Strain and Temperature Sensing Properties of Multiwalled Carbon Nanotube Yarn Composites

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Abstract

Strain and temperature response of Multiwalled Carbon Nanotube (MWCNT/CNT) yarns on a stainless steel test beam has been studied. The carbon nanotube yarns are spun from a multiwalled carbon nanotube forest grown on a silicon substrate to a 4-ply yarn with a diameter of about 15-20 μms. Four of the 4-ply CNT yarns are arranged in a Wheatstone bridge configuration on the stainless steel test beam using a thin layer of polyurethane resin that insulates and protects the yarns from the test beam. Strain sensitivities of the CNT yarn sensors range from 1.39 to 1.75 mV/V/1000 μstrain at room temperature, and temperature sensitivity of the CNT yarn bridge is 91 μA/°C. Resistance of the yarns range from 215 to 270 ohms for CNT yarn length of approximately 5 mm. Processes used in attaching the CNT yarns on the test beam and experimental procedures used for the measurements are described. Conventional metallic foil strain gages are attached to the test beam to compare with the CNT sensors. The study demonstrates multifunctional capability of the sensor for strain and temperature measurements and shows its applicability where engineering strain is less than 3%.

KEY WORDS : Sensor Technology, Nanotechnology, Nanocomposites

1. Introduction

1.1 Background

Conventional metal foil strain gages are widely used because they are sensitive, stable, low-cost, and easy to use. These strain gages are used to measure surface strain on the structure as a single function sensor. There is a need to develop new types of sensors that not only measure strain (both on and below the surface) but also perform an additional structural enhancement function. This makes the sensor a non-parasitic multifunctional device. There are a number of papers published about carbon nanotube composite sensors and the associated multifunctional features [1-4]. These papers report new findings about carbon nanotube composites and their responses to mechanical stress/strain. Recently strain sensing with a multiwalled carbon nanotube film has been reported [5]. However, there has not been any report of carbon nanotube yarn sensors for measuring both strain and temperature simultaneously.

This paper describes the development of a carbon nanotube yarn composite multifunctional sensor capable of measuring strain and temperature simultaneously. Multiwalled Carbon Nanotube (MWCNT/CNT) yarns are selected for this multifunctional sensor because they can be processed utilizing existing fabrication facilities/processes without downgrading the structural integrity of the host structure or system. The yarn composite consists of polyurethane (Ren 6401 or Ren 6405) and aligned 4-ply CNT yarns forming a Wheatstone bridge; this composite structure is placed on both sides of a stainless steel test beam that is used as a cantilever beam with free end loading.

A number of CNT [6] yarns of roughly 10 nm diameter are simultaneously drawn from a CNT forest on a silicone substrate and twisted at typically 20,000 turns/m. The yarn diameters varied from 2 to 10 μms and were set by controlling the width of the forest sidewall that was used to form an initial wedge-shaped ribbon. Yarn strengths have been reported up to 460 MPa for 2-ply yarns, which have diameters from 2 to 10 μms, electrical conductivity of ~300 S/cm at room temperature, and a negative Temperature Coefficient of Resistance (TCR) of ~ –0.1 Ω/C.

Figure 1a shows a yarn pulling nanotubes away from the multi-walled carbon nanotube forest substrate, while twisting at a rate of 20,000 turns/m clockwise. Figure 1b is an SEM picture of a single yarn. A 4-ply yarn is then plied from four of these single yarns, twisted together counter clockwise at a rate of 4,000 turns/m, as shown in Figure 1c. Diameters of these 4-ply yarns are about 15-20 μms, and the yarns consist of multi-walled carbon nanotubes approximately 300 μms long. This work uses 4-ply yarns because they are less prone to damage than single yarns during the subsequent processes.
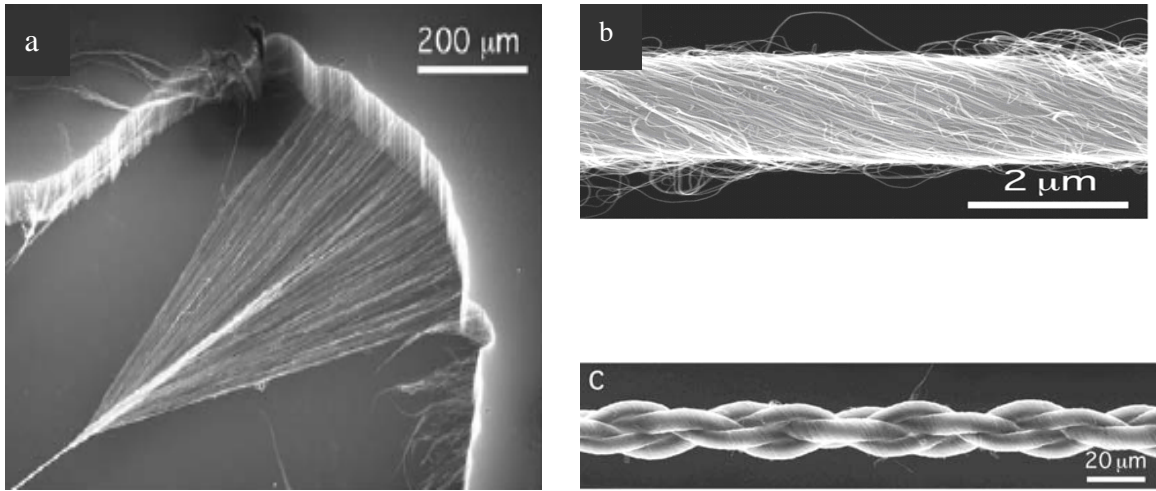

Figure 1: A carbon nanotube yarn is twist-pulled from vertically aligned multiwalled carbon nanotube forest on a silicone substrate in Figure 1a. Figures 1b and 1c are photomicrographs of a single yarn and a 4-ply yarn, respectively. (Courtesy of NanoTech Institute, University of Texas at Dallas)

Use of the CNT yarns for strain sensing assumes that the limit of engineering strain is within 3% and Hooke's law is valid within the specified strain level. Dog bone shape test specimens were prepared with five 4-ply yarns embedded in silicone rubber (GI-1000),

with 1 mm spacing, aligned lengthwise, and with an active region of 25 mm × 6 mm × 0.25 mm (as shown in Figure 2).
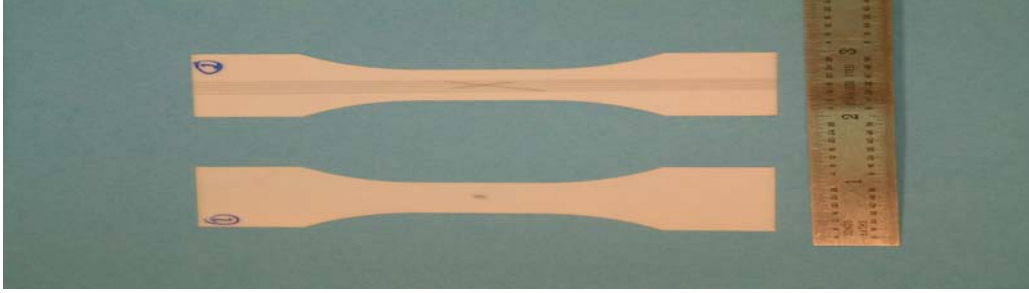

Figure 2: A typical dog bone shape test specimen is shown with overall length of 85 mm and thickness of 0.25 mm. The top figure shows 5 CNT yarns embedded along the entire longitudinal direction of the specimen. The active region of the specimen is 25 mm × 6 mm × 0.25 mm. The bottom part of the figure is a specimen without yarn.

It has been reported that the yarns in composite specimens fail catastrophically at strains exceeding 5% [7, 10]. Static loading tests of the dog bone test specimens indicate that the modulus of the specimen is nearly constant up to 3% strain as shown in Figure 3a. The stress-strain responses are nearly repeatable for 50 cycles. Figure 3b shows the 5-yarn composite specimen under Dynamic Mechanical Analysis (DMA) test for force reaching up to 0.35 N, at rate of 0.25 N/min for 50 cycles. The cyclic stress-strain responses show a degree of hysteresis and the specimen stabilizes at a strain value of 0.75% extension from the original length. Further investigation is needed to determine this hysteresis effect with an increased number of cycles. These experiments suggest that the use of the CNT yarn composite strain sensor is limited to 3% strain, and application of these sensors to strain levels exceeding 3% is not recommended.

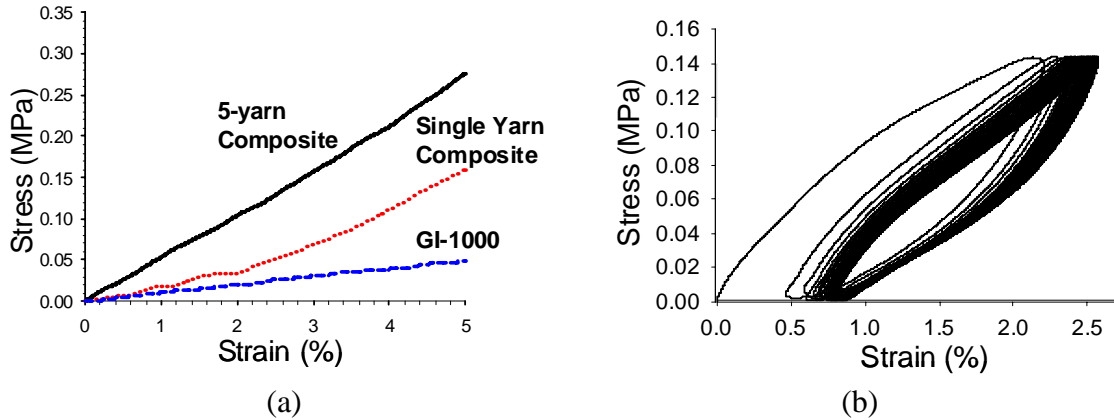(a)   (b)

Figure 3: Figure 3a shows Engineering Stress-Strain response of the 5-yarn composite dog bone shape specimen, that of single yarn and the GI-1000 silicone rubber. Figure 3b shows the dynamic mechanical analysis tests of 50 cycles of a 5-yarn with GI-1000 specimen.

2. Experimental

2.1 Multifunctional Strain and Temperature Sensing

To evaluate the strain and temperature sensing property of the CNT yarns, the yarns are embedded on the surface of a stainless steel (17-4PH) cantilever test beam, using polyurethane as an embedding composite material. The stainless steel test beam is 20.32 cm long, 2.54 cm wide and 0.318 cm thick. The yarn is placed in a Wheatstone bridge configuration, while the stainless steel cantilever beam is loaded in simple bending with known loads. The bridge output voltage is then recorded and compared against conventional metal foil strain gages placed on the same test beam. The temperature of the yarns is observed by the bridge current (or voltage drop across the external temperature monitoring 100 ohm resistor) on an external series resistance to the bridge. A multi-channel data acquisition unit (Keithley 2700) is connected to the outputs from the bridge (V) and temperature monitoring resistor. Figure 4 depicts the general set up for the measurement arrangements used.
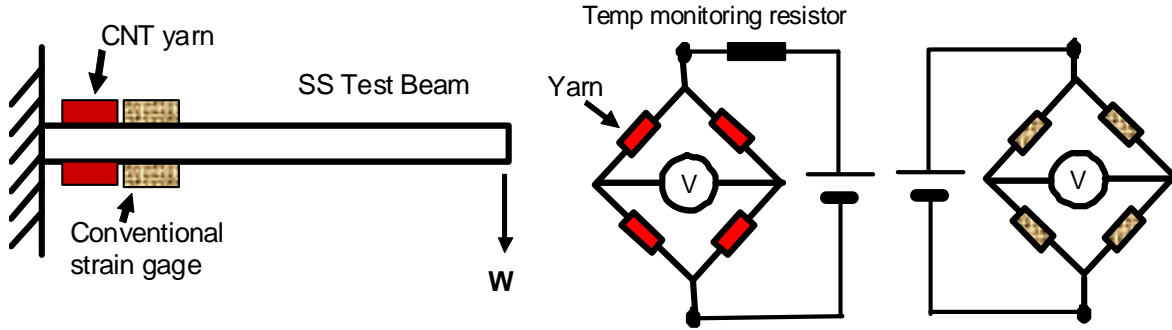

Figure 4: A stainless steel test beam is instrumented with CNT yarns and metal foil strain gages to form two Wheatstone bridges. A set of known weights is applied at the free end of the cantilevered test beam. "V" in the yarn bridge is connected to the Keithley 2700 unit.

A set of four CNT yarns is placed on both sides of the test beam, forming a Wheatstone bridge. Necessary electrical wires are placed on the electrodes on a polyimide sheet that is also used to place the yarns. The polyimide sheet has patterned copper thin film electrodes. The sheet is bonded to a stainless steel beam using a strain gage bonding adhesive (M-610). The CNT yarns are connected to the copper electrode on the polyimide sheet with a Cotronics silver epoxy and the yarns are then covered with polyurethane. Bonding and polyurethane preparation procedures are followed based on the manufacturer's instructions. Figure 5a shows two views of the yarns and test beam. Figure 5b is a picture of the yarns on the test beam covered with Ren 6405 polyurethane. Four pieces of polyimide sheet with copper electrode are used instead of one sheet to minimize unwanted mechanical interference between the four yarns on a single sheet. The dotted line in Figure 5b represents the location of one of the four yarns on the top side of the test beam.

Cross sectional view of the SS test beam

Top side

Bottom side

: CNT yarn

: Silver epoxy

: Cu electrode

Top side half view of the SS test beam

: Polyimide sheet
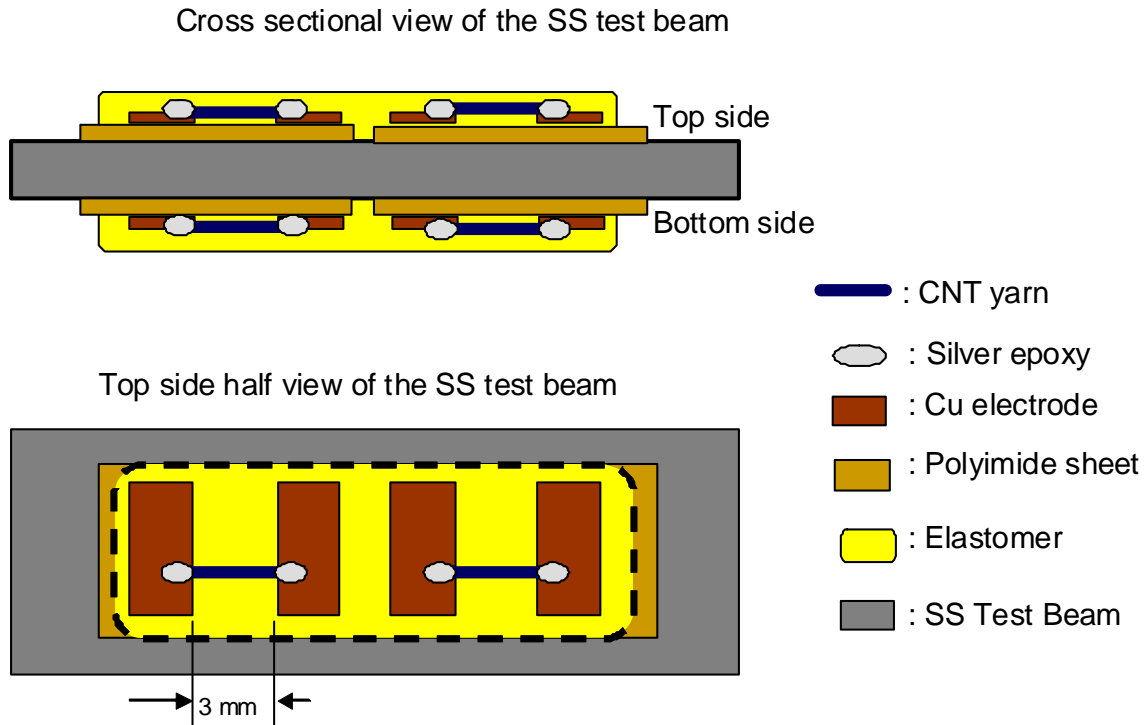
: Elastomer

: SS Test Beam

3 mm

Figure 5a: This figure shows part of the cross sectional and top views of the test beam. Top view shows only two yarns (half view).
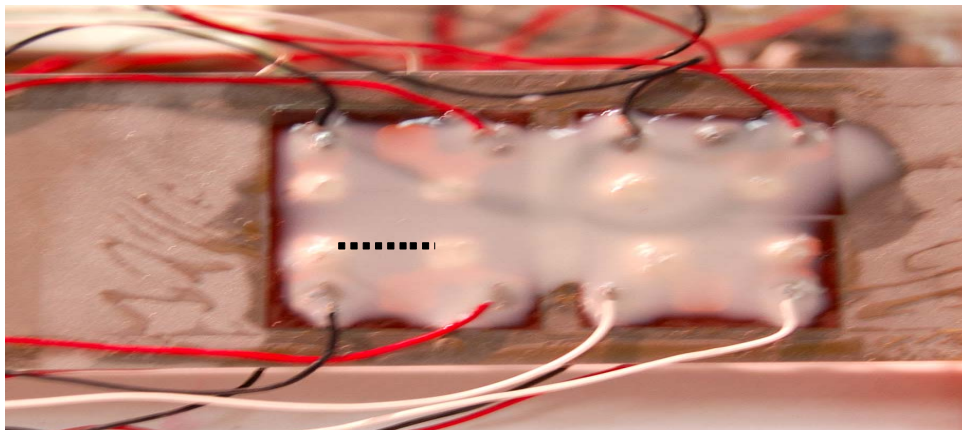

Figure 5b: Photograph of a test beam that shows polyimide sheets placed on the test beam, CNT yarns with silver epoxy, and Ren 6405 covering the yarns. Four yarns are installed on the test beam, a dotted line shows where CNT yarn is placed with silver epoxy.

Strain responses of the test beam with the yarn composite sensor are obtained on a static loading arrangement with a maximum load of 2.265 kg (5 pounds). Strain at the maximum load is also calculated and measured at 536 µstrains. Output voltages from the Wheatstone bridge on the test beam are recorded on a personal computer using a Keithley 2700 data acquisition unit and Keithley-provided ExceLINX data logging software. Input voltage to the bridge is limited to 30 mV to keep the yarns well within the maximum current density limit. All experiments were carried out at electrical current no higher than 100 µA for a 4-ply yarn. Figure 6a shows the strain response of the yarns on the test

beam. This set of data agrees with those taken earlier [8, 9] using different types of composites, namely GI-1000 and CF-95 as reported.

The sequence of loading is from zero to 2.265 kg (5 pounds) with an increment of a 0.453 kg (1 pound), returning to zero after each incremental loading and measurement. All 5 non-zero points and all 6 zero points in Figure 6a are averaged over 5 measurement readings. Strain sensitivity of 1.6 mV/V/1000 μstrain has been obtained, and it is noted that the bridge current was limited to 100 μA maximum per yarn.

Strain values obtained from the CNT yarn composite sensor, from calculations, and from measurements using conventional metal foil gages are plotted in Figure 6b. Both calculated and measured strain–load plots have nearly identical slopes, but the slope of the CNT yarn composite sensor is lower than that of the calculated curve. Loading weights were used to base the reference points because the strain gage measurements and calculations were made using these weights. The strain values from the CNT yarn composite sensor were read from the regression curve of the Figure 6a.
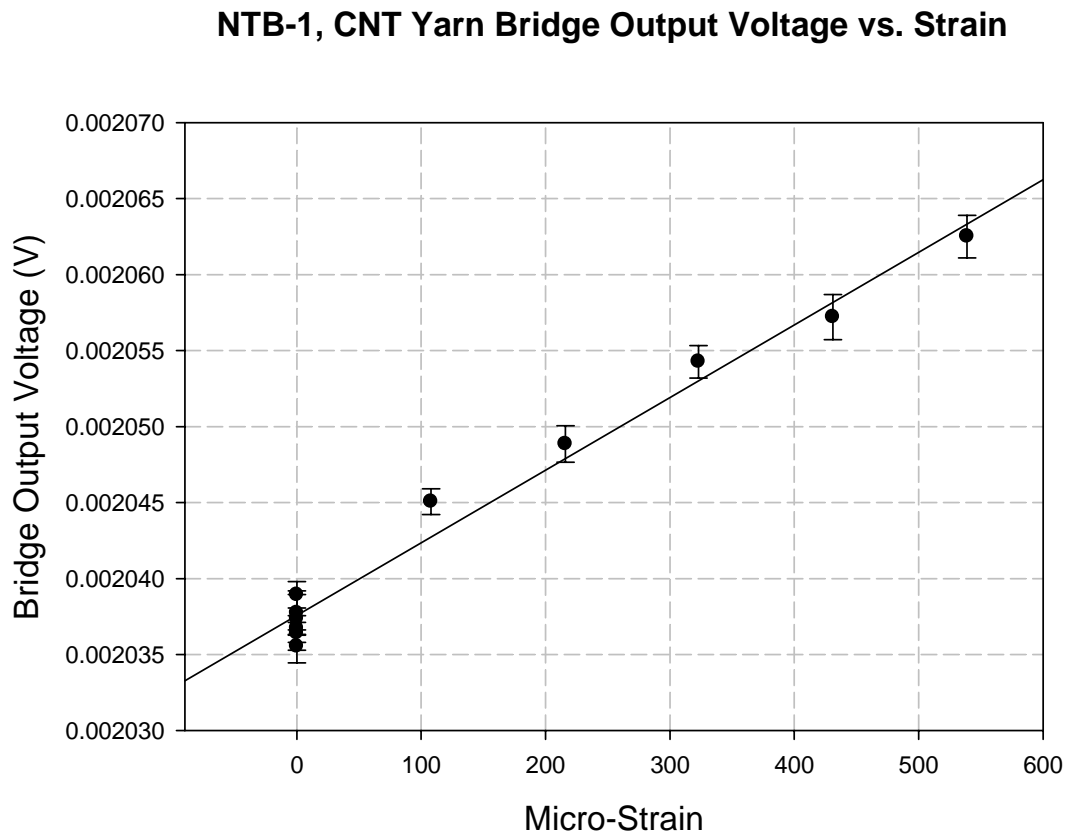
NTB-1, CNT Yarn Bridge Output Voltage vs. Strain

Figure 6a: Response of CNT yarn bridge output voltage of the test beam

Comparison of Strain Vaules from Calculation, Strian Gage Measurements, and CNT Yarn Composite Sensor Plot
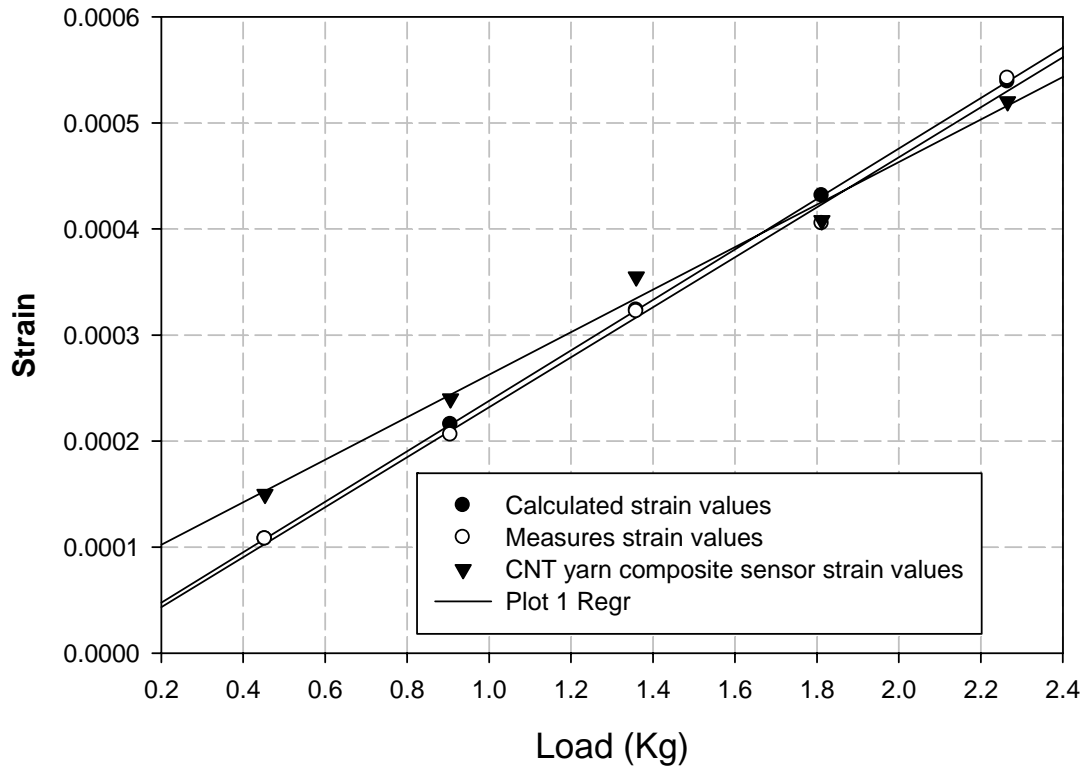

Figure 6b: Strain values from the CNT yarn composite sensor (Figure 6a), the strain measured with conventional strain gages, and that calculated are compared over the load ranges from 0 to 2.26 kg (5 pounds).

Temperature response of the test beam is made in a thermal chamber using the same data acquisition system (Keithley 2700) as used for the strain measurements. Figure 7a shows output voltages from the bridge output that are nearly temperature invariant as the temperature is varied from –50 to +50 ℃. The bridge current is increasing with temperature (see Figure 7b). This increasing trend of the bridge current is a reflection of negative temperature coefficient resistance of CNT yarns that is –0.1 $\Omega/℃$, as cited earlier. The bridge current shown in Figure 7b is a sum of two currents on the parallel paths on the test beam and the each path has two yarns in series.

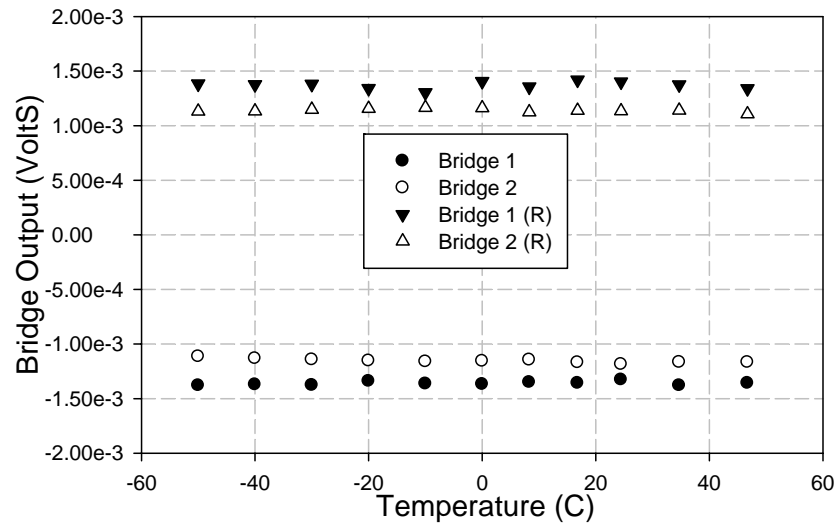**NTB-1, Bridge Output Voltage vs. Temperature
(with No Load)**

Figure 7a: Voltage outputs from the bridge as a function of temperature without load. The output voltage is nearly constant over a temperature range from -50 to +50 ºC. The figure shows four bridge outputs from the test beam under evaluation.

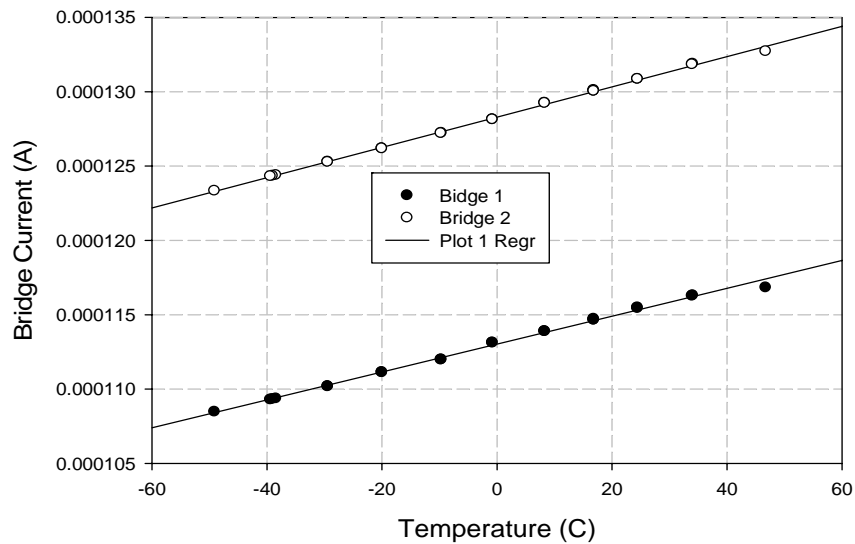**NTB-1, Bridge Current vs.Temperature**

Figure 7b: The bridge current measured from the external temperature monitoring series resistor to the bridge over the same temperature range. The electrical current is less than 100 µA for each yarn.

The strain and temperature measurements are made simultaneously by reading strain data from the Wheatstone bridge outputs and temperature data from the external current monitoring resistor. Within engineering strain values of 3%, it has been demonstrated that the CNT yarn composite sensor has a multifunctional sensing capability of measuring strain and temperature simultaneously. In most aerospace structural sensing applications, engineering strain values are well within 3% and the CNT yarn composite sensors provide promise for multifunctional sensing applications.

3. Conclusions and Discussions

We have studied carbon nanotube yarn composites as sensors for simultaneous sensing of strain and temperature. A CNT yarn composite Wheatstone bridge configuration is used on a stainless steel test beam for strain measurements and an external resistor is used for temperature measurements of the bridge. Measurement of strain and temperature are made simultaneously with the CNT yarn composite sensor and strain from a conventional metal foil strain gage.

Recent developments in fabrication technology of carbon nanotube yarns and fibers introduce a promising future for using carbon nanotube yarns, these yarns form macroscopic scale sensors that are relevant to realizing multifunctional measurements and structural enhancement functions. Bogdanovich and Baughman [11] have demonstrated that 3D micro-braids can be made solely of continuous carbon nanotube yarns and used as reinforcement for composites. 5-ply multi-walled carbon nanotube yarns are plied to 25-ply yarns. Fabrication of a 3-D braid to 36 five-ply woven yarns for structural enhancement is also demonstrated. This enhancement could lead to a third function in addition to temperature and strain sensing.

The glass transition temperature of the base composite material needs to be improved to higher values (> 200 °C) for compatibility with practical environments. Composites of glass fibers and carbon fibers are more desirable than the currently used polyurethanes. For conductive carbon fibers, electrical insulation of the yarns can be achieved with the use of glass fibers as a layer of insulating material.

5. References

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