Thermal deformation generated on a CFRP laminated reflector

Shun TANAKA*，Tadashige IKEDA* and Atsuhiko SENBA**
* Department of Aerospace Engineering, Nagoya University
Furo-cho, Chikusa-ku, Nagoya, 464-8603, Japan
E-mail: tanaka.shun@g.mbox.nagoya-u.ac.jp
** Department of Vehicle and Mechanical Engineering, Meijo University
1-501 Shiogamaguchi, Tempaku-ku, Nagoya, 468-8502, Japan

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Abstract
Carbon Fiber Reinforced Plastic (CFRP) has high specific stiffness and its thermal deformation can be controlled by fiber orientation. Therefore, it is often adopted as a material of space observation systems. In this study, experiment, numerical and analytical calculation on thermal deformation of CFRP reflector models were conducted to investigate the characteristics of thermal deformation of CFRP reflectors (mirrors) for space observation systems. Two types of reflector models were manufactured, which were comprised of a quasi-isotropic CFRP laminate with and without an sprayed aluminum layer and a polyurethane layer on the top surface. The experimental results showed that the out-of-plane thermal deformation of the reflector model with the aluminum and polyurethane layers is considerably larger than that of the reflector model without the aluminum and polyurethane layers and maximum and minimum displacement were observed in specific directions. The result of the numerical calculation showed the same trend. Additionally, this trend was discussed analytically. Moreover, uncertainty of the structure and method of reducing out-of-plane displacement were discussed. When shape control to suppress thermal deformation of CFRP reflectors is considered, the result obtained in this work is important to determine the optimal placement of actuators.

Key words: CFRP laminates, Reflector, Space observation systems, Thermal deformation, Shape stability

1. Introduction

High precision space observation systems are necessary to realize high resolution space observation. In order to avoid the effect of atmosphere of the Earth, space observation is often performed in space and space observation systems are exposed to severe temperature variation in space. Therefore, they are required to keep high precision when they are exposed to temperature variation. Additionally, space observation systems utilized in space are required to be light and stiff to keep their configuration in zero gravity condition.

Carbon Fiber Reinforced Plastics (CFRPs) have high specific stiffness and small coefficient of thermal expansion, which can be controlled by fiber orientation. Therefore, they were utilized as a material of structural elements of space observation systems to reduce thermal deformation (Ozaki et al., 2001). They were also adopted as a material of a 7.2 m diameter ground based reflector (mirror) of a science mission (Kawachi et al., 2001).

As a research for application of CFRPs in space reflectors, the effects of moisture absorption and microcrack on dimensional stability of CFRPs were investigated and it was reported that CFRPs can be successfully used for high-precision structures that require micron-meter order of the dimensional stability (Abusafieh et al., 2001). Arao et al. studied creep deformation, moisture absorption, self-shrinking behavior (Arao et al., 2009) and residual stress relaxation (Arao et al., 2010). Yoon et al. (2012) investigated the effects of outgassing deformation and thermal deformation of CFRP reflectors on optical performance of space telescopes and concluded that the optical performance was significantly degraded by thermal deformation of the structure more than outgassing deformation.
In our previous work, Tanaka et al. investigated the effect of fiber orientation angle on thermal deformation of the CFRP reflectors (Tanaka et al., 2016) and concluded that the maximum and minimum displacement of out-of-plane thermal deformation caused by fiber orientation error has its peaks on the directions inclined ±45 degrees from the fiber orientation angle of the most surficial layer. When the out-of-plane thermal deformation is suppressed by actuators to realize high precision CFRP reflectors, such a result is important to determine the optimal placement of actuators.

In general, the surface of the CFRP reflectors are coated with aluminum to decrease surface roughness. Hence, in this study, in order to acquire further knowledge on thermal deformation of CFRP reflectors, experiment and finite-element analysis (FEA) on the thermal deformation of CFRP reflector models were performed to examine the effect of surface coating such as aluminum layer on the thermal deformation of the CFRP reflectors. The obtained results were discussed analytically. Moreover, method of reducing out-of-plane displacement was discussed.

2. Nomenclature

\[
\begin{align*}
E_{\text{Al}} & \quad \text{Elasticity modulus of aluminum.} \\
E_{\text{PU}} & \quad \text{Elasticity modulus of polyurethane.} \\
E_{11} & \quad \text{Elasticity modulus of fiber direction (1-direction) of CFRP.} \\
E_{22} & \quad \text{Elasticity modulus of transverse direction of fiber (2-direction) of CFRP.} \\
G_{12} & \quad \text{Shear elasticity modulus in 12-direction of CFRP.} \\
N^T_x, N^T_y, N^T_{xy} & \quad \text{Thermal axial force in } x, y \text{-directions and shear force in } xy \text{-direction, respectively,} \\
M^T_x, M^T_y, M^T_{xy} & \quad \text{Thermal bending moment in } x, y \text{ and twisting moment in } xy \text{-directions, respectively,} \\
[Q_{ij}]_k & \quad \text{Reduced stiffness matrix of } k \text{th layer.} \\
[Q_{ij}]_{\text{Al}} & \quad \text{Reduced stiffness matrix of aluminum layer.} \\
[Q_{ij}]_{\text{PU}} & \quad \text{Reduced stiffness matrix of polyurethane layer.} \\
[\bar{Q}_{ij}]_k & \quad \text{Transformed reduced stiffness matrix of } k \text{th layer.} \\
t_{\text{Al}} & \quad \text{Thickness of aluminum layer.} \\
t_{\text{PU}} & \quad \text{Thickness of polyurethane layer.} \\
z_k & \quad \text{Distance between neutral axis and lower surface of } k \text{th layer (upper surface of } (k-1) \text{th layer).} \\
\alpha_{\text{Al}} & \quad \text{Coefficient of thermal expansion of aluminum.} \\
\alpha_{\text{PU}} & \quad \text{Coefficient of thermal expansion of polyurethane.} \\
\alpha_1 & \quad \text{Coefficient of thermal expansion in 1-direction of CFRP.} \\
\alpha_2 & \quad \text{Coefficient of thermal expansion in 2-direction of CFRP.} \\
\Delta T & \quad \text{Temperature variation.} \\
\epsilon_x, \epsilon_y, \epsilon_{xy} & \quad \text{Axial strain in } x, y \text{-directions and shear strain in } xy \text{-direction, respectively.} \\
\theta_k & \quad \text{Fiber orientation angle of } k \text{th layer of CFRP layer.} \\
\kappa_x, \kappa_y, \kappa_{xy} & \quad \text{Curvature in } x, y \text{ and } xy \text{-directions, respectively.} \\
\nu_{\text{Al}} & \quad \text{Poisson’s ratio of aluminum.} \\
\nu_{\text{PU}} & \quad \text{Poisson’s ratio of polyurethane.} \\
\nu_{12} & \quad \text{Poisson’s ratio in 12-direction of CFRP.} \\
\nu_{23} & \quad \text{Poisson’s ratio in 23-direction,} \\
\phi & \quad \text{Anti-clockwise angle from the 0-degree direction of the CFRP laminate.}
\end{align*}
\]

3. Experiment

3.1. CFRP reflector model

Reflector models used in this research were composed of a quasi-isotropic CFRP laminate (TMP Inc., XN60/NM31, [0/−45/90/45]s) and cup-shaped. One of the reflector models used in this research is shown in Fig. 1. It has aluminum sprayed layer and polyurethane coated layer on the top surface. Polyurethane was sprayed to improve the appearance of the reflector model. The radius of curvature was 1000mm and the diameter was 300mm. The thickness of the reflector model without the aluminum and polyurethane layers was 0.86mm. That of the reflector model with aluminum and polyurethane layers was 0.98mm. The target thickness of aluminum spray was 0.02mm and thus, that of polyurethane...
layer was approximately 1.0mm. They were fixed on a jig of the experimental setup shown in Fig. 2 with a screw attached at the center.

3.2. Shape measurement system

The thermal deformation of the reflector models was measured by the shape measurement system shown in Fig. 2. The jig that is fixed to the reflector models can rotate to change the relative direction of $x$, $y$-axis of the measurement system and zero degree direction of laminate. The reflector models were covered by a thermostatic chamber with a heat-resistant glass [SANMEC Inc., special-ordered] as shown in Fig. 3. The thermostatic chamber has small fan to stir the air inside and can heat up to 200°C uniformly inside. The shape of the reflector models was measured by a laser displacement sensor [Keyence, LK-H080] fixed on two-axis linear slider system [THK, KRF] through the glass. The measurement was performed at discrete points in interval of 10mm for $x$ and $y$-directions in 300mm $\times$ 300mm square domain before and after heating up the reflector models. Zero degree direction of laminate of reflector models corresponded to $x$-axis of the shape measurement system. The out-of-plane ($z$-directional) displacement of the reflector models was obtained by subtracting the shape measured before heating from that measured after heating. In this process, the effect of thermal expansion of the jig fixing the reflector models was removed by assuming that the displacement of center of the reflector model was equal to zero.
3.3. Experimental result

Figures 4 and 5 show the experimentally observed \( z \)-directional displacement of the reflector model with and without the aluminum and polyurethane layers, respectively, at the temperature difference of approximately 50\( ^\circ \)C. Note that the displacement of the point outside the reflector models is not zero because of the process to remove the effect of thermal expansion of the jig fixing the reflector models. The displacement was not uniform and both positive and negative displacement can be observed alternately along the edge of both the reflector models. The largest positive displacement was observed at approximately \( \phi = -30, 115 \) degrees directions around the edge of the reflector models and the largest negative displacement was observed at approximately \( \phi = -140, 45 \) degrees directions. The maximum displacement of the reflector model with aluminum and polyurethane layers was approximately 0.15mm and minimum displacement was approximately -0.25mm and those of the reflector model without aluminum and polyurethane layers were approximately 0.03mm and -0.03mm, respectively.

4. Finite-element analysis

4.1. Model of finite-element analysis

An engineering simulation software “ANSYS” was used in the FEA. The analytical model of the reflector models was composed of a shell element (SHELL181, 29,453 nodes) and assumed to be fixed at the center. Mechanical constants assumed in the calculation are shown in Table 1. The material constants for CFRP were measured by ourselves but typical values were used for those for the aluminum layer and the polyurethane layer. The reflector model used in experiment had 8 layers of CFRP and its thickness was 0.86mm. Accordingly, the thickness of each CFRP layer was assumed to be 0.86mm/8 = 0.1075mm. Those of aluminum and polyurethane layers were assumed to be 0.02mm and 0.1mm, respectively, because they could not be measured separately. The thermal load was assumed to be 50\( ^\circ \)C.

<table>
<thead>
<tr>
<th>CFRP:</th>
<th></th>
<th>Aluminum layer:</th>
<th></th>
<th>Polyurethane layer:</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{11} )</td>
<td>GPa</td>
<td>340</td>
<td>GPa</td>
<td>70</td>
</tr>
<tr>
<td>( E_{22} )</td>
<td>GPa</td>
<td>5.2</td>
<td>0.3</td>
<td>21 \times 10^{-6}</td>
</tr>
<tr>
<td>( G_{12} )</td>
<td>GPa</td>
<td>3.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( v_{12} )</td>
<td></td>
<td>0.35</td>
<td></td>
<td>100 \times 10^{-6}</td>
</tr>
<tr>
<td>( \alpha_1 )</td>
<td>1/K</td>
<td>-0.7 \times 10^{-6}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>( \alpha_2 )</td>
<td>1/K</td>
<td>35 \times 10^{-6}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

4.2. Result of finite-element analysis

Figures 6 and 7 show the calculated out-of-plane thermal deformation of the reflector model with and without the aluminum and polyurethane layers, respectively. Distribution of \( z \)-directional displacement on the edge of the reflector model with the aluminum and polyurethane layers is shown in Fig. 8. Maximum displacement of the reflector model with the aluminum and polyurethane layers was 0.202mm and it was found in the direction of approximately \( \phi = -22, 158 \) degrees.
degrees. Minimum displacement was \(-0.399\) mm and it was found in the direction of \(\phi = -119\), 61 degrees. Although the value of maximum and minimum displacement observed in the experiment and obtained in FEA do not agree quantitatively, trend of distribution of positive and negative displacement showed good agreement with the experimental result to some extent. On the other hand, those of the reflector model without the aluminum and polyurethane layers were quite small and distribution of positive and negative displacement was completely different. Maximum displacement was \(1.04 \times 10^{-3}\) mm and there were no negative displacement. This value is significantly smaller than the experimental result. It was made clear by considering the in-plane displacement that this displacement was a result of uniform expansion of the reflector model. However, the experimental result showed \(z\)-directional displacement of approximately \(0.03\) mm in maximum. A possible cause of this is that error existed in fiber orientation angle of the reflector model used in experiment. In our previous work, it was shown that saddle shaped out-of-plane thermal deformation is generated by fiber orientation error (Tanaka et al., 2016).

The results of FEA showed the trend that out-of-plane thermal deformation of the reflector model with the aluminum and polyurethane layers is larger than that of the reflector without the aluminum and polyurethane layers, and this trend is in good agreement with the experimental results. Thus, it can be concluded that aluminum spray and polyurethane coating degrades shape stability against temperature variation of the CFRP reflectors.

5. Analytical discussion

We will consider the deformation of the laminated plate by temperature variation analytically to discuss the cause of out-of-plane deformation of the reflector model. Strain induced by the force \([N^T]\) and the moment \([M^T]\) can be described...
as (Arao et al., 2010, Jones, 1975),

$$\begin{align*}
\mathbf{ε}_x &= \begin{bmatrix} A_{11} & A_{12} & A_{16} & B_{11} & B_{12} & B_{16} \\
A_{12} & A_{22} & A_{26} & B_{12} & B_{22} & B_{26} \\
A_{16} & A_{26} & A_{66} & B_{16} & B_{26} & B_{66} \\
B_{11} & B_{12} & B_{16} & D_{11} & D_{12} & D_{16} \\
B_{12} & B_{22} & B_{26} & D_{12} & D_{22} & D_{26} \\
B_{16} & B_{26} & B_{66} & D_{16} & D_{26} & D_{66} \end{bmatrix}^{-1} \begin{bmatrix} N_{x1}^T \\
N_{x2}^T \\
N_{xy}^T \end{bmatrix},
\end{align*}$$

(1)

The terms $A_{ij}$, $B_{ij}$ and $D_{ij}$ can be calculated as the following matrices,

$$\begin{align*}
[A_{ij}] &= \frac{1}{2} \sum_{k=1}^{8} [Q_{ij}]_{ik} (z_{k+1} - z_k) + [Q_{ij}]_A t_A + [Q_{ij}]_{PU} t_{PU},
\end{align*}$$

(2)

$$\begin{align*}
[B_{ij}] &= -\frac{1}{2} \sum_{k=1}^{8} [Q_{ij}]_{ik} \left( z_{k+1}^2 - z_k^2 \right) + \frac{1}{2} [Q_{ij}]_A \left( (z_9 + t_A)^2 - z_9^2 \right) - \frac{1}{2} [Q_{ij}]_{PU} \left( (z_9 + t_A + t_{PU})^2 - (z_9 + t_A)^2 \right),
\end{align*}$$

(3)

$$\begin{align*}
[D_{ij}] &= \frac{1}{3} \sum_{k=1}^{8} [Q_{ij}]_{ik} \left( z_{k+1}^3 - z_k^3 \right) + \frac{1}{3} [Q_{ij}]_A \left( (z_9 + t_A)^3 - z_9^3 \right) + \frac{1}{3} [Q_{ij}]_{PU} \left( (z_9 + t_A + t_{PU})^3 - (z_9 + t_A)^3 \right).
\end{align*}$$

(4)

Components of the reduced stiffness matrices $[Q_{ij}]_A$, $[Q_{ij}]_A$, and $[Q_{ij}]_{PU}$ can be obtained by the following equations,

$$\begin{align*}
Q_{11} &= \frac{E_{11}}{1 - \nu_{12} \nu_{21}}, \quad Q_{12} = \frac{\nu_{12} E_{22}}{1 - \nu_{12} \nu_{21}}, \quad Q_{22} = \frac{E_{22}}{1 - \nu_{12} \nu_{21}}, \quad Q_{66} = G_{12},
\end{align*}$$

(5)

$$\begin{align*}
(Q_{11})_A &= (Q_{22})_A = \frac{E_{Al}}{1 - \nu_{Al}^2}, \quad (Q_{12})_A = \frac{\nu_{Al} E_{Al}}{1 - \nu_{Al}^2}, \quad (Q_{66})_A = \frac{E_{Al}}{2(1 + \nu_{Al})},
\end{align*}$$

(6)

$$\begin{align*}
(Q_{11})_{PU} &= (Q_{22})_{PU} = \frac{E_{PU}}{1 - \nu_{PU}^2}, \quad (Q_{12})_{PU} = \frac{\nu_{PU} E_{PU}}{1 - \nu_{PU}^2}, \quad (Q_{66})_{PU} = \frac{E_{PU}}{2(1 + \nu_{PU})},
\end{align*}$$

(7)

where $\nu_{21}$ can be written as,

$$\begin{align*}
\nu_{21} &= \frac{\nu_{12} E_{22}}{E_{11}}.
\end{align*}$$

(8)

Components of the transformed reduced stiffness matrix $[Q_{ij}]_{ik}$ can be obtained by the following equations,

$$\begin{align*}
\tilde{Q}_{11} &= Q_{11} \cos^2 \theta_k + 2 (Q_{12} + 2Q_{66}) \sin^2 \theta_k \cos^2 \theta_k + Q_{22} \sin^4 \theta_k,
\end{align*}$$

(9)

$$\begin{align*}
\tilde{Q}_{12} &= (Q_{11} + Q_{22} - 4Q_{66}) \sin^2 \theta_k \cos^2 \theta_k + Q_{12} \left( \sin^4 \theta_k + \cos^4 \theta_k \right),
\end{align*}$$

(10)

$$\begin{align*}
\tilde{Q}_{22} &= Q_{11} \sin^4 \theta_k + 2 (Q_{12} + 2Q_{66}) \sin^2 \theta_k \cos^2 \theta_k + Q_{22} \cos^4 \theta_k,
\end{align*}$$

(11)

$$\begin{align*}
\tilde{Q}_{16} &= (Q_{11} - Q_{12} - 2Q_{66}) \sin \theta_k \cos^3 \theta_k + (Q_{12} - Q_{22} + 2Q_{66}) \sin \theta_k \cos \theta_k,
\end{align*}$$

(12)

$$\begin{align*}
\tilde{Q}_{26} &= (Q_{11} - Q_{12} - 2Q_{66}) \sin \theta_k \cos \theta_k + (Q_{12} - Q_{22} + 2Q_{66}) \sin \theta_k \cos^3 \theta_k,
\end{align*}$$

(13)

$$\begin{align*}
\tilde{Q}_{66} &= (Q_{11} + Q_{22} - 2Q_{66}) \sin \theta_k \cos^2 \theta_k + Q_{66} \left( \sin^4 \theta_k + \cos^4 \theta_k \right).
\end{align*}$$

(14)

The force $[N^T]$ and the moment $[M^T]$ are thermal force and moment that generates deformation which actually generated by thermal deformation. These can be obtained by following equations,

$$\begin{align*}
[N^T] &= \sum_{k=1}^{8} [T_k]^{-1} [Q_{ij}]_{ik} \Delta T (z_{k+1} - z_k) + [Q_{ij}]_A \Delta T t_A + [Q_{ij}]_{PU} \Delta T t_{PU},
\end{align*}$$

(15)

$$\begin{align*}
[M^T] &= -\frac{1}{2} \sum_{k=1}^{8} [T_k]^{-1} [Q_{ij}]_{ik} \Delta T (z_{k+1}^2 - z_k^2) - \frac{1}{2} [Q_{ij}]_A \Delta T \left( (z_9 + t_A)^2 - z_9^2 \right)
\end{align*}$$

$$\begin{align*}
&- \frac{1}{2} [Q_{ij}]_{PU} \Delta T \left( (z_9 + t_A + t_{PU})^2 - (z_9 + t_A)^2 \right),
\end{align*}$$

(16)
where,
\[
[T_k]^{-1} = \begin{bmatrix}
  \cos^2 \theta_k & \sin^2 \theta_k & -\frac{1}{2} \sin 2\theta_k \\
  \sin^2 \theta_k & \cos^2 \theta_k & \frac{1}{2} \sin 2\theta_k \\
  \sin 2\theta_k & -\sin 2\theta_k & \cos 2\theta_k
\end{bmatrix},
\]  
(17)

\[
\{\alpha\} = \begin{bmatrix}
  \alpha_1 \\
  \alpha_2 \\
  0
\end{bmatrix}, \quad \{\alpha_{AI}\} = \begin{bmatrix}
  \alpha_{AI} \\
  \alpha_{AI} \\
  0
\end{bmatrix}, \quad \{\alpha_{PU}\} = \begin{bmatrix}
  \alpha_{PU} \\
  \alpha_{PU} \\
  0
\end{bmatrix}.
\]  
(18)

Note that positive direction of moment \(\{M^T\}\) was defined so that it provides convex upward \(z\)-directional displacement. The curvature induced by temperature variation in the \(\phi\)-direction \(\kappa_T\) can be obtained as,
\[
\kappa_T = \kappa_x \cos^2 \phi + \kappa_y \sin^2 \phi + \frac{1}{2} \kappa_{xy} \sin 2\phi.
\]  
(19)

Again, note that positive curvature \(\kappa_T\) provides convex upward \(z\)-directional displacement. This equation can be transformed as,
\[
\kappa_T = \frac{1}{2} \left( \kappa_x + \kappa_y \right) + \sqrt{\left(\kappa_x - \kappa_y\right)^2 + \kappa_{xy}^2 \cos 2(\phi - \beta)}.
\]  
(20)

where,
\[
\beta = \frac{1}{2} \tan^{-1}\left(\frac{\kappa_{xy}}{\kappa_x - \kappa_y}\right).
\]  
(21)

It can be understood from Eq. (20) that \(\kappa_T\) takes the maximum and minimum when \(2(\phi - \beta) = 180n [\text{deg.}]\), where \(n\) denotes arbitrary integer.

If the aluminum and polyurethane layers do not exist, the term \(B_{ij}\) is zero because of symmetry. As a result, the normal force \(\{N^T\}\) and the curvature \(\kappa_x, \kappa_y\) and \(\kappa_{xy}\) are not coupled. The moment induced by temperature variation \(\{M^T\}\) also vanish because of symmetry. As a result, the curvature \(\kappa_T\) is zero and no out-of-plane thermal deformation is generated by temperature variation.

However, if the aluminum and polyurethane layers exist on the top surface, neither the term \(B_{ij}\) nor the moment \(\{M^T\}\) are zero because of asymmetry. As a result, the curvature \(\kappa_T\) is not zero and out-of-plane thermal deformation is generated.

Calculated results of \(\kappa_x, \kappa_y\) and \(\kappa_{xy}\) were approximately \(-0.128 \times 10^{-6} \text{ m}^{-1}\), \(-0.57 \times 10^{-6} \text{ m}^{-1}\) and \(-0.524 \times 10^{-6} \text{ m}^{-1}\), respectively. The calculated \(\kappa_T\) of the plate with the aluminum and polyurethane layers is shown in Fig. 9. \(\kappa_T\) has its maximum and minimum at directions of approximately \(\phi = -25\), 155 degrees and \(\phi = -115\), 65 degrees, respectively, which can be understood by Eqs. (20) and (21). The distribution of the curvature is not uniform. This is because \(\kappa_x\) and \(\kappa_y\) are different with each other and \(\kappa_{xy}\) exists. The directions of maximum and minimum curvature do not agree with any fiber orientation angle. This is due to existence of the torsional curvature \(\kappa_{xy}\) in fiber direction. These directions agree with the experimentally observed directions of maximum and minimum \(z\)-directional displacement, respectively, to some extent. This calculated result also shows that the asymmetry caused by the aluminum and polyurethane layers significantly degrades shape stability of CFRP reflectors against temperature variation.

6. Discussion on results

6.1. Difference between experimental result and analytical result

In the experiment, the largest positive displacement and the largest negative displacement were found on the directions of approximately \(\phi = -30\), 115 degrees and \(\phi = -140\), 45 degrees, respectively. However, in the finite-element analysis, the maximum and minimum displacement were found on the directions of \(\phi = -22\), 158 degrees and \(\phi = -119\), 61 degrees, respectively. Candidates of the cause of this difference are mentioned as follows;

- Fiber orientation error of CFRP
- Irregularity of thickness of CFRP layers
- Irregularity of thickness of surface coating
- Others
As pointed out in the previous study, the fiber orientation error of CFRP is inevitable and it has effect on out-of-plane thermal deformation of CFRP reflectors (Tanaka et al., 2016). When fiber orientation error of +1 degree or −1 degree is assumed in the top layer of the CFRP layers, the distribution of out-of-plane displacement rotates. In case of the fiber orientation error of +1 degree, the largest positive displacement and largest negative displacement are observed in directions of $\phi = -14^\circ$, 166 degrees and $\phi = -117^\circ$, 63 degrees, respectively. The displacements in this case decrease by 13%. On the other hand, in case of the fiber orientation error of −1 degree, they are observed in the directions of $\phi = -27^\circ$, 153 degrees and $\phi = -121^\circ$, 59 degrees, respectively. The displacements in this case increase by 13%.

In the analysis, the thickness of each layer was assumed to be uniform. However, there is possibility of existence of thickness irregularity in each CFRP layer. When the thickness of the top layer of the CFRP laminate is reduced 10%, the distribution of out-of-plane displacement rotates and the largest positive displacement and the largest negative displacement are observed in directions of $\phi = -40^\circ$, 140 degrees and $\phi = -124^\circ$, 56 degrees, respectively. The displacements in this case decrease by 13%.

The thickness of surface coating may have also uncertainty. When the thickness of the aluminum and polyurethane layers was assumed to be 0.03mm and 0.09mm, respectively are assumed, which were originally assumed to be 0.02mm and 0.1mm, respectively, the distribution of out-of-plane displacement slightly rotates and largest positive displacement and negative largest displacement are found in the directions of $\phi = -21^\circ$, 159 degrees and $\phi = -119^\circ$, 61 degrees, respectively. The rotation of the displacement is relatively small, but the magnitude of the displacement increased by 29%.

These results indicate that the distribution of the out-of-plane displacement is affected by the uncertainties of components of the reflector. In order to reveal detailed phenomenon, further investigation is required.

6.2. Performance degradation caused by thermal deformation

A previous study by Yoon et al. (Yoon et al., 2012) concluded that thermal deformation significantly degrades the optical performance of CFRP reflectors. In this Section, the effect of aluminum and polyurethane layers on optical performance of CFRP reflectors is investigated.

Root Mean Square (RMS) error is an important parameter of the optical performance of reflectors. In general, optical performance of reflectors extremely degrades when this value exceeds 1/14 of the wavelength of electromagnetic wave to be measured (Suiter, 1994).

The calculated thermal RMS error of the reflector model with surface coating was 1.754μm/°C. Note that this value is a result of a reflector model with 300mm diameter and if the size of the reflector increases, the RMS error also increases accordingly.

As mentioned before, in order for high resolution observation, the RMS error must be less than 1/14 of the wavelength and temperature variation should be controlled strictly to guarantee the required precision. For example, if the observation system has the same size of the reflector model used in this study and the wavelength is assumed to be 10μm, which is typical wavelength of thermal infrared, temperature variation should be controlled within 0.407°C. However, if the size of the reflector increases, the temperature range decreases and temperature control becomes difficult accordingly. For another example, if the wavelength is assumed to be 0.5μm, which is typical wavelength of visible light, temperature variation should be less than 0.0204°C and temperature control of this order is almost impossible. Accordingly, in order to realize high resolution space observation with CFRP reflectors, some other methods of suppressing out-of-plane thermal deformation of the reflector are necessary.

6.3. Method of reducing out-of-plane thermal deformation

In order to realize large space reflectors, out-of-plane thermal deformation must be suppressed. Additionally, the geometry variation caused by other phenomena such as outgassing deformation, moisture absorption and manufacturing error cannot be ignored. In order to deal with those geometry variations, active shape control on reflectors has been studied. Chen et al. reduced shape error caused in inflation of structure of 0.2-meter-diameter polymer based reflector model by thin polyvinylidene difluoride (PVDF) piezo-electric actuators attached on the surface (Chen et al., 2007). Tanaka controlled surface shape of 300mm diameter, 1mm thickness secondary mirror model composed of aluminum alloy by piezo-electric stack actuators and surface shape error of 0.9mm in maximum was controlled by six linear actuators (Tanaka, 2014). Wang et al. optimized placement of distributed piezo-electric actuators attached on a honeycomb sandwich reflector to reduce out-of-plane displacement caused by gravity (Wang et al., 2015).

When the active shape control is adopted to achieve the desired precision, the knowledge of the thermal deformation...
distribution shown in Sections 3 to 5 and the discussions in this Section are useful to determine optimal placement of the actuators. However, the detailed mechanism of actual thermal deformation has not been revealed yet. Further discussions not only on the mechanism but also on methods to suppress out-of-plane thermal deformation are planned as a future work.

7. Conclusion

In this study, experiment on thermal deformation of CFRP reflector models composed of quasi-isotropic CFRP laminate with and without the aluminum spray and polyurethane coating was performed. As a result, considerably large out-of-plane thermal deformation was generated on a reflector model with the aluminum and polyurethane layers compared to that without the aluminum and polyurethane layers. The same trend was observed in FEA on thermal deformation of these CFRP reflector models and it was demonstrated analytically that the aluminum and polyurethane layers degrade shape stability against temperature variation of CFRP reflectors. Accordingly, some methods to suppress the thermal deformation of the CFRP reflectors, such as controlling surface shape by actuators are needed for practical application of them. In the analysis, the maximum and minimum displacement were observed in the directions incline approximately -27 degrees and 59 degrees, respectively and this result from this research is useful to determine placement of actuators. However, the result of error evaluation indicated that further discussion on the mechanism of the thermal deformation is necessary.

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References


