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Experimental evaluation of Coefficient of Thermal Expansion of Carbon Fiber Reinforced Polymer tube

Shubham V. Rupani[1*], Rahul Dev[2], Shivang S. Jani[3], Dr. G.D.Acharya[4]

[1]*PG scholar, Atmiya Institute of Technology and Science, Rajkot, Gujarat.*
[2]*Scientist/Engineer, Space Application Center, Ahmedabad, Gujarat.*
[3]*Assistant Professor, Atmiya institute of Technology and Science, Rajkot, Gujarat.*
[4]*Principal, Atmiya Institute of Technology and Science, Rajkot, Gujarat.*

Abstract : *Carbon fiber reinforced polymer is used in structural application due to its unique characteristics like high strength to weight ratio, high stiffness, low conductivity and negative or near zero achievable coefficient of thermal expansion. In applications where structural components are subjected to wide range of temperature changes, deflection of members due to thermal effect is unavoidable. Specifically truss structures need to be designed in such a way that overall deflection of structural member between end connections is nearly zero. Most metallic materials expands with increase in temperature and hence have positive CTE. To compensate this positive deflection of metallic end connection, struts made of carbon fiber reinforced polymer are desired to have negative CTE. In this paper, experimental evaluation of CTE is presented for two different test specimens. Deformation of tube with respect to temperature changes is measured and based that CTE is calculated. Fiber material properties and laminate layup definition have significant effect on overall CTE of tube specimen.*

Keywords: *Coefficient of thermal expansion, CFRP, composite tube, Experimental method, CTE measurement*

I. INTRODUCTION

The coefficient of thermal expansion (CTE) is defined as the fractional change in length per unit change in temperature[1]. Measurement of the CTE is carried out by measuring the change in dimension and the accompanying change in temperature. Thus given two measurements of the linear dimension of a sample, L_1 and L_2 made at temperature T_1 and T_2 the mean CTE over the temperature range T_2-T_1 is given by[2]

$$\alpha = \frac{L_2 - L_1}{L} \frac{1}{T_2 - T_1} = \frac{\Delta L}{L \Delta T}$$

where L = length of sample at given reference temperature
ΔT = change in temperature of sample
ΔL = change in length of sample corresponding to change in temperature

According to international standard ISO all the measurements are to be performed considering 20°C as reference temperature. This means that for all precise dimensional measurements, correction are to be applied, if the measurements are not carried out at 20°C, taking into account the thermal expansion coefficient of work piece to be measured[3]. For applications such as space borne payload structure, composite materials are used to achieve thermally stable structure with minimum weight. Composite materials can be tailored to achieve negative or near zero CTE in specific temperature range[4][5].Researcher have used optical positioning sensor to develop automated CTE measurement systems[6]. Interferometry is the most widely used method for CTE measurement[7][8][9].Use of Linear Variable Differential Transformer (LVDT) facilitate fast and simultaneous measurement of multiple test specimens[10].Measurement of CTEmay be represented as generalized dilatometer system. The four main components required are as follows[2].

1. A means for sensing ends of the specimen. This may be mechanical contact type gauges.
2. A measurement system for detecting and measuring the change in length. In general practice LVDT, laser interferometry etc. can be used.
3. A structure system or frame that position the components relative to sample. The structure can be C frame of simply V block.
4. A method of changing the temperature of the sample. Electric heater, furnace or cooler can be used.

II. SPECIMEN PROPERTIES

In this study two test specimen are tested. One is made from high strength and moderate modulus fiber T700S and another is made of high modulus fiber M60J. Huntsman XB4532/Aradur 5021 resin system is used as matrix material.Laminate configuration is quasi-isotropic $[0,60,-60,-60,60,0]_{2s}$ for both specimen. Specimen is manufactured third party manufacturer by fabric winding process.

III. TEST SETUP

Measurement of coefficient of thermal expansion is performed in closed room. Electric heater is wound around outer surface of the tube and bonded with conductive film adhesive. Power is supplied with variable voltage DC power source. Deformation of the tube due to temperature changes is measured by LVDT.

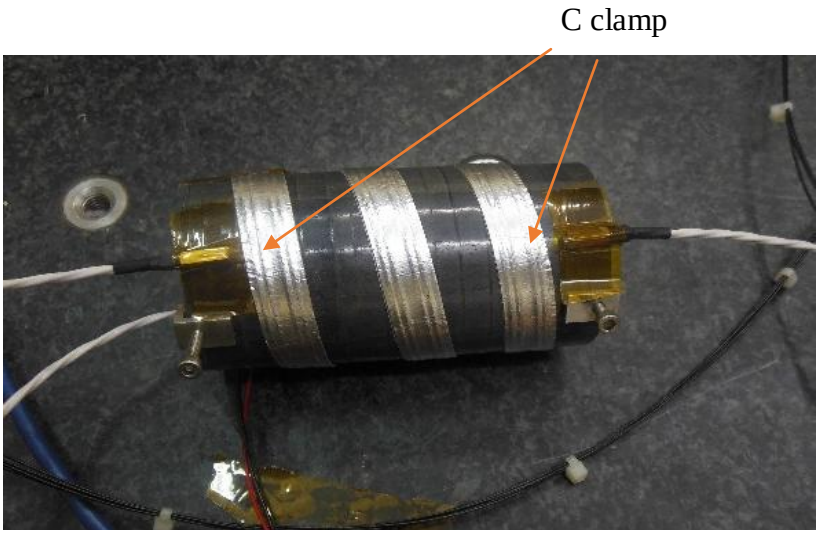

Figure 1 : Specimen Preparation

To avoid friction between touch probe of LVDT and rough end surfaces of tube, C clamps made of Invar are attached at two ends of the tube as shown in fig 1.
LVDTs are mounted on reference bar made of zerodur. As zerodur has nearly zero CTE, deflection of LVDT due to temperature change is minimized[4]. Resistance temperature detectors are attached on specimen to measure temperature. As heater is wound on outer surface of the tube, resistance temperature detectors (RTD) on inner surface at midway is considered to represent overall temperature of tube. Specimen is rested on V block and allowed to expand freely when heated.

IV. DATA ACQUISITION SYSTEM

A real time data acquisition system is required to continuously monitor temperature and deformation readings. To acquire readings of deformation of tube measured by LVDT, milimar is attached with modem recorder. Compatible software for recording of deformation reading is installed in computer which facilitate set of data in text format. RTD is attached with pico log recorder and compatible software is used to record temperature readings on computer. In our test recorder is used which can record temperature readings from four sensors simultaneously.

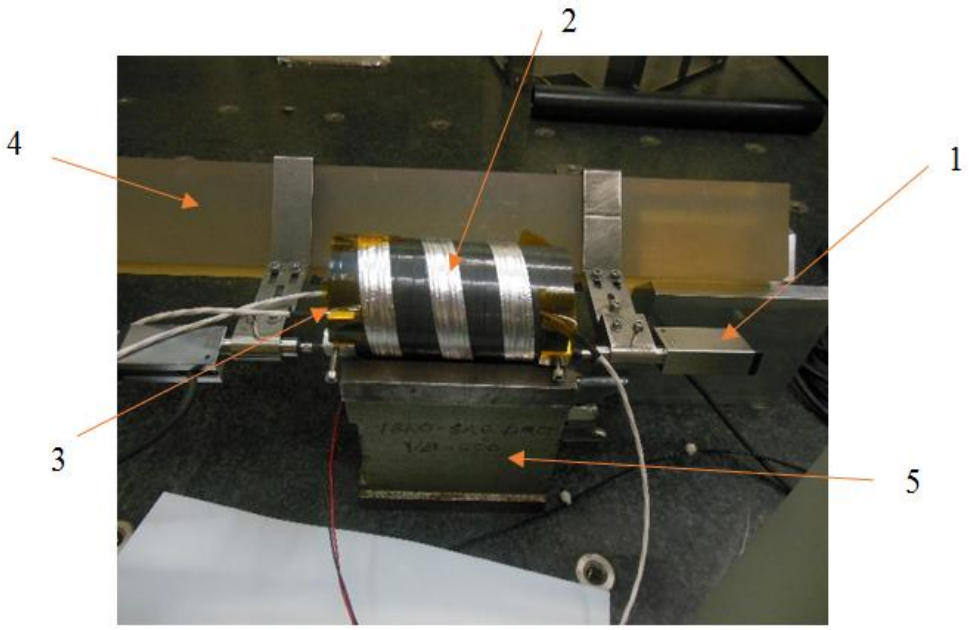

Figure 2 : Placement of LVDT for Deformation Measurement (1) LVDT (2) Heater (3) RTD (4)Zerodur reference bar (5) V block

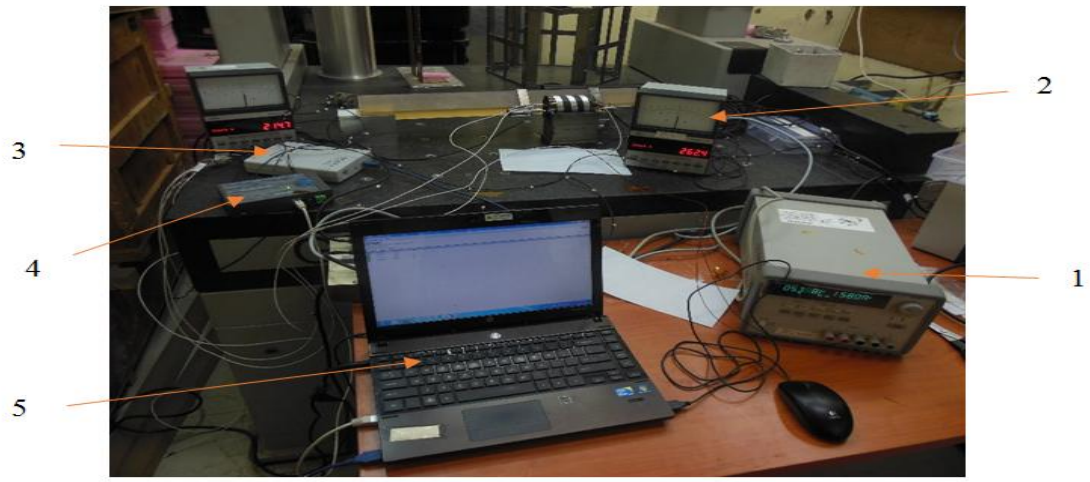

Figure 3 :Complete Testsetup: (1) Power supply (2) Milimar (3) Picolog recorder (4) Modem for milimar (5) Computer

V. TEST PROCEDURE

In this study test is started from room temperature. Initially test specimen is heated upto two degree Celsius more than room temperature and retained at that temperature for 30 minutes to achieve equilibrium state.For very long temperature range, heating rate generally used is around 3-5°C min^{-1}[11]. In this test procedure, heating rate of 0.12-0.14 °C min^{-1} is used as temperature range of investigation is from room temperature to 45°C.Applied voltage to heater is increased slowly to increase temperature of the specimen. Over a span of 60 minutes temperature is increased by 6 °C. Then again specimen is retained at that temperature to allow residual stresses to get relieved and achieve equilibrium. Again applied voltage is increased with power source and temperature is increased. Variation of temperature and deformation with respect to time is shown in table and accordingly graphs are plotted.

VI. RESULTS

Temperature and deformation readings are as shown in table. Here T_1 and T_3 are temperature at the end of the tube and T_2 is temperature at the middle of tube on inner surface. In our test setup tube is allowed to expand on both sides in longitudinal direction. Hence for overall deformation of the tube, readings of both gauges are added.

Table 1 : Results for Tube 1

Time (min.)	Temperature readings (°C)			LVDT readings (µm)	
	T_1	T_2	T_3	Gauge A	Gauge B
0	30	29.6	28.2	215.1	217.5
25	30.16	29.72	28.34	215.2	217.5
35	30.88	30.70	28.39	215.8	217.5
45	31.64	31.73	28.44	216.3	217.5
55	32.42	32.71	28.52	216.8	217.5
65	33.17	33.71	28.59	217.4	217.5
75	33.68	34.72	28.62	217.8	217.5
85	34.30	35.70	28.63	218.1	217.7
110	35.05	36.38	28.63	218.4	217.8
120	36.20	37.38	28.72	218.7	217.9
125	36.35	38.30	28.73	219.1	218.2
132	36.83	39.29	28.75	219.4	218.3
138	37.88	40.32	28.77	219.6	218.7
144	38.79	41.30	28.82	219.9	218.9
150	39.94	42.31	28.94	220.2	219.2
180	39.62	42.63	28.98	220.3	219.3

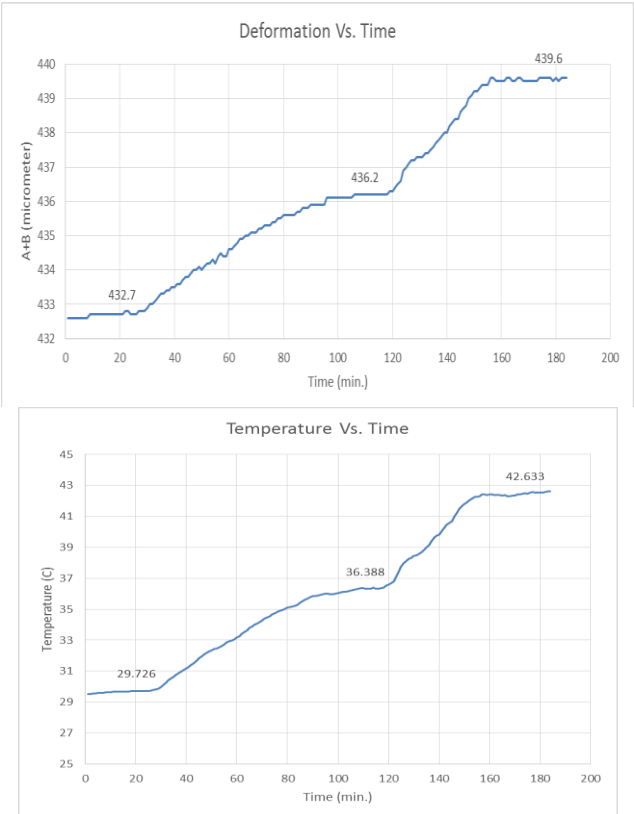

Figure 4 : Deformation and Temperature variations with respect to time for Tube 1

Table 2: Results for Tube 2

Time (min.)	Temperature readings (°C)			LVDT reading (μm)	
	T_1	T_2	T_3	Guage A	Guage B
0	32.38	33.26	32.72	214.2	265.6
30	33.04	34.38	33.45	214.2	265.5
38	33.65	35.53	33.99	214.1	265.3
46	34.14	36.47	34.47	214.1	265.2
54	34.63	37.52	35.04	214.1	265.1
62	35.10	38.49	35.54	214.1	265.0
70	35.66	39.51	36.02	214.0	264.8
78	36.18	40.52	36.61	214.0	264.7
108	36.23	40.97	36.90	214.0	264.6
116	36.78	41.90	37.32	214.0	264.4
124	37.47	42.94	37.92	214.0	264.2
132	37.91	43.92	38.37	214.8	262.9
140	38.51	44.90	38.94	214.8	262.8
148	39.04	45.98	39.50	214.8	262.7
156	39.25	47.08	40.14	214.8	262.6
186	39.20	47.63	40.72	214.7	262.4

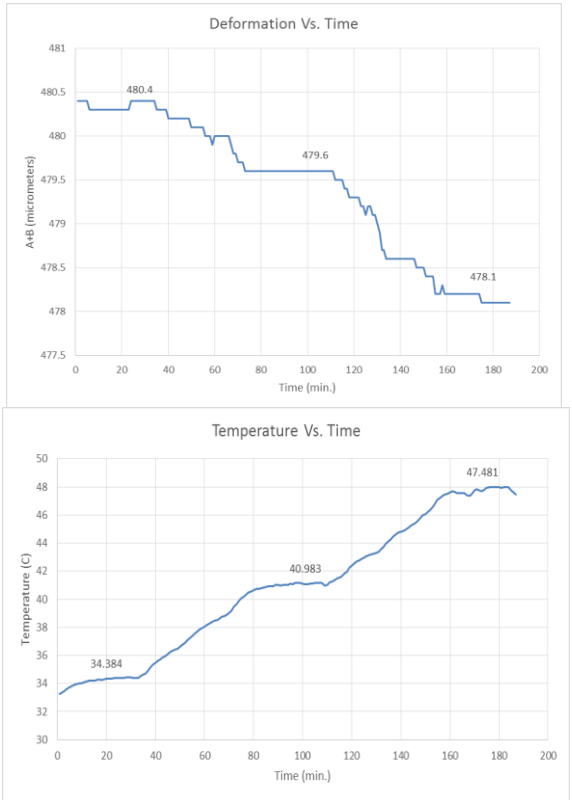

Figure 5: Deformation and Temperature Variations with respect to Time for Tube 2

VII. CALCULATION OF CTE

Coefficient of thermal expansion is ratio of change in length to original length per unit temperature change.

$$\text{CTE} = \frac{\Delta l}{L\,\Delta T}$$

Where Δl = change in length

L = original length of specimen

ΔT = change in temperature

For calculation, values at the end of soaking period are considered.

For tube 1

$$\text{CTE} = \frac{(439.6-432.7)}{0.111(42.633-29.726)} = 4.186\ \mu\text{m/m°C}$$

For tube 2

$$\text{CTE} = \frac{(478.1-480.4)}{0.1(47.481-34.584)} = -1.783\ \mu\text{m/m°C}$$

VIII. CONCLUSION

In this paper an experimental approach to find coefficient of thermal expansion of composite tube has been illustrated. From the test results we can see that for low modulus and high strength fiber material T700S CTE is 4.186 µm/m°C whereas for high modulus fiber M55J corresponding value is -1.783 µm/m°C. Hence for structural applications where deformation of tube due to temperature variations is required to be minimum, high modulus fiber should be selected.

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