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A Novel Measurement Method for Linear Thermal Expansion Coefficient of Laminated Composite Material Tubular Specimen

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Materials of satellite integration truss frame are required to withstand temperature that range from about – 250 °C ~ + 150 °C. In order to reduce structural components deformation caused by such temperature change, material of truss frame mostly adopts laminated composite material tubes, whose linear thermal expansion coefficient (LTEC) is very small. Therefore, accurate measurement of LTEC of truss frame materials over a broad temperature range is essential for successful mission. To address this issue, this paper proposes a general experiment platform for measuring LTEC of laminated composite material specimen reaching length up to one meter in the temperature range from – 100 °C to +100 °C. The platform uses light-density optical fiber probe to measure length variation and thermocouple to record temperature variation. Thereafter, the thermal expansion coefficient and its measurement uncertainty can be obtained by establishing and solving mathematical model. Finally, LTEC measurement of a tubular composite materials specimen is conducted. The experiment result demonstrates the validity and practicality of the experiment platform and the measurement accuracy of LTEC which can reach up to 10^{-7}/°C.

Keywords: laminated composite material, linear thermal expansion coefficient, length variation, uncertainty.

1. INTRODUCTION

The truss frame is an important part of the satellite integration framework. It can provide structural support for other space borne equipment of satellite. When the satellite is in space environment, temperature ranges from approximately – 250 °C to + 150 °C. Temperature changes can severely distort structural components if materials with very high thermal expansion coefficient (LTEC) are used [1]. Meanwhile, the LTEC mismatch between different materials leads to the distortion and delamination of structural materials because different materials have different LTEC. Laminated composite materials are increasingly adopted in truss frame structures due to their lower linear thermal expansion coefficient. Because the LTEC of such type of composite materials depends largely on the orientation of fibers, fiber fraction, type of resin and reinforcement [2], the LTEC may be different for different specimen. In order to avoid oversize distortion of the truss structure and predict the structure deformation caused by temperature, accurate measurement of LTEC of truss materials over a broad temperature range is essential for mission success.

Determination of the LTEC requires the measurement of two physical quantities, displacement and temperature [3]. Examination of the literature reveals that many different experimental approaches have been employed to measure the LTEC of different materials. Han presents a measuring system for LTEC of ultralow expansion material by using a fiber ring laser. Through measuring the optical frequency change caused by the temperature change, the LTEC in the temperature range from 5 °C to 60 °C can be obtained [4]. Martelli developed a heterodyne interferometric dilatometer which can be used to measure the TEC of solid in the temperature range of 4 K ~ 300 K, and the accuracy better than 200 nm [5]. This dilatometer can also measure the thermal expansion of AISI 420 between 20 K and 293 K [6]. Destrycker measured the TEC of steel with the aid of a digital image correlation (DIC) technique. The technique is used to measure SS409 tubular samples within higher temperature interval (up to 600 °C) [7]. Badami designed instrument which can measure LTEC in the temperature range 0 ~ 100 °C, and analysed the error source in the measurement [8]. However, the specimens of these studies mentioned above are very small due to the restrictions of experimental equipment. Additionally, most of them use the theory precision of length variation measurement method as precision of LTEC and measurement uncertainty is not taken into account leading to incompletion of the measurement result of LTEC.

This paper proposes a LTEC experiment platform and measurement method for laminated composite materials. The platform uses light-density optical fiber probe to measure length variation and thermocouple to record temperature variation. Length of specimen can be up to 1.2 m and the precision of length variation can reach 5 nm. The thermal expansion coefficient has been calculated by its mathematical model and using a statistical method, measurement uncertainty has been obtained.

2. EXPERIMENTAL SETUP

The hardware platform consists of three subsystems, the measurement subsystem, the environment subsystem and the structure subsystem. Each subsystem includes two

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units to perform specific functions. The schematic of the hardware platform layout can be seen in Fig. 1 and the architecture of the hardware platform as shown in Fig. 2.

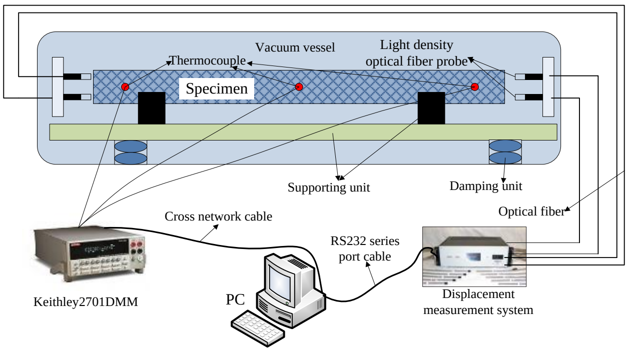

Fig. 1. The hardware platform layout

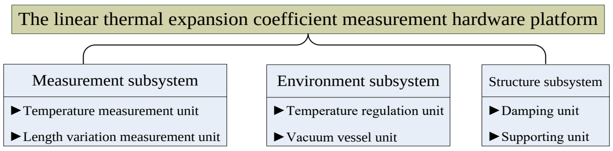

Fig. 2. Hardware platform architecture

2.1. Measurement subsystem

The measurement subsystem includes the temperature measurement unit and the length variation measurement unit.

2.1.1. Temperature measurement unit

Two insulated adhesive tapes were used in the temperature measuring unit. One adhesive tape was glued between thermocouples and tested surface in order to avoid the contact resistance, and another insulated adhesive tape was used to fix the thermocouple on the surface. Twenty T-type thermocouples are evenly glued to the surface of the specimen to measure the temperature of the specimen, as seen in Fig. 3. The corresponding tolerance of temperature over the whole sample is ± 0.25 ℃, out-of-tolerance data will be abandoned. Parameters of T-type thermocouple are presented in Table 1. The voltage signals collected by thermocouples are first converted to temperature values in Keithley 2701DMM, then they are input to PC.

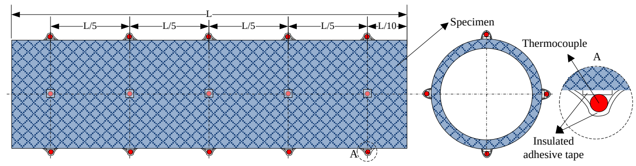

Fig. 2. Arrangement of thermocouples

Table 1. Parameters of T-type thermocouple

Measurement range, ° C	Resolution, °C	Reference error, °C	Synthesis error, ° C
–200 ~ 400	0.01	0.2	0.2002

2.1.2. Length variation measurement unit

In this unit, PHILTEC D63-model light density optic fibre probe is used to measure the length variation of the specimen. Total of eight probes were used, of which four probes are arranged at one end of the specimen, and the remaining four are arranged at other end, as seen in Fig. 4. Meanwhile, because the tubular specimen is used in this experiment, the follow-up surface which is made of silica glass is installed at the ends of the specimen to provide a reflecting surface.

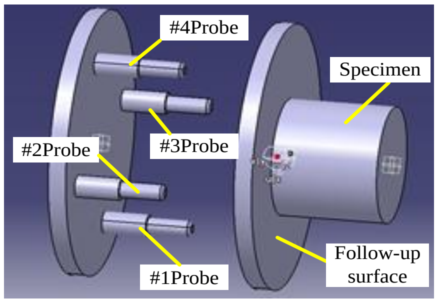

Fig. 3. Arrangement of optic fiber probes (one end)

As the specimen changes length along the axis, the distances between fiber optic probes and specimen ends change accordingly. As illustrated in Fig. 5, the changes are sent to displacement measurement system and converted into the voltage signal. Through the RS232 series port cable, voltage signal output to the PC. The displacement variation can be obtained by translating the voltage according to the function relation between distance and voltage. The probe has a measuring precision of up to 5 nm.

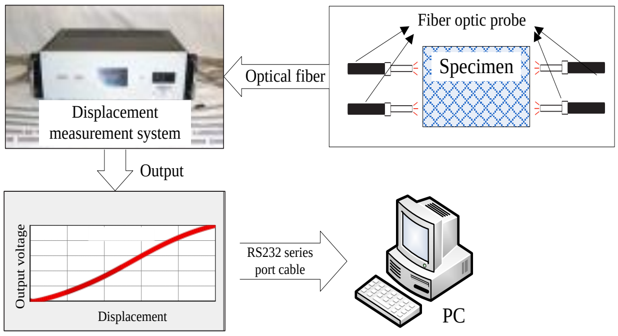

Fig. 4. Schematic of length measurement unit

2.2. Environment subsystem

The environment subsystem consists of the temperature regulation unit and the vacuum vessel unit. The temperature regulation unit can cool the specimen by liquid nitrogen in the cooling process, and heat the specimen by use of non-contacted heater-wire in the heating process. The vacuum vessel unit ensures the specimen in the vacuum environment which can prevent moisture condensation in the cooling process.

2.3. Structure subsystem

As shown in Fig. 2, the structure subsystem includes two units, the damping unit and the supporting unit. The function of the damping unit is to reduce the influence of vibration. The supporting unit can provide stable support for specimen. Furthermore, it can reduce the deformation caused by the gravity.

3. SOFTWARE SYSTEM

Temperature and length variation data automatically collected by the measurement subsystem input to PC through cross-network cable and RS232 serial port cable respectively. Parameter configuration, measurement data collection or recording, LTEC computation and report output are integrated with the software platform. Based on LABVIEW software, Virtual Instrument System Architecture (VISA) and database, this software can record the temperature and length variation measurement results simultaneously. Furthermore, it can compute the LTEC and uncertainty through computation function. The reports which include the measurement data and the computation results can be output.

4. MEASUREMENT PROCEDURE

A typical LTEC measurement can be carried out by following steps:

Step 1: Cooling the specimen approximately down to the reference temperature (the reference temperature is 20 ℃) and waiting for several minutes. Then, (1) measuring the initial length L_0 in reference temperature by using coordinate measuring machine (CMM); (2) recording the data collected by the optic fibre probe; (3) recording the temperature data collected by the thermocouples. These measurement processes independently repeat n times, the measurement data are as following,

$$L_0 : \{L_{01}, L_{01}, \cdots\cdots, L_{0n}\}\ , \tag{1}$$

where, L_{0i} denote the No. i measurement value of initial length.

$$\textit{data collected by the optic fiber probe}:$$

$$\begin{cases} \delta_1^1, \delta_2^1, \delta_3^1, \delta_4^1, \cdots\cdots \delta_1^n, \delta_2^n, \delta_3^n, \delta_4^n, \textit{one end} \\ \delta_5^1, \delta_6^1, \delta_7^1, \delta_8^1, \cdots \delta_5^n, \delta_6^n, \delta_7^n, \delta_8^n, \textit{the other end} \end{cases} . \tag{2}$$

δ_i^k represents the data collected by No. i optic fiber probe in the No. k measurement. The average of each optic fiber probe data can be calculated as follow,

$$\begin{cases} \delta_1 = \dfrac{\sum_{i=1}^{n} \delta_1^i}{n} \\ \cdots\cdots \\ \delta_8 = \dfrac{\sum_{i=1}^{n} \delta_8^i}{n} \end{cases} ; \tag{3}$$

$$\textit{Temperature data} : \{T_{0-1}^1, T_{0-2}^1 \cdots\cdots T_{0-1}^n, T_{0-2}^n \cdots T_{0-20}^n\}\ , \tag{4}$$

where, T_{0-i}^k is the temperature data collected by No. i thermocouple in the No. k measurement. The average of each thermocouple data can be calculated as follow,

$$\begin{cases} T_{0-1} = \dfrac{\sum_{i=1}^{n} T_{0-1}^i}{n} \\ \cdots\cdots \\ T_{0-k} = \dfrac{\sum_{i=1}^{n} T_{0-k}^i}{n} \end{cases} . \tag{5}$$

The temperature of the specimen is,

$$T_0 = \frac{\sum_{k=1}^{20} T_{0-k}}{20}\ . \tag{6}$$

Step 2: Sealing the vessel and conducting vacuum. Then, heating/cooling the specimen to a certain temperature T, and waiting for several minutes. After that, (1) recording the data collected by the optic fibre probe; (2) recording the temperature data collected by the thermocouples. These measurement processes independently repeat n times, the measurement data are as following,

$$\begin{cases} \delta_{T1}^1, \delta_{T2}^1, \delta_{T3}^1, \delta_{T4}^1, \cdots\cdots \delta_{T1}^n, \delta_{T2}^n, \delta_{T3}^n, \delta_{T4}^n, \textit{one end} \\ \delta_{T5}^1, \delta_{T6}^1, \delta_{T7}^1, \delta_{T8}^1, \cdots \delta_{T5}^n, \delta_{T6}^n, \delta_{T7}^n, \delta_{T8}^n, \textit{the other end} \end{cases} . \tag{7}$$

δ_{Ti}^k represents the data collected by No. i optic fibre probe in the No. k measurement when the specimen temperature is approximately T.

The average of each optic fiber probe data can be calculated as follow,

$$\begin{cases} \delta_{T1} = \dfrac{\sum_{i=1}^{n} \delta_{T1}^i}{n} \\ \cdots\cdots \\ \delta_{T8} = \dfrac{\sum_{i=1}^{n} \delta_{T8}^i}{n} \end{cases} ; \tag{8}$$

$$\textit{Temperature data} : \{T_1^1, T_2^1 \cdots T_1^n, T_2^n \cdots T_{20}^n\}\ , \tag{9}$$

where, T_i^k is the temperature data collected by No. i thermocouple in the No. k measurement when the specimen temperature is approximately T.

The average of each thermocouple data can be calculated as follow,

$$\begin{cases} T_1 = \dfrac{\sum_{i=1}^{n} T_1^i}{n} \\ \cdots\cdots \\ T_k = \dfrac{\sum_{i=1}^{n} T_k^i}{n} \end{cases} . \tag{10}$$

According to the formula (6), the temperature of the specimen is,

$$T = \frac{\sum_{k=1}^{20} T_k}{20}\ . \tag{11}$$

5. LTEC AND UNCERTAINY CALCULATION

5.1. LTEC calculation

The most-general definition of LTEC is the average LTEC, which is given in ASTM [9 – 10]:

$$\alpha_{T_0,T} = \frac{(L_T - L_0)}{L_0 (T - T_0)} = \frac{\Delta L}{L_0 \Delta T}\ , \tag{12}$$

where, $\alpha_{To,T}$ is average LTEC over the temperature range from T_0 to T. The fractional increase in length is calculated by dividing the increase in length by the length at T_0. Furthermore, the T_0 is usually defined as a reference temperature, the value of T_0 is 20 ℃ in these experiments.

According to the formula (1), the L_0 can be computed by following formula,

$$L_0 = \frac{\sum_{i=1}^{n} L_{0i}}{n} . \tag{13}$$

Based on the formula (3) and (8), displacement of each specimen end can be calculated as follow,

$$\begin{cases} \Delta_1 = \dfrac{(\delta_{T1}-\delta_1)+(\delta_{T2}-\delta_2)+(\delta_{T3}-\delta_3)+(\delta_{T4}-\delta_4)}{4} \\ \Delta_2 = \dfrac{(\delta_{T5}-\delta_5)+(\delta_{T6}-\delta_6)+(\delta_{T7}-\delta_7)+(\delta_{T8}-\delta_8)}{4} \end{cases} . \tag{14}$$

The length change of the specimen is the displacement sum of both ends,

$$\Delta L = \Delta_1 + \Delta_2 = \frac{\sum_{k=1}^{8} (\delta_{Tk}-\delta_k)}{4} . \tag{15}$$

The temperature variation of specimen can be obtained according to the formula (6) and (11),

$$\Delta T = T - T_0 . \tag{16}$$

5.2. Uncertainty analysis

The measurement uncertainty can be estimated with [8], in which each term is associated with the uncertainty of the measurement of initial length, length variation, and temperature variation. Then, the combined uncertainty can be determined by taking the square root of standard deviation of sum of each term. Therefore, the combined uncertainty of LTEC is,

$$u_\alpha = \sqrt{(c_{\Delta L} u_{\Delta L})^2 + (c_{\Delta T} u_{\Delta T})^2 + (c_{L_0} u_{L_0})^2} ; \tag{17}$$

$$\begin{cases} c_{\Delta L} = \dfrac{\partial \alpha}{\partial \Delta L} = \dfrac{1}{L_0 \Delta T} \\ c_{\Delta T} = \dfrac{\partial \alpha}{\partial \Delta T} = -\dfrac{\Delta L}{L_0 (\Delta T)^2} \\ c_{L_0} = \dfrac{\partial \alpha}{\partial L_0} = -\dfrac{\Delta L}{L_0^2 \Delta T} \end{cases} . \tag{18}$$

Using formula (13) to calculate L_0, the measurement uncertainty of L_0 is,

$$u_{L_0} = \sqrt{\frac{\sum_{i=1}^{n} (L_{0i} - L_0)}{n(n-1)}} . \tag{19}$$

According to A-type evaluation method of uncertainty, the $u_{\Delta T}$ and $u_{\Delta L}$ can be determined as follow:

$$\begin{cases} u_{\Delta T} = \sqrt{u_T^2 + u_{T_0}^2} \\ u_{T_0} = \dfrac{\sqrt{\sum_{i=1}^{20} u_{T_{0-k}}^2}}{20}, u_T = \dfrac{\sqrt{\sum_{i=1}^{20} u_{T_k}^2}}{20} \\ u_{T_{0-k}} = \sqrt{\dfrac{\sum_{i=1}^{n} \left(u_{T_{0-k}}^i - u_{T_{0-k}}\right)^2}{n(n-1)}}, u_{T_k} = \sqrt{\dfrac{\sum_{i=1}^{n} \left(u_{T_k}^i - u_{T_k}\right)^2}{n(n-1)}} \end{cases} ; \tag{20}$$

$$\begin{cases} u_{\Delta L} = \sqrt{u_{\Delta 1}^2 + u_{\Delta 2}^2} \\ u_{\Delta 1} = \dfrac{\sqrt{u_{(\delta_{T1}-\delta_1)}^2 + u_{(\delta_{T2}-\delta_2)}^2 + u_{(\delta_{T3}-\delta_3)}^2 + u_{(\delta_{T4}-\delta_4)}^2}}{4} \\ u_{\Delta 2} = \dfrac{\sqrt{u_{(\delta_{T5}-\delta_5)}^2 + u_{(\delta_{T6}-\delta_6)}^2 + u_{(\delta_{T7}-\delta_7)}^2 + u_{(\delta_{T8}-\delta_8)}^2}}{4} \\ u_{(\delta_{Tk}-\delta_k)} = \sqrt{u_{\delta_{Tk}}^2 + u_{\delta_k}^2} \\ u_{\delta_{Tk}} = \sqrt{\dfrac{\sum_{i=1}^{n} \left(\delta_{Tk}^i - \delta_{Tk}\right)^2}{n(n-1)}}, u_{\delta_k} = \sqrt{\dfrac{\sum_{i=1}^{n} \left(\delta_k^i - \delta_k\right)^2}{n(n-1)}} \end{cases} . \tag{21}$$

6. LTEC MEASUREMENT OF LAMINATED COMPOSITE MATERIAL TUBULAR SPECIMEN

In order to validate this instrument, this paper measured the LTEC of a tube that was made by Carbon-epoxy laminated composite material. Its outer diameter is 30 mm and thickness is 2 mm. Meanwhile, its length is approximately 1 m. The glass transition temperature of this material is above 210 °c. The experiment aim is to measure its LETC data between –100 °C and +100 °C.

Twenty calibrated T-type thermometers were glued on the sample, and eight optic fiber probes were used to measure the length change as described in section 2.1. After the thermocouples and optic fiber probes are configured. The system was cooled down to approximately 20 C and thermalized for several minutes. The initial length of the specimen was independently measured six times by CMM, and the initial length of the specimen is presented in Table 2.

Table 2. Initial length of the specimen (20 °C)

Sequence number	L_{0i}, mm
1	1019.97
2	1019.95
3	1019.97
4	1019.98
5	1019.96
6	1020.00

At the same time, by use of LTEC software tool (Fig. 6), recording the displacement and temperature data, as shown in Table 3. Then, heating the system from 20 °C to 100 °C every 10 °C interval, recording the displacement and temperature data simultaneously. Moreover, cooling the system from 20 °C to –100 °C by use of liquid nitrogen and recording corresponding data. Each measurement repeats five times, temperature change and its uncertainty are shown in Fig. 7.

Table 3. Computed results

Theoretical temperature variation, °C	Actual temperature variation, °C	Length variation, μm	LTEC, 10^{-6}°C^{-1}	LTEC Uncertainty, 10^{-6}°C^{-1}
20~-100	-120.0114	59.9687	0.490	0.0145
20~-90	-110.0108	58.6532	0.523	0.0131
20~-80	-100.0110	54.1099	0.530	0.0124
20~-70	-90.0106	47.3524	0.516	0.0121
20~-60	-80.0102	42.8547	0.467	0.0120
20~-50	-70.0092	35.1850	0.493	0.0112
20~-40	-60.0085	28.6591	0.468	0.0105
20~-30	-50.0079	22.4847	0.441	0.0103
20~-20	-40.0071	18.5389	0.455	0.0113
20~-10	-30.0069	15.2263	0.497	0.0121
20~0	-20.0030	10.3951	0.509	0.0112
20~10	-10.0014	6.2656	0.610	0.0114
20~20	—	—	—	—
20~30	10.0007	-5.9810	-0.587	0.0127
20~40	20.0008	-7.6855	-0.377	0.0106
20~50	30.0108	-10.0506	-0.329	0.0102
20~60	40.0094	-15.1820	-0.372	0.0101
20~70	50.0100	-19.3872	-0.380	0.0103
20~80	60.0104	-23.3062	-0.381	0.0105
20~90	70.0126	-27.7682	-0.389	0.0110
20~100	80.0119	-31.5793	-0.387	0.0124

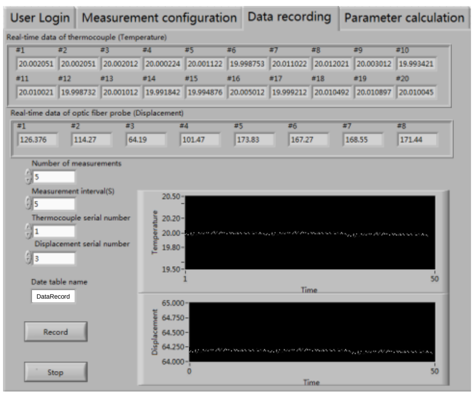

Fig. 5. Measurement data collection

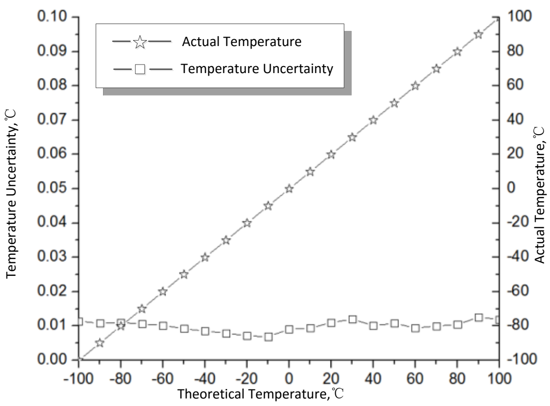

Fig. 6. Temperature change and its uncertainty

After the measurement, LTEC and other parameters can be calculated according to the formula (6) – (21), the results are shown in Table 3. The results show that the LTEC and its uncertainty can reach 10^{-7}/℃ and 10^{-8} /℃ respectively. The length variation versus temperature can be seen in Fig. 8.

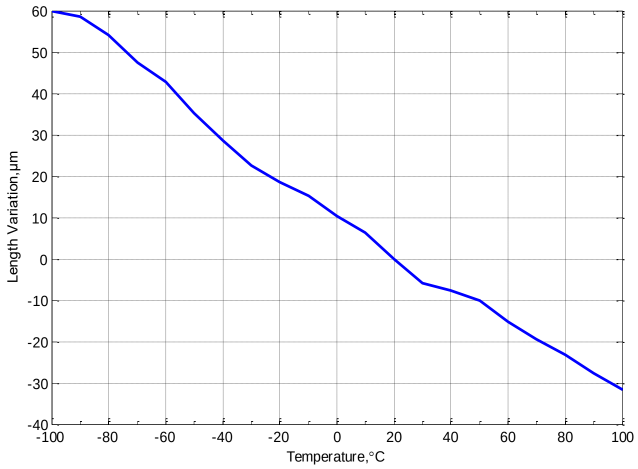

Fig. 7. Length variation versus temperature curve

7. DISCUSSION AND CONCLUSION

In this research, it has been shown that the linear LTEC of composite material tubular specimen can be measured with the aid of the LTEC measurement hardware and software system. Through the calculation models of LTEC and uncertainty, it is able to determine the LTEC with good accuracy and lower measurement uncertainty.

Further improvements of the study are also planned. Since most of the uncertainty comes from the systematic effects that are characterized through the non-uniform temperature of the specimen, an improvement of instrument performance could be obtained by improving the temperature control scheme. Moreover, another future research area could be the improvement of this platform in order to measure the LTEC of composite material tubular specimen in the temperature range of about –200 °C ~ +200 °C.

From the perspective of product design, on the other hand, the experiment results of this research can be used as basis parameter for performance analysis and prediction since LTEC is an essential input for finite elements analysis (FEA) simulation of truss frame which is made of these composite material tubes. Thermal stresses in the adhesively bonded joints that often connect structural members and overall deformation of the whole truss frame can be simulated. Therefore, potential problem of frame structure can be predicted based on the obtained LTEC data in the product design phase.

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