DESIGN OF CFRP WITH FIBERS PLACED BY USING AN EMBROIDERY MACHINE

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1 Introduction

Mechanical properties of composite laminates significantly depend on the fiber orientation of each layer. Accordingly, if the fibers can be placed along desired orientations within a layer, a composite structure can be designed so as to be optimized for some properties. To this end some tailored fiber placement (TFP) methods were suggested [1, 2]. Tatting and Gurdal [1] used prepregs for processing the laminates, while Tosh and Kelly [2] used dry tows placed on a substrate by using an embroidery machine and this preform was impregnated with resin. The latter method is expected to be lower-cost because the prepregs themselves and their storage are costly.

To find the optimal orientations of the fibers an optimization method, such as the first order optimization method (FOO) [3], the particle swarm optimization (PSO) [4], and the method that the fibers are placed along the principal stress direction (PSD), can be applied. FOO has good convergence, although the obtained solutions may be in local solutions. PSO can find global solutions, although much iteration may be needed to get global solutions. PSD is better than the other methods with respect to the computational cost, although PSD is not always good method, when multiaxial stress condition or dynamic problems are considered.

In this paper, a method to design composites with optimal fiber orientations for an objective is established. The embroidery-based TFP is adopted and a stiffness property of a plate to which a load is applied around a corner is optimized.

2 Design method for composites with fibers placed along optimal path

2.1 Optimal fiber path

Continuous optimal path, along which fibers are placed by an embroidery machine, is obtained as follows. First, the target plate is divided into finite elements to predict quantities, such as displacements, stress, and strain, in an objective function or constraints of an optimization method by using an FEM. The optimal fiber angle θ in each element is estimated by using combination of the FEM and an optimization method. The paths of the fibers in the plate are determined if initial points of the paths along the edge of the plate are determined. In this paper the initial points are obtained by a streamline analogy [5].

Since a value of a stream function ψ does not vary along a streamline,

$$\begin{aligned}\frac{\partial\psi}{\partial s} &= \frac{\partial\psi}{\partial x}\frac{\partial x}{\partial s}+\frac{\partial\psi}{\partial y}\frac{\partial y}{\partial s} \\ &= \frac{\partial\psi}{\partial x}\cos\theta+\frac{\partial\psi}{\partial y}\sin\theta = 0\end{aligned} \quad . \tag{1}$$

The coordinate along the streamline is defined as *s*, and the *x*-*y* coordinates and the fiber angle θ are illustrated in Fig. 1. If the slope along the normal to the streamline is assumed to be constant $\overline{\psi}_{,n}$ along the edge on which the initial points are located;

$$\begin{aligned}\frac{\partial\psi}{\partial n} &= \frac{\partial\psi}{\partial x}\frac{\partial x}{\partial n}+\frac{\partial\psi}{\partial y}\frac{\partial y}{\partial n} \\ &= -\frac{\partial\psi}{\partial x}\sin\theta+\frac{\partial\psi}{\partial y}\cos\theta = \overline{\psi}_{,n}\end{aligned} \quad , \tag{2}$$

the initial points are determined by

$$\begin{bmatrix} \frac{\partial\psi}{\partial x} \\ \frac{\partial\psi}{\partial y} \end{bmatrix} = \overline{\psi},_n \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}, \quad (3)$$

for a certain constant $d\psi$. The coordinate along the normal to the streamline is defined as *n*.

2.3 Process of the composites

A carbon fiber dry preform is made by the embroidery machine as shown in Fig. 2, where the dry carbon fiber bundles are placed along the optimal paths on a substrate of a plain woven carbon fabric (PWCF). The preform is impregnated with epoxy resin by using the vacuum assisted resin transfer molding (VaRTM) method.

3 Results

3.1 Bending-torsion problem

To verify availability of the above mentioned procedure, it was applied to a bending-torsion problem shown in Fig. 3. In this case, TFP layers of the plate were divided into 15 regions in the *x*-direction and the fiber angles in the regions were optimized by three optimization methods; FOO, PSO, and PSD. The optimization problem was given by

$$\begin{aligned} &\text{Find: } \boldsymbol{\theta} = [\theta_1 \cdots \theta_{15}] \\ &\text{which minimalizes: } z_F \\ &\text{subject to constraints: } -90° \le \theta_i \le 90° \\ &|\theta_{i+1} - \theta_i| \le 15°, (i = 1 \cdots 15) \end{aligned} \quad (4)$$

z_F is the displacement of the load point shown in Fig. 3 and it is calculated by using a commercial FEM program ANSYS.

The stacking sequence of the laminates was [PWCF(0^o, 90^o)/TFP layer/PWCF(0^o, 90^o)/PWCF(0^o, 90^o)]$_{sym}$. The dry carbon bundles (Toho Tenax HTS40-12K) were placed on the PWCF (Toho Tenax W-3101) by inputting the optimized paths of the fiber bundles into the embroidery machine (Tajima TCWM-101) shown in Fig. 2. The preform was impregnated with epoxy resin (West System Z105 /Z206).

The thickness of the PWCF layer and TFP layer were assumed to be 0.22 mm and 0.54 mm, respectively. The elastic constants were set at values shown in Table 1.

Table 1. Elastic constants

PWCF	$E = 54.9[GPa], \nu = 0.28$
EPOXY	$E_m = 3.17[GPa], \nu_m = 0.35$
TFP	$E_{11} = 101.8[GPa], E_{22} = E_{33} = 5.62[GPa]$ $G_{12} = G_{31} = 1.76[GPa], G_{23} = 1.94[GPa]$ $\nu_{12} = 0.28, \nu_{23} = 0.45, \nu_{31} = 0.02$

3.2 Optimization results

The optimized fiber angles for the three optimization methods are shown in Figs. 4 (a), (b), and (c). These figures show a similar distribution of the fiber angles except for the distribution around the free end edge opposite the clamped edge for the PSD in Fig. 4 (c). This region is, however, not important in this case because the region is located within the free end edge and the load point and no stress are generated there in the material.

The fiber paths obtained from the fiber angle distribution optimized by FOO is shown in Fig. 5. The width between the neighbor fiber paths is not uniform along the streamline, that means the volume fraction of the fiber is not uniform.

The numerical and experimental results of the bending-torsion stiffness defined as z_F divided by the load are shown in Fig. 6. Laminate plates with layers of straight fibers placed in 0^o or -45^o direction instead of the optimized layers were also processed and their stiffness was compared with that of the plate with the optimized layers. It is seen that there is no difference among the optimization methods and that the stiffness can be improved by 13% compared to the plate with 0^o layers and by 95% to the plate with -45^o layers.

4 Discussion

The stiffness obtained by the calculation is much higher than that obtained from the measured data as shown in Fig. 6. This is because the mathematical model does not include the embroidery effects such as the damage by the sewing needle and the thickness distribution due to the non-uniform width between the paths.

When the carbon fiber bundles are placed on the PWCF by the embroidery machine, they are damaged by the embroidery needle. Accordingly, the stiffness of the laminate plates decreases. To include this needle effect into the FEM model, the stiffness in the tiny damaged portions shown in Fig. 7 was assumed to be lower than the healthy area in the TFP layer. Here it was assumed that the damaged portions were assumed to be square with the size of 10 mm^2, because the diameter of the sewing needle was about 1.0 mm, and only epoxy resin existed there.

The thickness of the TFP layer is distributed due to the difference in width between the neighbor paths of the placed fiber bundles. This also affects the stiffness of the plate. The thickness of the TFP layer t is inversely proportional to the width between the fiber paths d and d is inversely proportional to $\partial \Psi / \partial n$ [5]. The thickness distribution t can be estimated by

$$t \propto \frac{1}{d} \propto \frac{\partial \psi}{\partial n}. \quad (5)$$

The thickness distribution for FOO is shown in Fig. 8. The thickness of the laminates around the load point is thicker than the other region, where the thickness of the TFP layer along the clamped end was assumed to be the original thickness 0.54 mm. The obtained thickness distribution was applied to the FEM analysis.

The numerical results considering the effects of the sewing needle and the thickness distribution are shown in Fig. 9. It is seen that the error in the bending-torsion stiffness of the calculation from the experiment is drastically reduced from 136% to 24% for FOO. In this case, the thickness distribution in the TFP layer was not effective, because the thick region is concentrated around the load point only. Generally the thickness distribution is one of the significant factors in the composite property. Therefore, it is important to consider the effect of the thickness distribution.

The error is still large, although the numerical result approaches the experimental result by considering the embroidery effects. Since the damage of carbon fiber bundles is more complicated, it is necessary to observe the damage in detail and make a more realistic damage model. The material constants in the data sheet from the manufacturer were used in this calculation. To obtain more precise result the material constants of the processed plate should be measured.

5 Conclusion

A design method for an embroidery-based TFP was proposed. To verify availability of the method the laminate plate optimized for the bending-torsion problem was processed. The stiffness of the plate could be improved by the TFP. It was seen that the damage of the fiber bundles and the thickness distribution due to the embroidery play important roles on prediction of the properties of composites with the TFP layers. To predict the properties of the composites more precisely, more realistic damage model due to the sewing needle should be established. Moreover, the material constants of the processed plate should be measured.

References

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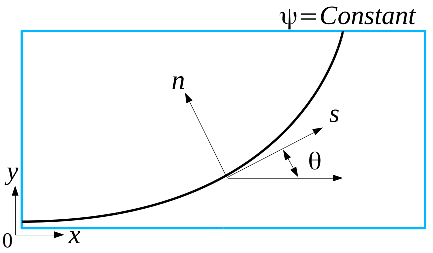

Fig. 1. Definition of stream function.

Fig. 2. Embroidery machine (Tajima TCWM-101).

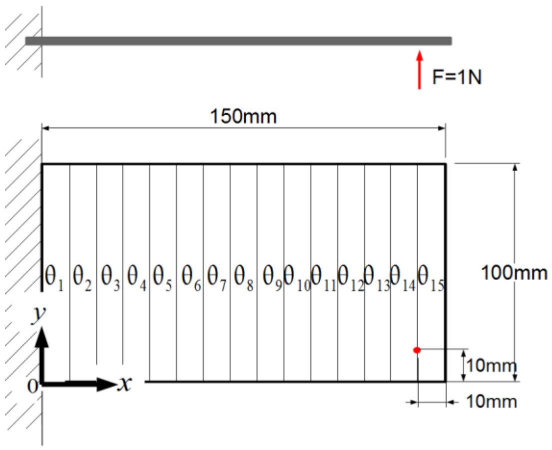

Fig. 3. Bending-torsion problem.

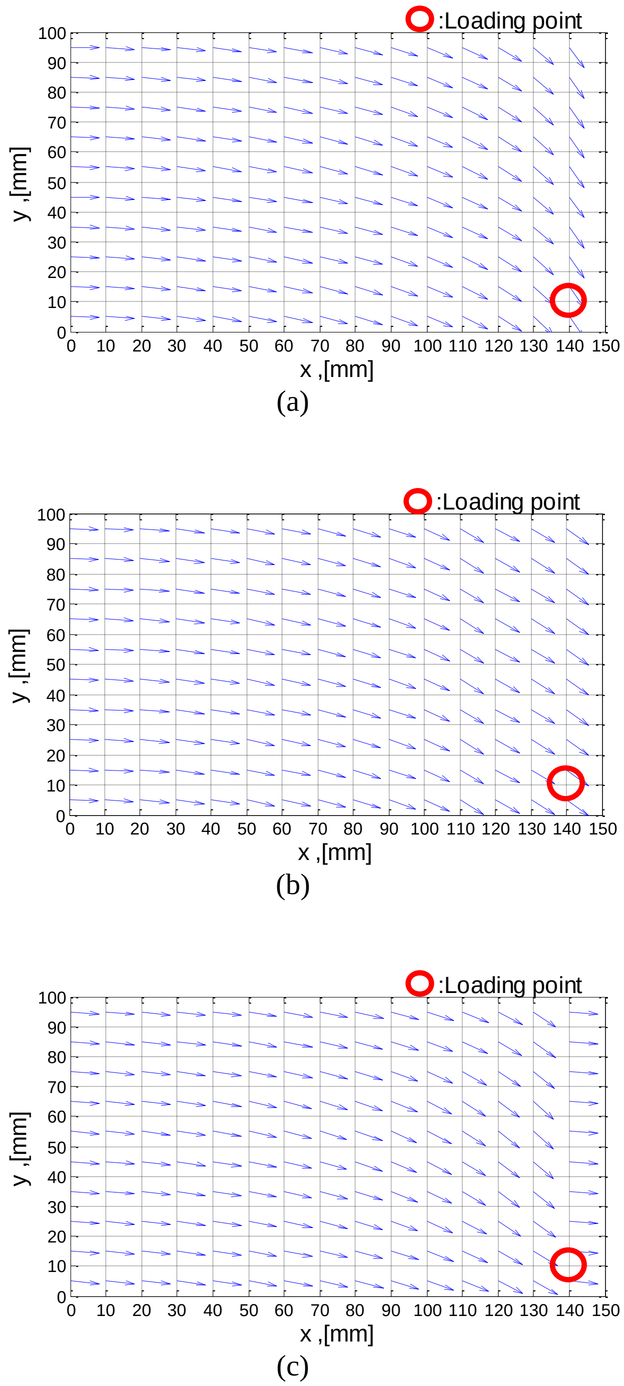

Fig. 4. Optimized fiber angles distribution.
(a) FOO, (b) PSO, (c) PSD.

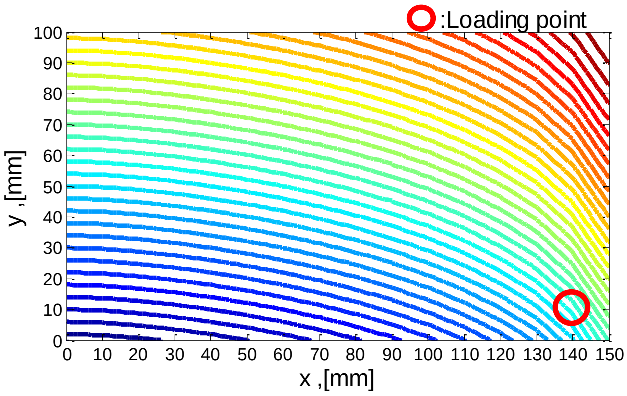

Fig. 5. Fiber paths.(FOO)

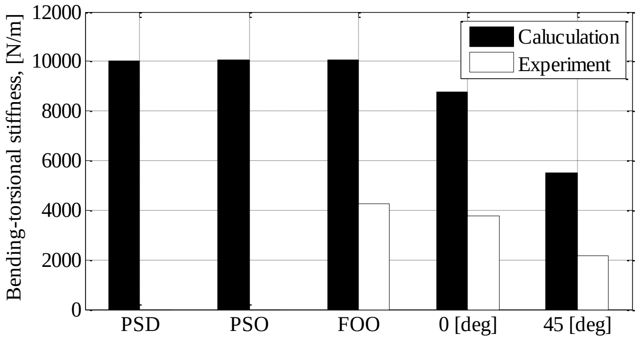

Fig. 6. Bending-torsional stiffness.

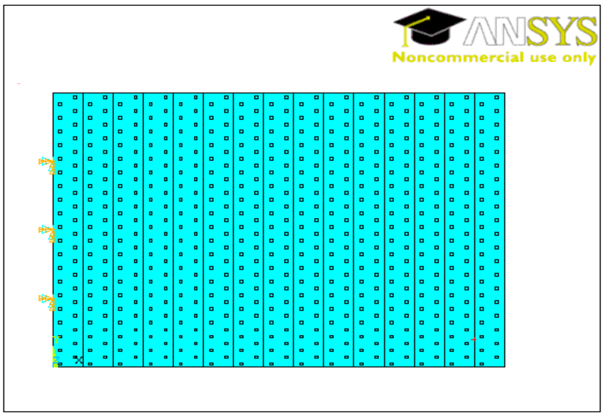

Fig. 7. FEM model for sewing needle effect

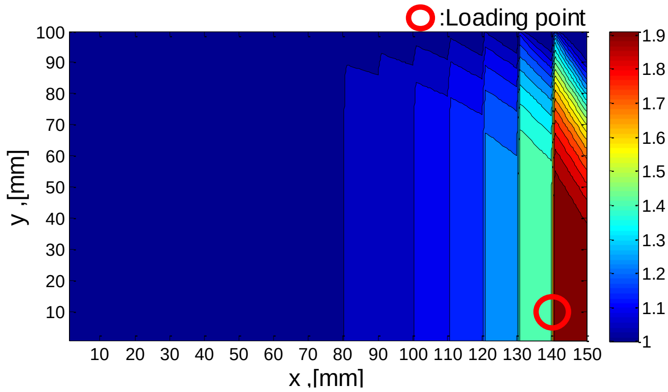

Fig. 8. Thickness distribution. (FOO)

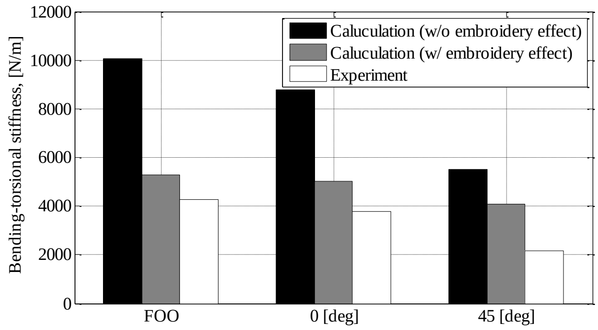

Fig. 9. Effect of sewing needle and thickness distribution.