DURABILITY OF CARBON FIBER REINFORCED COMPOSITE LAMINATES FOR LARGE PRECISE SPACE STRUCTURE UNDER CYCLIC THERMAL LOADING

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1 Introduction
A large antenna on orbit is useful equipment for the field of radio astronomy and communication technologies. As a higher accuracy antenna reflector, a deployable reflector composed by tensioned radial ribs and circumferential cable structure build on a truss structure were proposed. Under space environment, variations in temperature, for example, in and out of the Earth’s shadow, cause cyclic thermal deformation of the structure, which reduces accuracy of the geometry and resultant resolution of the antenna. In order to overcome this situation, Carbon-fiber-reinforced plastics (CFRP) are expected as a candidate material. Coefficient of thermal expansion (CTE) of carbon fiber is less than 0. Thus zero CTE of CFRP laminate might be attained if an appropriate laminate configuration is designed. On the other hand, in the laminate, mismatch of the thermal expansion coefficients between plies of different orientations causes thermal residual stress which becomes the main reason for matrix cracking. Moreover, cyclic temperature variations cause cyclic thermal stress condition. It is very important to clarify the microscopic damage development in CFRP laminates under thermal cycling in the view of the practical use because such damages affect mechanical properties of CFRP, such as elastic modulus. Previously, microscopic damage behavior in CFRP laminates under cyclic thermal loading has been investigated by many researchers 1-4). However, little study about variation in mechanical properties under cyclic thermal loading 5). In the present study, we selected both PAN and PITCH-based carbon fiber as reinforcements and Epoxy and polycyanate as matrices, respectively, designed and fabricate CFRP laminates which has nearly zero CTE. Cyclic thermal impact tests were conducted on both types of specimens to clarify the microscopic damage behavior. Bending tests were also conducted to discuss effect of microscopic damage on mechanical properties.

2 Test specimens and experimental condition
Material systems used, laminate configurations and geometries were shown in Table 1. M46J and YSH50 are PAN based and PITCH based carbon fibers, respectively. Polycyanate ester resin much lower hygroscopic absorption properties. In the remaining part, we referred the type of specimen as the symbol defined in table 1. Laminates were stacked in width direction as shown in Fig. 1, which are different from general composites. Laminate configurations were designed as 0 thermal expansion coefficient. Specimen surfaces were polished and finished using 0.03μm alumina suspension. Before testing, specimens were dried in a vacuum desiccator to avoid moisture effect.

In order to simulate thermal loading under space environment (-170°C~120°C), we used an electric furnace (120°C, DK-240S, Yamato) and liquid nitrogen (LN2, -197°C). At first specimens were put in an electric furnace with temperature 120°C for 10 min., then they were put in a foam carton filled with LN2 for 5 min. This cycle was repeated up to 100 cycles. Surface observations and initial elastic modulus measurement were conducted periodically. Surface observation was conducted using a video microscope system (VW-5000, Keyence). Observation area is 25mm at the center of the specimen.

Elastic modulus variation was measured by three-point bending testing using universal testing machine (AG-1000A, Shimadzu). Span length was 140mm. During tests, specimen deflection and load were measured with a dial gauge (DT-10D, Kyowa) and a load cell (LUR-A50NSAI, Kyowa), respectively. Only a tiny deflection, which gives 0.2% strain, was loaded.
Table 1 Specimens configurations and geometries.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Matrix</th>
<th>Fiber</th>
<th>Stacking Sequence</th>
<th>(width[mm])x(thickness[mm])</th>
</tr>
</thead>
<tbody>
<tr>
<td>CM</td>
<td>Polycyanate</td>
<td>M46J</td>
<td>[0/30/90/-30/0]_{4S}</td>
<td>(4.32±0.01)x(1.48±0.03)</td>
</tr>
<tr>
<td>CY</td>
<td>Polycyanate</td>
<td>YSH-50</td>
<td>[0/35/90/-35]_{4S}</td>
<td>(3.36±0.05)x(1.55±0.01)</td>
</tr>
<tr>
<td>EM</td>
<td>Epoxy</td>
<td>M46J</td>
<td>[0/30/90/-30/0]_{4S}</td>
<td>(3.66±0.02)x(1.55±0.01)</td>
</tr>
</tbody>
</table>

Fig. 1 Geometry of specimen.

3 Results and discussion

Microscopic damage observed in specimen CM is shown in Fig. 2. In specimen CM, delamination at every 90/-30 interface and transverse cracks in the outermost 90° plies initiated at 1 cycle. Fig 2 (b) shows growth of the microscopic damage. Delamination grew and associated crack opening displacement increased with cycles. Transverse cracks also initiated in all 90° plies and the number of cracks increased. Cracks in 30° plies initiated from the tip of some transverse cracks, whereas some cracks were arrested at the resin rich region at the ply interfaces.

Fig. 3 shows microscopic damage in specimen CY. At 1 cycle, delamination at outermost 35/90 and 90/-35 interfaces, transverse cracks in outermost 90 plies and cracks in outermost ±35° plies initiated. Those damages grew with cycles. Furthermore, cracks in other 90° and -35° plies and cracks in 35° plies initiated from transverse cracks were observed with further cycles.

Fig. 4 shows microscopic damage in specimen EM at 1 cycle. Micro-debonding between fiber and matrix was observed. However, cracks which penetrated in ply thickness were not observed. Figure 6 shows observation results at 50 cycles. Micro-debonding growth to the transverse crack and delamination from the transverse crack tip were observed, whereas transverse crack growth to adjacent plies was inhibited by resin rich region at the ply interfaces.

Fig. 5 shows microscopic damage in each specimen at 100 cycles. Delamination crack opening displacement and number of cracks were larger in specimen CY. This is due to higher thermal stress due to larger negative thermal expansion coefficient of PITCH-based carbon fiber.

(a) at 1 Cycle

Figure 2 Microscopic damage in specimen CM.
Figure 3 Microscopic damage in specimen CY at 1 cycle.

Figure 4 Microscopic damage in specimen EM.
In the present study, crack density is defined as the number of crack per unit length to evaluate microscopic damage quantitatively. Figures 6, 7 and 8 show crack density in specimens CM, CY and EM, respectively. As shown in the observation results, transverse crack density was larger in outermost plies in all types of specimens. In specimen EM, crack density in inner plies was smaller, which suggest higher interfacial strength between fiber and matrix. Crack density gradually increased with cycles in specimen CM, whereas increasing crack density was decelerated at about 50 cycles in specimen CY and CM. Then, crack density seemed to saturate at a certain level.

Bending moduli of specimens CM, CY and EM during thermal cycling are shown in Figures 9, 10 and 11, respectively. Bending modulus of specimen CM decreased at 1 cycle. Form the result above, this is mainly due to initial delamination initiation. In specimen CY, modulus decreased gradually and the decrease in modulus was decelerated at 70 cycles. This tendency is very different from in specimen CM.

In specimen EM, the decrease in modulus was decelerated at 50 cycles, which was more similar to transverse crack behavior than in specimen CY. In specimen CY, cracks in adjacent plies to 90° plies and delamination initiated, which also affected bending modulus.

In order to evaluate the contribution of types of damage to modulus reduction, normalized elastic modulus was shown in Fig. 12. Normalized elastic modulus is defined as bending modulus at each cycles divided by bending modulus at 0 cycles. Modulus of CM specimens decreased more than 1% at initial cycles. However, little change was observed after 10 cycles. Therefore, material CM is the best candidate to consider the long-term geometrical stability. Normalized modulus in specimen CY was lower than in specimen CM and EM. This result suggests that modulus reduction mainly depends on delamination and the contribution of transverse cracks to modulus reduction is lower.
Figure 6 Transverse crack density in specimen CM as a function of cycles.

Figure 7 Transverse crack density in specimen CY as a function of cycles.
Figure 8 Transverse crack density in specimen EM as a function of cycles.

Figure 9 Bending modulus of specimen CM as a function cycles.
Figure 10 Bending modulus of specimen CM as a function of cycles.

Figure 11 Bending modulus of specimen CM as a function of cycles.
4 Conclusions

In the present study, three types of CFRP laminate, such as PAN-based carbon fiber/ polycyanate ester resin (CM), PITCH-based carbon fiber/ polycyanate ester resin (CY) and PAN-based carbon fiber/ epoxy resin (EM), with near 0 thermal expansion coefficient were prepared as candidate materials for a large precise space structure. Cyclic thermal impact tests were conducted on the specimens to simulate space environment. For CY, delamination was a dominant microscopic damage during thermal cycles, whereas transverse cracking in 90° plies and associated matrix cracking in CM. In EM, transverse cracking in 90° plies was arrested by matrix rich region between plies. Elastic modulus decreased with cycles, especially for CY. This result suggested that delamination affects mechanical properties more than transverse cracks.

References