differ substantially from those of the following cycles. Nonetheless, most of the accommodation of the CNT fiber sensors occurred during the first loading cycle; b) the stability of the CNT fiber sensor measurements is inferior to that of the metallic foil strain-gauge but is comparable to that of the video gauge; c) the behavior of the CNT fiber sensors during monotonic loading and unloading is shown to be nonlinear after accommodation, which makes calibration difficult.



(a) (b)

Figure 7 – Measurement results for specimen #3 for four loading-unloading cycles: (a) CNT A; (b) metallic foil strain-gauge.

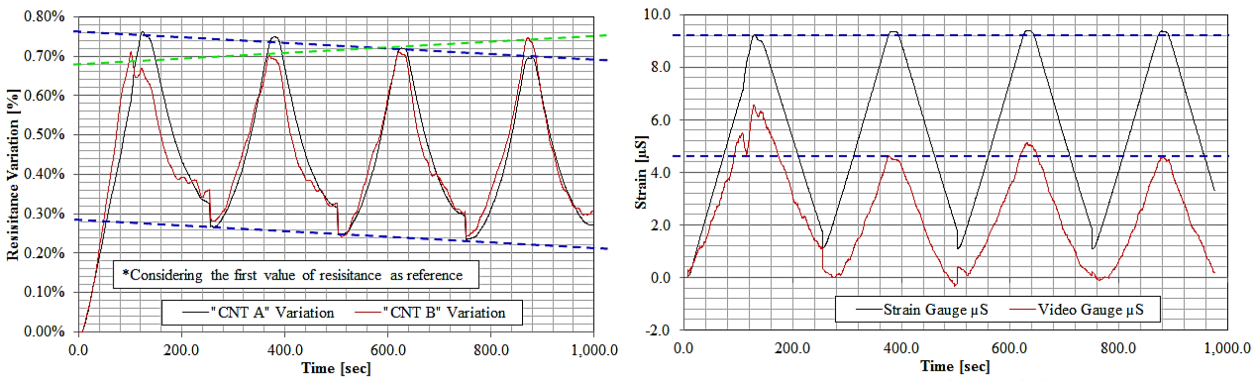


(a) (b)

Figure 8 – Measurement results for specimen #3 for four loading-unloading cycles: (a) CNT B; (b) video gauge (after noise filtering).

In order to better characterize the behavior of the measurements obtained from the three measurement techniques during cyclic loading, the results shown above are presented in continuous time in Fig. 9 (the 2-minute idle times between cycles have been excluded). For both CNT A and CNT B fiber sensors, the resistance variations were calculated with respect to the initial value of the resistance, measured at the beginning of the first loading cycle. It should be noticed that, since the reference for computation of the resistance variation is not the same as that used for computing the results shown in Figs. 7 and 8, the variations appear to be smaller in Fig. 9. To facilitate the observation of the trends, the maximum measurement values in each cycle are connected by the blue and green lines for CNT A and CNT be, respectively.

Figure 9(a), once more, illustrates the accommodation exhibited by the two CNT fiber sensors.



(a) (b)

Figure 9 – Measurement results shown in continuous time.

Comparing Figs. 9(a) and 9(b), it is noticed that the differences between metallic foil strain-gauge and video gauge measurements are much larger than that between CNT A and CNT B measurements. This is attributted to the variations of sensitivity of the CNT fiber sensors provoked by the manual lamination and installation of the two sensors.

Figure 10 illustrates the resistance variations of CNT plotted against the corresponding values obtained from the metallic foil strain-gauge (the first loading cycle has been removed), showing the occurrence of nonlinear behavior and accommodation of the sensor.

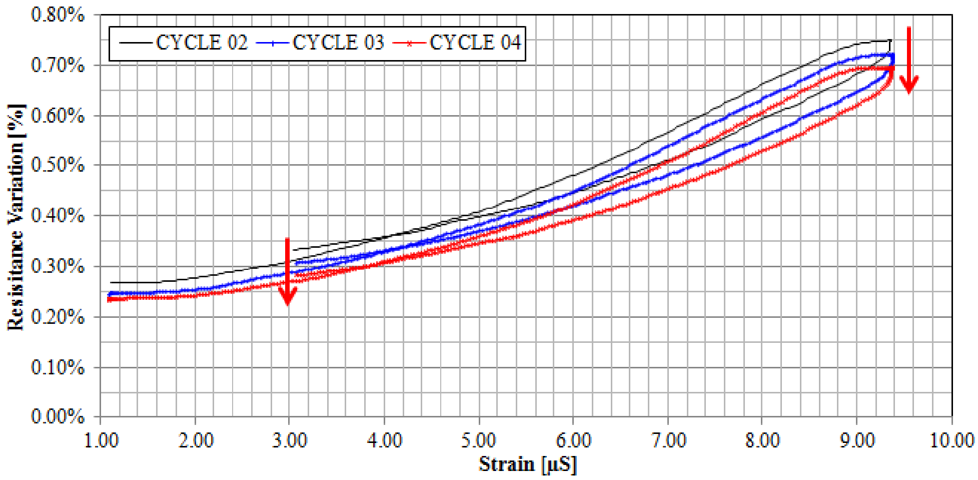


Figure 10 – Resistance variation of CNT A versus strain measured with the metallic foil strain-gauge.

5. CONCLUSIONS

This work describes the investigation of the behavior of a carbon nanotube fiber sensor manufactured with a carbon nanotube fiber impregnated within an epoxy resin as applied to the measurement of strains on metallic plates.

Confirming previous studies in which these sensors were tested as applied to polymeric materials, this investigation shows the potential of the CNT fiber sensors for structural monitoring, especially due to its high piezoresistive sensitivity and little intrusiveness.

The experimental results show that, from the qualitative standpoint, the CNT sensor are capable of reproducing, with satisfactory agreement, the measurements obtained from other traditional strain measurement techniques, especially metallic foil strain-gages. However, the occurrence of nonlinear behavior and the lack of repeatability, observed in the data, makes it difficult the use of the CNT sensor for quantitative measurements of strain.

It should be considered, however, that the difficulties mentioned above could have been, at least partially, induced by the manual lamination and installation process of the sensors on the specimens, which makes it difficult to control certain parameters that can exert influence on the sensor behavior, such as preload and thickness of the resin layer. In addition, influences can be exerted by some features of the manufacturing process of the CNT fiber, such as the twisting angle (Anike *et al*., 2019). Hence, further research is necessary aiming at improving the behavior of the CNT sensors as used for quantitative strain measurements, by controlling the inherent features of the CNT fibers and the lamination and installation process.

6. ACKNOWLEDGEMENTS

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