CHANGES IN THERMAL EXPANSION COEFFICIENT OF CFRP LAMINATE DUE TO THERMAL CYCLE

A. Kato[1,2], K. Goto[2], Y. Kogo[1], R. Inoue[1]

[1] Tokyo University of Science, kato.akifumi@ac.jaxa.jp, kogolab@me.com, inoue.ryo@rs.tus.ac.jp
[2] Department of Space Flight Systems, Institute of Space and Astronautical Science, JAXA
goto.ken@jaxa.jp

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ABSTRACT

Carbon fiber reinforced plastic (CFRP) laminates are used for structures of space satellites because of their high stiffness and low coefficient of thermal expansion (CTE). Recently, the CFRP laminate layup $[0/30/90/\text{-}30/0]_{4s}$ composed of poly-cyanate resin and PAN-based carbon fibers was designed with the CTE being approximately zero. Therefore, the thermal deformation of the satellite structures made of the CFRP laminate is suppressed. However, the change of the CTE and Young's modulus of the CFRP laminate is due to long-term environmental exposure in the space. In this study, the CTE of unidirectional CFRP composite was measured between -150 ^{o}C and 120 ^{o}C. After that the CTE measurements and damage observation of the CFRP laminate under the thermal cycling between -196 °C and 120° C were examined. Experimental results showed that the CTE of the CFRP laminate reduced significantly after applying 100 thermal cycles. In addition, the thermal cycle loading caused the delamination and transversal cracks of the CFRP laminate. Moreover, finite element modeling of the CFRP laminate subjected to the thermal cycle loading was conducted to investigate the CTE change using ABAQUS software. Numerical results showed that the transversal cracks play a major role in decreasing the CTE of the CFRP laminate.

1 INTRODUCTION

Carbon fibers have a low specific gravity, unique mechanical and thermal properties, low heat expansion and high dimensional stability. They exhibit a negative coefficient of thermal expansion (CTE) in the axial direction and a positive CTE in the radial direction. Carbon fiber reinforced plastic (CFRP) laminates which are designed to have the CTE being almost zero by controlling laminate sequence are often used in precise structures of satellite systems, such as optical benches and antenna reflectors. The CFRP laminates with the CTE close to zero can suppress the thermal deformation of their structures under thermal loading. However, the change of the CTE and Young's modulus of the CFRP laminate was attributed to prolonged exposure to the space environment [1]. In addition, the delamination and transversal cracks in the CFRP composite laminates were attributed to thermal cycle loading [2]. Moreover, the damage simulation of CFRP composite laminates using finite element analysis (FEA) showed that Young's modulus change caused by the delamination [3].

Recently, Goto et al. [4] reported that the CTE and elastic modulus of CFRPs are known to be changed by environmental exposure in the space i.e., thermal cycles, ultraviolet rays and radial rays. Particularly, thermal cycle loading caused the significant change in the mechanical and thermal properties of the CFRP laminate. More recently, Asai et al. [5] showed that after 20 thermal cycles Young's modulus of the CFRP laminate degraded about 6% from its original value, however, the CTE of the CFRP laminate enhanced slightly. Therefore, studies of the CTE and elastic modulus changes as well as the damage in the CFRP laminate under thermal cycle loading became necessary for applying the CFRP structures in satellite systems.

Main purposes of this study are to investigate the effects of thermal cycle loading on the CTE change and to elucidate the relationship between the damage factors (delamination and transversal crack) and the parameters required for the CFRP laminate design. The CTE measurements and damage observation of the CFRP laminate under the thermal cycling between -196 °C and 120 °C were investigated. Effects of the thermal cycle loading on the delamination and transversal cracks of the CFRP laminate were examined. Moreover, finite element (FE) modeling of the CFRP laminate subjected to the thermal cycle loading was conducted using ABAQUS software to elucidate the CTE change caused by the damage mechanism of the CFRP laminate.

2 EXPERIMENTAL PROCEDURES

2.1. Materials

The CFRP laminate was made of poly-cyanate resin (NM31, JX Nippon Oil & Energy Corporation, Japan) and PAN-based carbon fibers (M64JB, Toray Industries, Japan). Two specimens were prepared. One is 0 degree unidirectional (UD). The other is angleplied laminate. The stacking sequences of the CFRP laminate was $[0/30/90/-30/0]_{4s}$. The laminate was designed to have near-zero CTE in 0 degree direction.

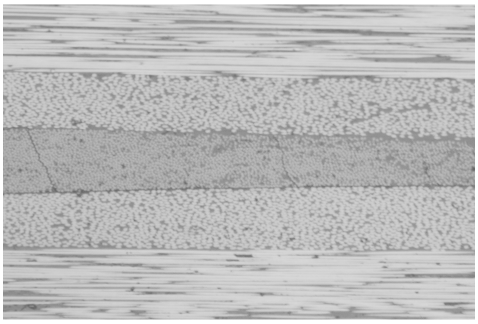


Figure 1: surface of the angleplied laminate.

2.2. Thermal cycle test

Thermal cycle test was carried out between -196 °C and 120 °C using a drying oven (DX602, Yamato-scientific). A thermal cycle including the heating in air and the cooling by liquid nitrogen exposure is following: 20 ^{o}C → 120 ^{o}C → 20 ^{o}C → - 196 ^{o}C → 20 ^{o}C. At each step of the thermal cycles the CFRP specimens were maintained at constant temperatures for 10 minutes(Figure 2). The CFRP specimens with dimension of 10 x 4.5 x 5 mm^3 were subjected to a 100 thermal cycles.

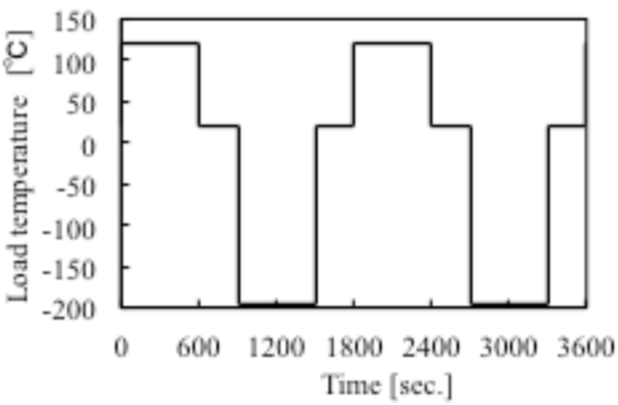


Figure 2: Thermal cycle history.

2.3. Damage observation

The delamination and transversal cracks of the CFRP laminate specimens subjected to 100 thermal cycles were observed using optical microscope and scanning electron microscope (SEM).

3 FINITE ELEMENT MODELING

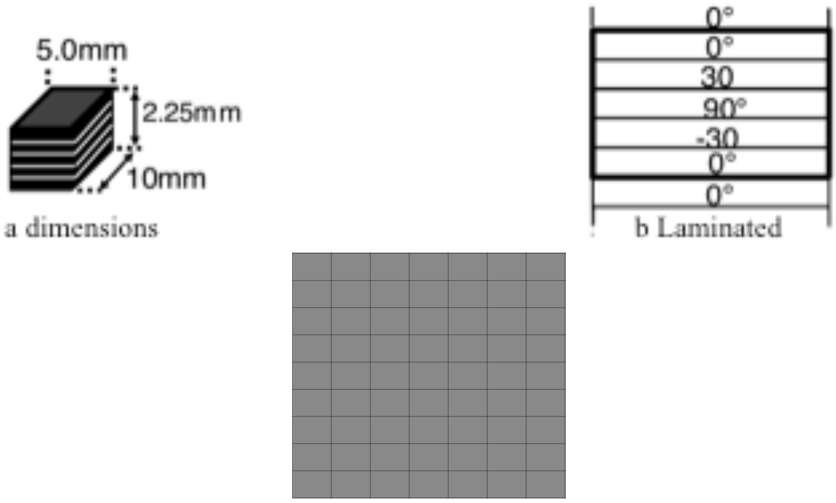
3.1 FE modeling of the CFRP laminate

In this research, FEA for the CFRP laminate was carried out in ABAQUS software. The FE model was built similarly to the structures of the CFRP laminate (Figure 3). The volume fraction of carbon fibers in the CFRP laminate was 60% [1,2]. However, the structure of the CFRP laminate is symmetric in the stacking direction. Therefore, the dimensions of the FE model were considered as 10 mm in the fiber direction, 2.25 mm in the stacking direction, and 5.0 mm in the lateral direction (see Figure 3).

A 20-layer model with the laminate configuration of $[0/30/90/-30/0]_{4s}$ and a single layer thickness of 225 μm was built in the ABAQUS. The boundary conditions are specified taking into account the symmetry of the system. The bottom surface of the FE model was constrained to have zero displacement in stacking direction, while the other surfaces were free. The expansion displacements are used to calculate the CTE. CTE is shown as equation (1).

$$\mathrm{CTE} = \frac{1}{\mathrm{L}}\frac{\mathrm{dL}}{\mathrm{dT}} \tag{1}$$

Where L is the specific length measurement and dL / dT is the rate of change of the linear dimension per unit change displayed.



c element

Figure 3: FEM model dimensions (a) , laminated (b) and element (c)

3.2 FE models for modeling transversal cracks and delamination

Transversal cracks often appear at the 90° layer of the CFRP laminate. Therefore, transversal cracks with the oval shape of 2 μm were created in FE model at the 90° layer. The crack density is the number of cracks per length (/ mm). There models (0 / mm, 2.5 / mm, and 5.0 / mm) for FE modeling of the transversal cracks corresponding to 0, 2.5, and 5.0 cracks per mm were created. The delamination with the shape of equilateral triangle with a side length of 2 μm was created between ± 30° layers and 90° layer. The peeling percentage was estimated from peeled length over the total length. With the lateral direction of 5.0 mm the delamination was added to the FE transverse model of 5 / mm. The model name is 0%, 1.125%, 10% indicated by peeling ratio. The FE models for modeling the transversal cracks and delamination were depicted in Figure 4 and 5.

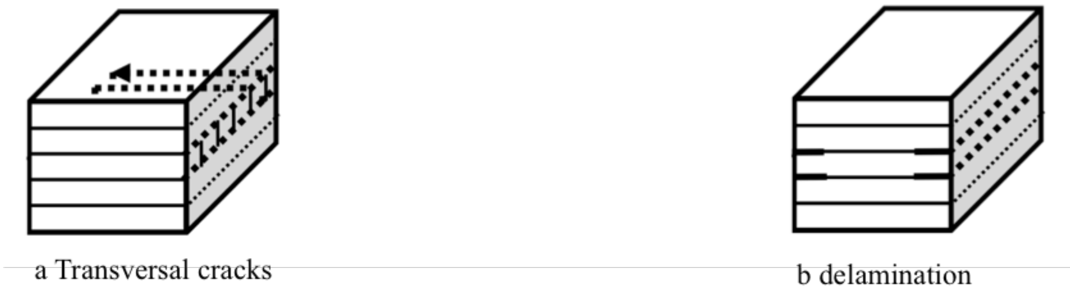


Figure 4: FE transverse model (a) and delamination model (b)

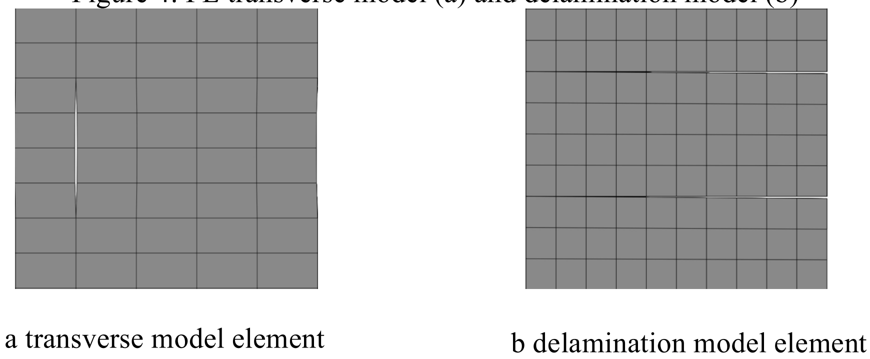


Figure 5: FE transverse model element (a) and delamination model element (b)

4 RESULS AND DISCUSSION

4.1 Experiment

4.1.1 CTE of UD CFRP composite

The CTE of UD CFRP composite was measured in 0° direction and 90° direction between -150 ^{o}C and 120 ^{o}C with results presented in Figure 6. Results show that the CTE in 0^{o} direction increases gradually with increasing the temperature to about 0 ^{o}C and enhance rapidly from about 30 ^{o}C to 120 ^{o}C. The CTE in 90^{o} direction increases concomitantly with increasing the temperature from -150 ^{o}C and 120 ^{o}C. The CTEs of UD composite at the temperature around 20 °C measured in 0° and 90^{o} directions respectively were -0.32 and 33.3 ppm/K.

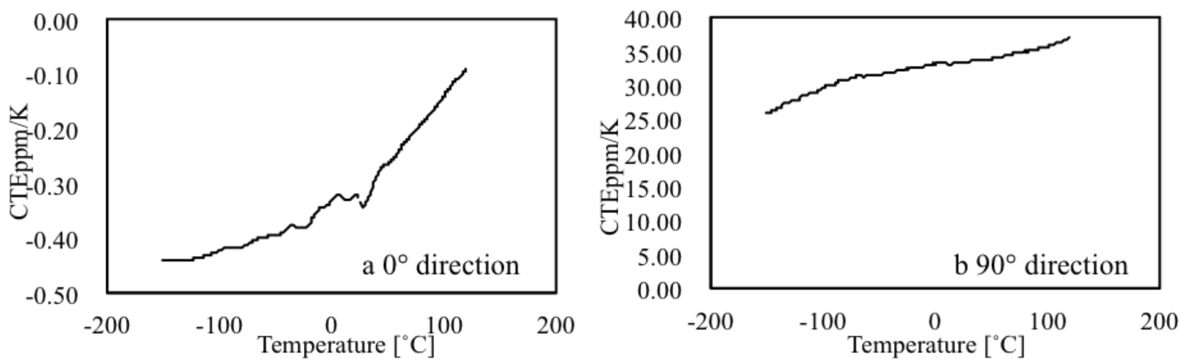


Figure 6: CTE of UD composite in 0° (a) and 90° direction (b)

4.1.2 CTE of the CFRP laminate

The CTEs of the CFRP laminate without exposure and subjected to 100 thermal cycles were presented in Figure 7. Results show that the CTE of the CFRP laminate decreased about 0.2 ppm/K after 100 thermal cycles. The CTE of the CFRP laminate at the temperature around 30 ^{o}C was 0.1

ppm/K. The damage of the CFRP laminate was observed at around 30 °C using SEM . The magnitude of damage acquired from the SEM is shown in Figure 8. It can be seen that the magnitude of transverse cracks and delamination is micro order.

4.1.3. Damage observation

The damage of the CFRP laminate under thermal cycle loading was observed on the outer laminate. After 100 thermal cycles, the transversal crack density was measured as about 5.0 / mm. The peeling amount to the inside of the delamination was 10%, and the increase in cycle amount and transverse cracking is shown in Figure 9.

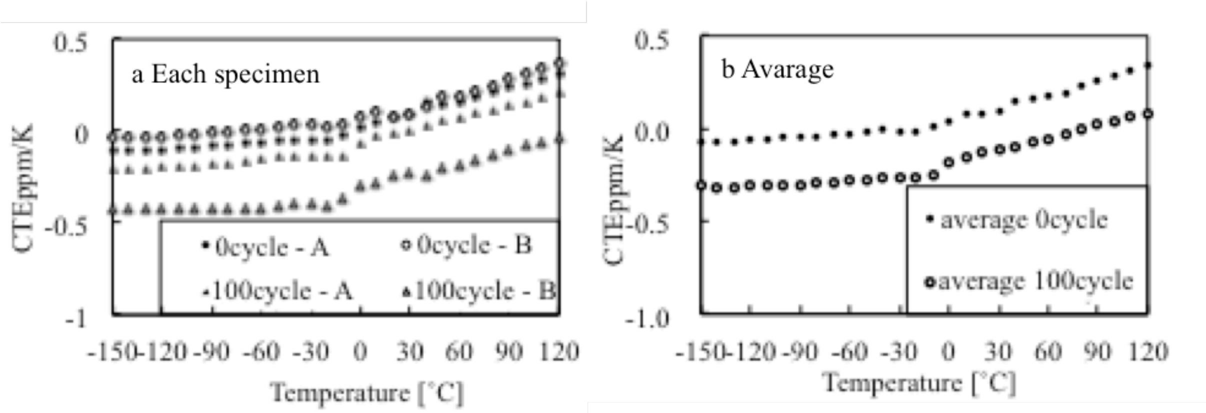


Figure 7: The CTE of the CFRP laminate subjected to 0 (a) and 100 (b) thermal cycles

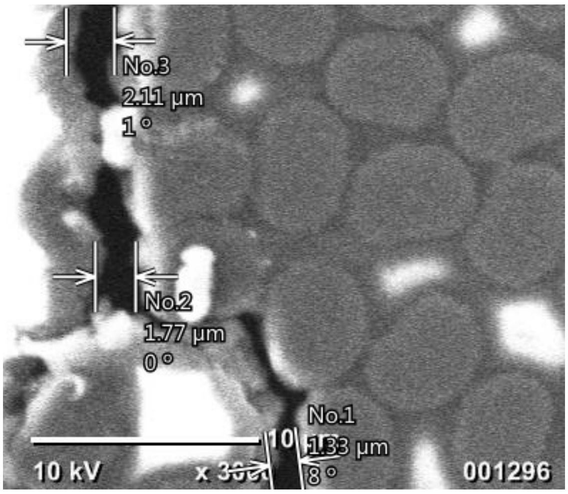


Figure 8: The magnitude of damage acquired from the SEM

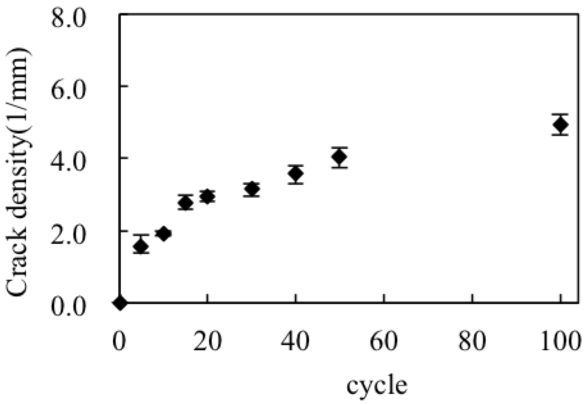


Figure 9: the increase in cycle amount and transverse cracking

4.2 FE modeling results

The CTE results for the CFRP laminate obtained from FE modeling were compared with those obtained from experiment. The CTE of the CFRP laminate obtained from 0 / mm FE model at around 30 °C is 0.08 × 10 ppm/K and shows an agreement with the experimental results. For the transversal crack model, the CTE decreased because of the increase in crack density. This result was presented in Figure 10. As Figure 10 shows, the CTE reduced strongly with increasing the crack density up to about 5 / mm, followed by almost invariability of the CTE. The CTE change was caused by the transversal cracks in the 90° layer.

For the 5 / mm model, the decreased amount of the CTE was 0.08 × ppm/K and is lower than that (0.2 × ppm/K) obtained from the experimental result. The difference is attributable to the difference of the transversal crack FE model and actual specimens in experiment. In general, it can state that the decreased CTE is due to the damage in the CFRP laminate. It is considered that the decreased amount of the CTE is almost constant if the fiber orientation is 30°. However, it is considered to be greatly variable as the angle of the fiber direction changes. In addition, the ± 0^{o} layer exhibits the lowest CTE and the CTE increases although the angle changes [6].

The difference between FE modeling and experimental results is attributable to the error of the fiber angle (about 5^{o}) during fabrication of the CFRP laminate. Besides, the transversal cracks created the FE model can differ from the actual cracks in the experimental specimens. Moreover, since the limit of measurement accuracy of the laser interferometry method is approximately 0.07 ppm/K. Therefore, the change CTE can derive from the measured error. Generally, it is necessary to investigate effects of other parameters such as the fiber angle on the CTE change.

Furthermore, changes in the CTE caused by the delamination are presented in Figure 10. Although the delamination was observed, the CTE almost does not change with increasing of the peeling amount. Actually, the model including both transversal cracks and the delamination was used for FE modeling to calculate the CTE. Results showed that the CTE change was similarly to that obtained from the model with transversal cracks only. Therefore, the CTE change is derived from the transversal cracks in the CFRP laminate.

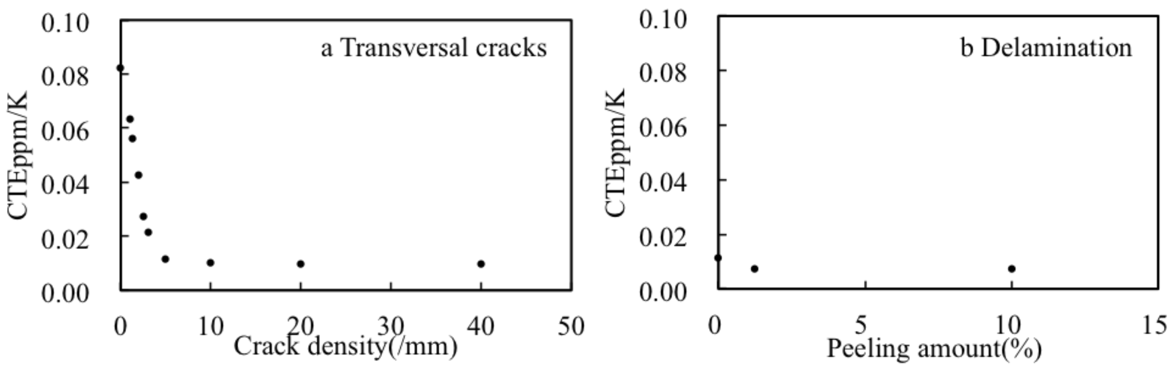


Figure 10: Reduction in CTE by transversal cracks (a) and delamination (b)

5. CONCLUSIONS

This study examined the CTE change of the CFRP laminate subjected to thermal cycle loading. The CTE change was due to the damage of the CFRP laminate caused by the thermal cycling. After applying the thermal cycling the CTE obtained from the experiment was decreased although the transversal cracks and delamination were increased. The FE models were built similarly to the specimen structure in the experiments. The FE modeling results showed that the transversal cracks play a major role in the CTE change, whereas the delamination does not effect on the CTE change. However, the CTE change might not be derived from the transversal cracks only, but also other parameters such as fiber angle.

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