STATISTICAL EVALUATION ON THE OUT-OF-PLANE THERMAL DEFORMATION OF CFRP LAMINATES DUE TO FIBER ORIENTATION ERROR

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Abstract

Carbon fiber reinforced plastic (CFRP) exhibits high specific stiffness and low coefficient of thermal expansion. Thus, it is regarded as a suitable material for high-precision, large reflectors for space observation systems. However, it was made clear that non-negligible out-of-plane thermal deformation would be generated on CFRP reflectors due to fiber orientation errors which occur during laminating process. In this research, as a first step to find the method to suppress the effect of fiber orientation errors on the out-of-plane thermal deformation of CFRP reflectors, the out-of-plane thermal deformations of CFRP plates with some different stacking sequences were simulated probabilistically and discussed statistically. As a result, it was made clear that the effect of fiber orientation errors can be mitigated by increasing the number of layers, i.e., utilizing as thin a prepreg as possible. It was also made clear that optimizing stacking sequence is an effective method to mitigate the effect of fiber orientation errors and quasi-isotropic laminate is not the optimal stacking sequence from this point of view.

1. Introduction

High-precision space observation systems are essential to achieve further advances in space science. For these observation systems, high-precision and large reflectors (mirrors) are necessary. Space observations are sometimes performed in space to avoid the effect of Earth's atmosphere. Therefore, the observation systems are mounted on satellites and launched by rockets into space. Reducing the payload is one of the greatest importance and thus observation systems should be as light as possible. Also, they are exposed to severe temperature conditions in space. Therefore, their thermal deformation would be an issue. Additionally, the shape irregularity occurs due to the difference of the gravity between ground and space is non-negligible. Considering these conditions, the material of space observation systems is required to have both high specific stiffness and low coefficient of thermal expansion. Carbon fiber reinforced plastic (CFRP) exhibits aforementioned characteristics and is therefore expected as a next-generation material for space-based reflectors.

As research toward the realization of the space-based CFRP reflectors, Abusafieh et al. investigated the effect of moisture absorption and microcrack in CFRP on its dimensional stability and concluded that CFRP can be used for high-precision structures which require micron-orders of dimensional stability [1]. Then, Arao et al. studied the long-term deformation such as residual stress relaxation [2], creep deformation, moisture absorption, and self shrinking [3] of the CFRP. Yoon et al. assessed the effects of the thermal deformation and the outgassing deformation of the composite structure of a telescope on its optical performance and concluded that the thermal deformation degraded the optical performance of the telescope more than the outgassing deformation [4]. From this result, when considering the feasibility of the space-based CFRP reflectors, their thermal deformation should be investigated.

In the previous study, authors manufactured a reflector model composed of a quasi-isotropic CFRP laminate and measured its out-of-plane thermal deformation. As a result, it was demonstrated that non-negligible out-of-plane thermal deformation occurs in spite of the symmetrical stacking sequence [5]. Also, the finite-element analysis simulating the same condition was performed to find the cause of this out-of-plane thermal deformation and it was concluded that the errors of the fiber orientation angle was one of the most significant causes of the deformation [6]. When manufacturing CFRP laminate, the fiber orientation errors are unavoidable. Thus, in order to realize space-based CFRP reflectors which require high dimensional stability against large temperature variations, the method to suppress the out-of-plane thermal deformation due to fiber orientation errors is essential.

In this study, as a method to mitigate the effect of the fiber orientation errors on the out-of-plane thermal deformation of CFRP reflectors, changing the number or layers and/or the stacking sequence was proposed. As a first step to find the stacking sequences that suppress the effect of the fiber orientation errors, the out-of-plane thermal deformations of CFRP laminated plates with different stacking sequences caused by the existence of fiber orientation errors were investigated probabilistically and their characteristics such as the magnitude and the distribution were assessed. Then, the stacking sequences that minimize the magnitude of the out-of-plane thermal deformation were sought.

2. Probabilistic assessment on the thermal deformation of CFRP plates

In this study, the curvatures of CFRP plates with different stacking sequences which include fiber orientation errors were simulated probabilistically and their statistics values such as the standard deviations and the kurtosises of the distributions were assessed.

First, the original stacking sequences which does not include fiber orientation errors were introduced. In this simulation, in order to investigate the effects of changing the number of layers and the stacking sequence on the out-of-plane thermal deformation of CFRP laminates, three target stacking sequences were introduced. One had eight layers in total and was $[0/-45/90/45]_s$. Others had 16 layers and were $[0_2/-45_2/90_2/45_2]_s$ and $[0/-45/90/45]_{2s}$. The total thickness of the CFRP laminates was assumed to be 0.8 mm, which was kept the same regardless the number of layers. Thus, the thickness of each layer was 0.1 mm for 8 layers and 0.05 mm for 16 layers.

Then, the fiber orientation errors were added on the orientation angle of each layer. In this study, the fiber orientation errors were assumed to be random numbers which follow the normal distribution of 0.4° in standard deviation, according to the result of the assessment by Arao et al [7]. The curvatures in 0°-, 10°-, 20°-,…, 170°-directions of each CFRP plate with the stacking sequence which includes fiber orientation errors generated by temperature variation of +1 K were calculated with classical lamination theory [8]. The assumed material constants are listed in Table 1. The curvatures of the 18 directions were assessed as the samples of the curvatures. The standard deviation and the kurtosis of the distribution of the samples were obtained from the results of 50,000 patterns of the stacking sequence with fiber orientation errors.

Table 1. The material constants assumed in the analysis.

E_L	340 GPa
E_T	5.2 GPa
G_{LT}	3.9 GPa
ν_{LT}	0.35
ν_{TT}	0.3
α_L	-0.7×10^{-6} K^{-1}
α_T	35×10^{-6} K^{-1}

3. Simulation results

Figures 1 to 3 shows the histograms of the frequency of the simulated curvatures for $[0/-45/90/45]_s$, $[0_2/-45_2/90_2/45_2]_s$, and $[0/-45/90/45]_{2s}$, respectively. The calculated standard deviations and kurtosises are listed in Table 2.

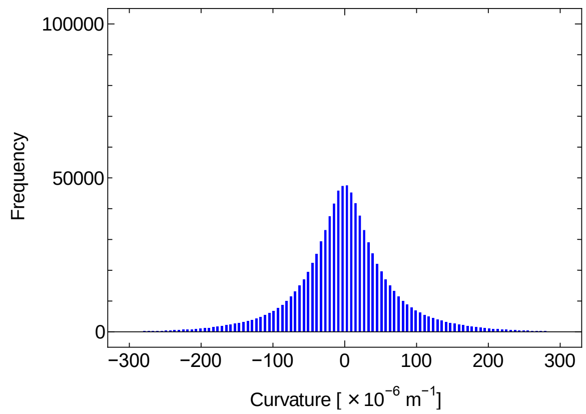

Figure 1. A histogram of the simulated curvatures generated by the thermal deformation of the CFRP plate due to fiber orientation errors (target stacking sequence: $[0/-45/90/45]_s$).

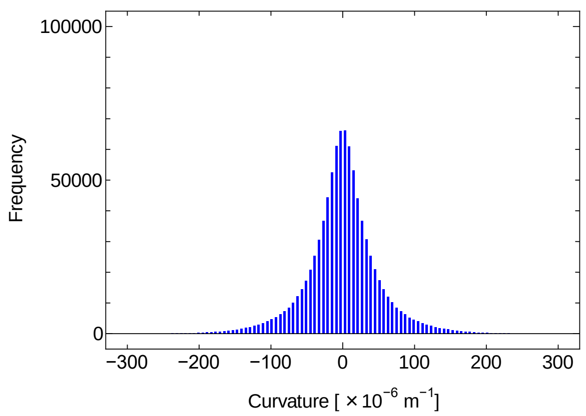

Figure 2. A histogram of the simulated curvatures generated by the thermal deformation of the CFRP plate due to fiber orientation errors (target stacking sequence: $[0_2/-45_2/90_2/45_2]_s$).

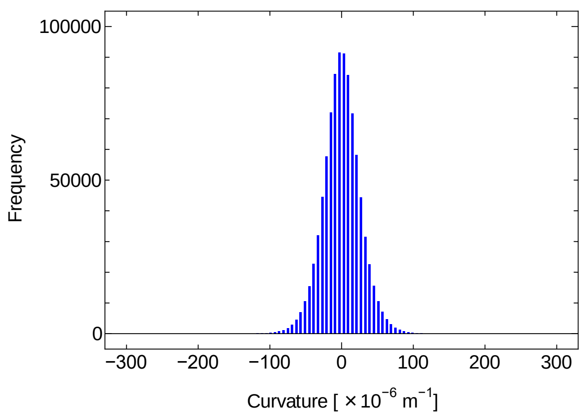

Figure 3. A histogram of the simulated curvatures generated by the thermal deformation of the CFRP plate due to fiber orientation errors (target stacking sequence: $[0/-45/90/45]_{2s}$).

Table 2. The standard deviations and kurtosises of the calculated curvature distributions.

Number of layers	Stacking sequence	Standard deviation [$\times 10^{-6}$ m^{-1}]	Kurtosis
8	$[0/-45/90/45]_s$	70.1	2.55
16	$[0_2/-45_2/90_2/45_2]_s$	49.6	2.51
16	$[0/-45/90/45]_{2s}$	25.8	0.78

Comparing the result of $[0/-45/90/45]_s$ with that of $[0_2/-45_2/90_2/45_2]_s$, it can be understood that the standard deviation decreased by increasing the number of layers. Thus, to suppress the out-of-plane thermal deformation generated on CFRP laminates due to fiber orientation errors, increasing the number of layers, i.e., utilizing as thin a prepreg as possible is an effective method. However, the kurtosis of the distribution remained almost the same.

On the other hand, comparing the result of $[0/-45/90/45]_s$ with that of $[0/-45/90/45]_{2s}$, both the standard deviation and the kurtosis of the distribution decreased with increasing the number of layers and changing the target stacking sequence. Moreover, the standard deviation of $[0/-45/90/45]_{2s}$ was smaller than that of $[0_2/-45_2/90_2/45_2]_s$, although the number of layers was the same. Thus, both the magnitude and the shape of the distribution of the curvature differed with the same number of layers but the different stacking sequences. Thus, it was implied that the further suppression of the out-of-plane thermal deformation of CFRP laminates due to fiber orientation errors by optimizing target stacking sequence can be expected.

4. Optimization of stacking sequence

4.1. Optimization conditions

The target stacking sequences for 8 layers and 16 layers were optimized so that each of them minimizes the standard deviation of the distribution of the curvatures generated by the out-of-plane thermal deformation due to fiber orientation errors of 0.4° in standard deviation. The target fiber orientation angles of the uppermost and the lowermost layers were kept to be 0°. Also, the target stacking sequences were kept symmetric. Thus, the target stacking sequences for 8 layers and 16 layers can be described as $[0/\theta_1/\theta_2/\theta_3]_s$ and $[0/\theta_1/\theta_2/\theta_3/\theta_4/\theta_5/\theta_6/\theta_7]_s$, respectively, with the variables of the fiber orientation angles θ_i.

4.2. Optimization results

The optimized target stacking sequences for 8 layers and 16 layers were $[0/-47/71.5/5]_s$ and $[0/-65/59.5/58/-46/-45/56/4]_s$, respectively. The histograms of the simulated curvatures of the CFRP plates with these target stacking sequences are shown in Fig. 4 and 5. The standard deviations and the kurtosises of the distributions are listed in Table 3. As shown in this table, the standard deviation of the curvatures of eight-layer plate was suppressed by approximately 31% from that with the target stacking sequence $[0/-45/90/45]_s$. This was slightly smaller than that of the plate with the target stacking sequence $[0_2/-45_2/90_2/45_2]_s$, although the number of layers was smaller. From this result, it was demonstrated that the out-of-plane thermal deformation of CFRP plates due to fiber orientation errors can be suppressed by arranging the appropriate stacking sequence and the quasi-isotropic laminate is not the optimal stacking sequence from this point of view. Similarly, the standard deviation of the curvatures of 16-layer plate was reduced by approximately 16% from that with the target stacking sequence $[0/-45/90/45]_{2s}$, and this result indicated the effectiveness of the stacking sequence optimization. Also, the kurtosis was reduced and became almost zero, which indicates that the distribution of the curvature became similar to the normal distribution.

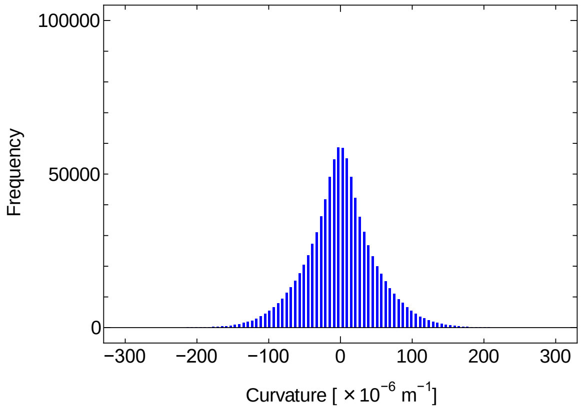

Figure 4. A histogram of the simulated curvatures generated by the thermal deformation of the CFRP plate with the optimized target stacking sequence due to fiber orientation errors (target stacking sequence: $[0/{-47}/71.5/5]_s$).

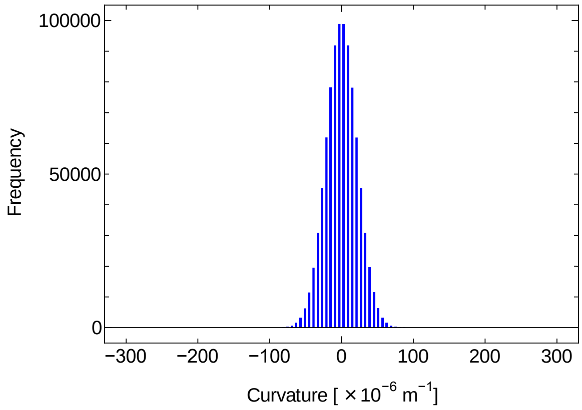

Figure 5. A histogram of the simulated curvatures generated by the thermal deformation of the CFRP plate with the optimized target stacking sequence due to fiber orientation errors (target stacking sequence: $[0/{-65}/59.5/58/{-46}/{-45}/56/4]_s$).

Table 3. The standard deviations and kurtosises of the curvature distributions for CFRP plates with the optimized stacking sequences.

Number of layers	Stacking sequence	Standard deviation [$\times 10^{-6}$ m^{-1}]	Kurtosis
8	$[0/{-47}/71.5/5]_s$	48.5	0.93
16	$[0/{-65}/59.5/58/{-46}/{-45}/56/4]_s$	21.6	0.03

5. Conclusion

In this study, the out-of-plane thermal deformations of CFRP laminated plates with some different stacking sequences due to the existence of fiber orientation errors were simulated probabilistically. As a result, it was made clear that increasing the number of layers, i.e., utilizing as thin a prepreg as possible is an effective method to suppress the effect of fiber orientation errors. Also, it was demonstrated that arranging appropriate stacking sequence is effective and the quasi-isotropic laminate is not the optimal stacking sequence when considering suppression of the out-of-plane thermal deformation due to fiber orientation errors. As a future work, the effect of optimizing the stacking sequence on the actual CFRP reflectors should be investigated.

Acknowledgments

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