ANISOTROPIC BEHAVIOR IN BENDING DEFORMATION OF CF/EPOXY AND CF/PPS LAMINATES UNDER CONCENTRATED AND THERMAL LOAD

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1 Introduction

With expanding the use of carbon fiber reinforced plastic (CFRP) composites in many consumer products, not only durability and reliability in strength but also the quality of appearance including textile pattern and painting, and the dimensional accuracy are strictly required. However, it is not easy to satisfy those demands, because CFRP show complex anisotropic behavior such as in-plane shear deformation and out-of-plane torsion deformation under on-axis loading. To predict the elastic properties of unidirectional CFRP, classical laminate theory (CLT) and finite elemental analysis (FEA) have been utilized commonly. However the accuracy in actual shape measurements and the numerical simulations for out-of-plane elastic deformation of CFRP has been less verified. This might be due to complicated problems as follows: inhomogeneity such as misalignment of fibers and non-uniform resin layers, the residual thermal stress derived after curing which were caused by incomplete quality control during production, and poorly-reproducible boundary conditions in loading and fastening and restricted numerical modeling and so on. Continuous fiber reinforced thermoplastics (cFRTP) composites are attracting attention recently because they have advantages of superior toughness in addition to high productivity and recyclability. However cFRTP is affected remarkably by service temperature because of the low glass-transition temperature. Thus it is very important to understand the anisotropic behavior in deformation of cFRTP caused by not only external force, but also thermal loading.

In this fundamental study, the anisotropic behavior of unidirectional CFRP laminated composites and carbon woven fabric thermoplastic composites (cFRTP) under concentrated load and thermal load by dimensional measurement and FEA.

2 Materials and procedure

2.1 Test specimens

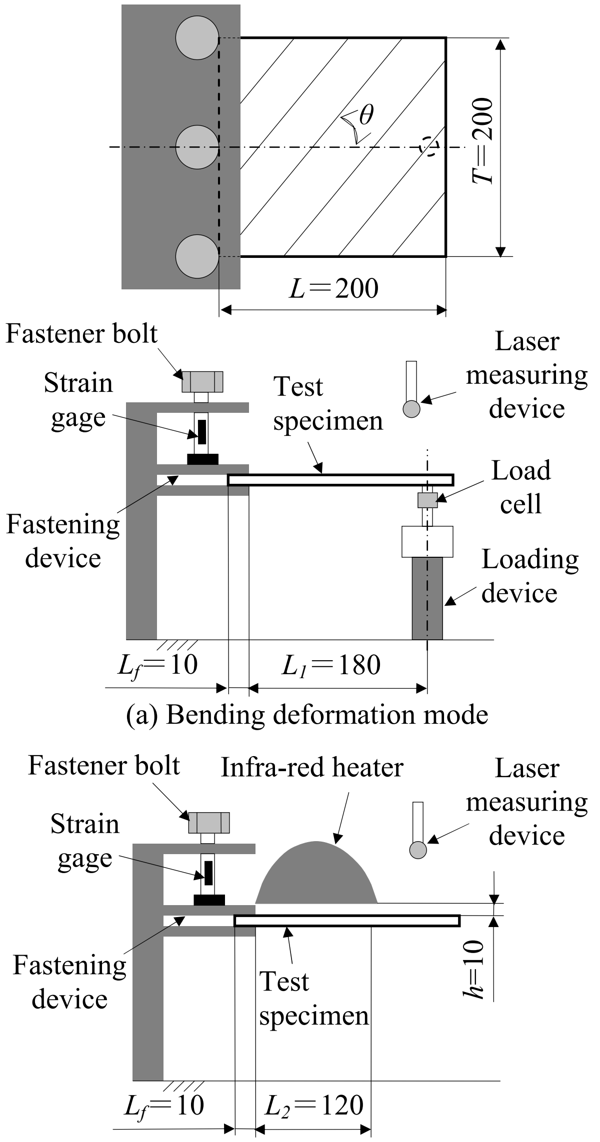
The materials used are CF/Ep, CF/PPS and GF/PPS as listed in Table 1. The CF/Ep is unidirectional composite (Toho Tenax Co., Ltd., Tenax-J® Q-1111 1950, 2kg/m^2, V_f=67%), which was laminated with 10 prepreg sheets in autoclaving. CF/PPS and GF/PPS are woven fabric composites (Bond Laminate Co., Ltd., TEPEX® Dynalite 107, 207, V_f=45%), which was crossly-laminated with 4 sheets. Each composite plates with t=2mm (CF/Ep) and t=1mm (CF/PPS, GF/PPS) in thickness were cut into test specimens (T=L=200mm on a side) with a diamond saw. Using different cut of angles will produce different specimen fiber orientation angle (θ) from 0° to 90° at 15° intervals.

Table 1 Materials used for test specimen

ID	Fiber	Matrix	Tg
CF/Ep	Unidirectional carbon fiber	Epoxy	125°C
CF/PPS	Carbon twill 2/2 woven fabric	Poly-phenylene sulfide	80°C
GF/PPS	Glass twill 2/2 woven fabric	Poly-phenylene sulfide	80°C

2.2 Experimental methods

The experimental apparatus is shown in Fig.1. Test specimens were cantilever-clamped with three bolts on the one end L_f=10mm. A concentrated load was applied below the test specimen, which was located at L_1=180mm from the edge of fastening device and placed on the central axis of the test specimen. A thermal load was applied on the test specimen at a range of L_2=120mm from the edge of fastening device by a long-wavelength infra-red heater. The output of the heater is P=80W and the distance from the test specimen is d=10mm. Fastening force and concentrated load were controlled by strain gage and load cell. The deformed shape of test specimens with various fiber orientation angles was measured by a laser measuring machine (repeat accuracy: 0.5μm). The shape deformation caused by the concentrated load was evaluated by the Z-displacement of width direction (T-axis) (δ_T) and longitudinal direction (L-axis) (δ_C). The shape deformation caused by the thermal load was evaluated by the Z-displacement of three different points (δ_{TL}, δ_{TC}, δ_{TR}) that was located



(a) Bending deformation mode

(b) Thermal deformation mode

Fig.1 Apparatus for coordinate measurement under bending deformation of a plate subjected to concentration load and thermal load.

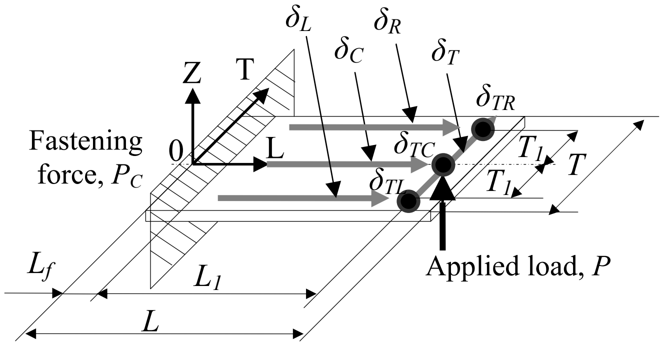


Fig.2 Measuring positions for evaluating deformation and resin segregation of laminates.

along the width direction (T-axis), L_1=180mm from the fastening device, as shown in Fig.2.

The amount of torsion (T_w) caused by the difference in two-sided Z-displacement (δ_{TR}, δ_{TL}) as given by Eqn.1, thus the degree of anisotropy (γ) was defined as the ratio of amount of torsion (T_w) divided by Z-displacement at applied load position (δ_{TC}) as shown in Eqn.2.

$$T_w = \left|\delta_{TL} - \delta_{TR}\right| \quad (1)$$

$$\gamma = T_w / \delta_{TC} \quad (2)$$

To verify the resin distribution of CF/PPS laminates, the cross-section and surface of specimens were observed by microscope (KEYENCE Co., Ltd., VHX-100) and the resin distribution was evaluated by image analysis.

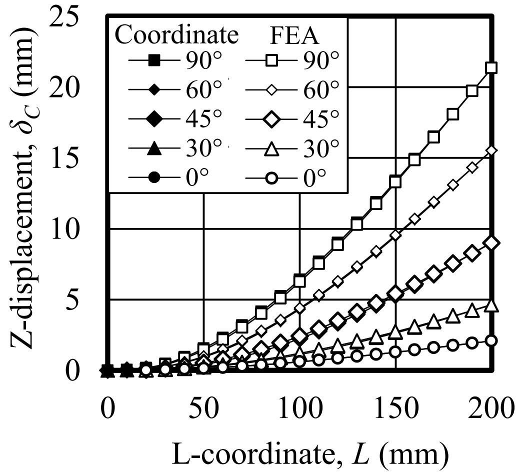
2.3 Finite elemental analysis

The analytical model was divided by 8-nodes 40×40×4 solid elements. The program code used for elastic structural analysis is general-purpose finite element solver (MSC. software Co., Marc2005). The cantilevered fastening force applied to the end of test specimens was calculated using the compressive load applied to the elements of the fastening device, and the concentrated load was expressed by applying Z-displacement at applied load point (δ_{TC}) obtained by laser measuring instrument to a node near applied load point. Mechanical properties of unidirectional CF/Ep (V_f=0.67) laminated composites used for test specimen were assumed to be an orthotropic material, and the material constants were used for FEA.

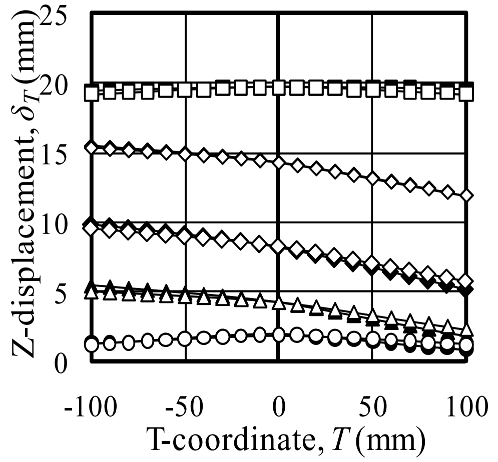
3 Results and Discussions

3.1 Effects of concentrated load

Fig.3 shows the profiles of (a) Z-displacement in longitudinal direction (δ_C) and (b) Z-displacement in width direction (δ_T) of unidirectional CF/Ep laminates with various fiber orientation angles, which were obtained by experiment and FEA. The concentrated load of P=10N was applied in the experiment. Experimental results show similar tendencies as FEA ones, and there is no significant difference in Z-displacements obtained by experiment and FEA. From Fig.3(a), the values of Z-displacement (δ_C) increases as fiber orientation angle increases, because bending modulus of laminates become lower accordingly. It is also revealed from Fig.3(b) that the value of Z-displacement (δ_T) increases with increasing fiber orientation angle.



(a) Displacement in longitudinal direction (δ_C)



(b) Displacement in width direction (δ_T)

Fig.3 Effects of fiber orientation angle on bending deformation of CF/Ep laminates.

However, when the fiber orientation angle is not at θ=0° and θ=90°, the profile of Z-displacement (δ_T) shows left-right asymmetry at the center of test specimens; the highest value of Z-displacement (δ_T) appears not at the applied load position (T=0mm), but at the side edge position (T= -100mm). In other words, the degree of anisotropy is higher for cases of off-axis fiber reinforced composites.

Fig.4 shows the amount of torsion (T_w) and degree of anisotropy (γ) as function of fiber orientation angle (θ) which was obtained by experiment and FEA. The highest amount of torsion is at θ=45°, whereas the highest degree of anisotropy is at θ=25° for both experiments and FEA. The experiment shows a 20% larger T_w value than FEA. A further investigation on material constants and boundary conditions for fastening are required.

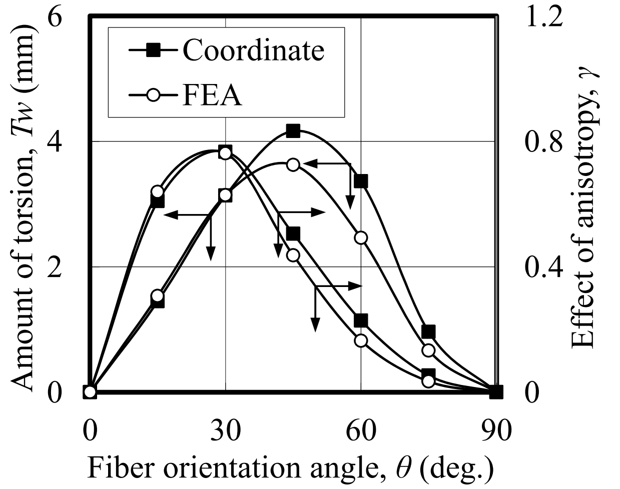
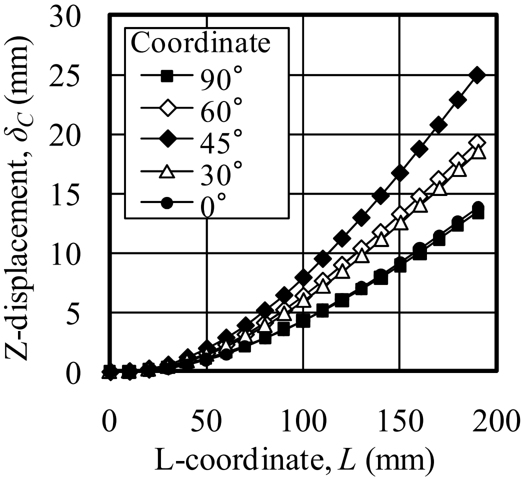
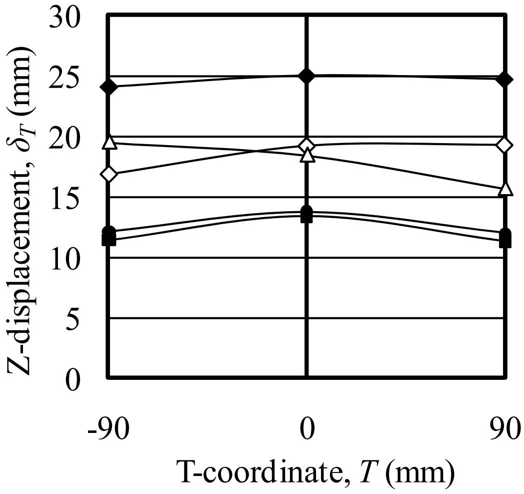


Fig.4 Effects of fiber orientation angle (θ) on torsion deformation of CF/Ep laminates.

Fig.5 and shows the profiles of (a) Z-displacement in longitudinal direction (δ_C) and (b) Z-displacement in width direction (δ_T) of CF/PPS laminates with various fiber orientation angles, which were obtained by shape measurement. When fiber orientation angle is θ=45°, both values of Z-displacement in longitudinal (δ_C) and width directions (δ_T) show the maximum. On the other hand, in θ=0° and θ=90°, the values of the Z-displacement are absolutely low and the change shows a symmetry shape in width direction, that is less anisotropic properties. In θ=30° and θ=60°, the values of Z-displacement differ largely between the both sides and the change shows asymmetry shape, that is high anisotropic properties.



(a) Displacement in longitudinal direction (δ_C)



(b) Displacement in width direction (δ_T)

Fig.5 Effects of fiber orientation angle on bending deformation of CF/PPS laminates.

Fig.6 shows the amount of torsion (T_w) and degree of anisotropy (γ) as function of fiber orientation angle (θ) which was obtained by shape measurement. When fiber orientation angle is θ=30° and θ=60°, the amount of torsion (T_w) and degree of anisotropy (γ) shows the peak values, whereas the highest amount of torsion and degree of anisotropy are at θ=30°. This is because the difference of elastic modules arises in the warp yarn direction and the weft yarn direction.

In comparison, the results for GF/PPS laminates are obtained as similar to CF/PPS ones, the values of Z-displacement are larger in GF/PPS compared to CF/PPS, because the elastic modulus of GF/PPS laminates is lower than CF/PPS ones.

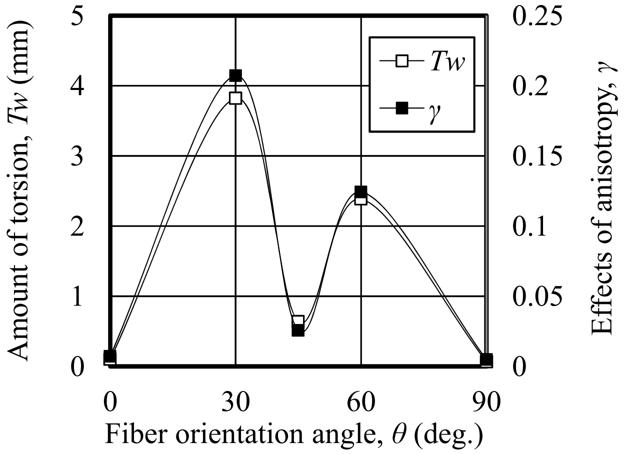
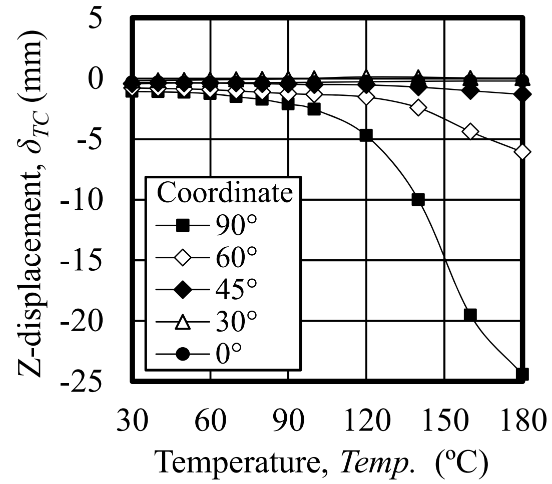


Fig.6 Effects of fiber orientation angle (θ) on torsion deformation of CF/PPS laminates.

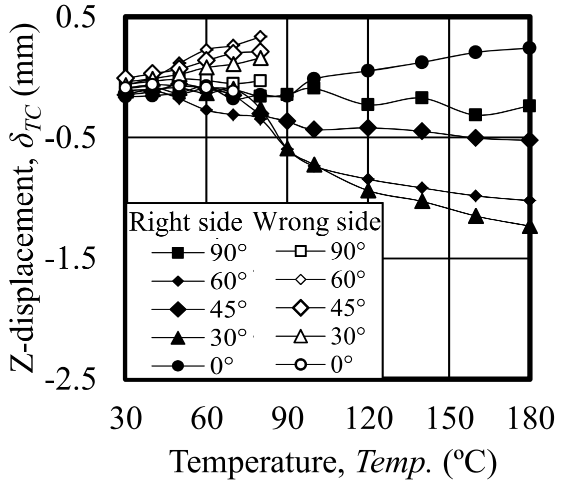
3.2 Effects of thermal load

Fig.7 shows the behavior of the thermal deformation of CF/Ep, CF/PPS and GF/PPS laminates with various fiber orientation angles, which were obtained by shape measurement. The thermal load was applied from T=30ºC to T=180ºC on the top surface of test specimen by infra-red heater. It is revealed from Fig.7(a) that the Z-displacement (δ_{TC}) increased to minus value i.e. lower direction as fiber orientation angle increases. It is supposed that this is due to the reasons as follow: 1) the difference of thermal expansion was occurred by changing fiber orientation angle because the thermal expansion coefficient of the fiber is much smaller than that of matrix resin, 2) the difference in thermal expansion between top surface and bottom one occurred because of the difference in temperature increase between them, and 3) specimen's gravity. From Fig.7(b) and Fig.7(c), the thermal deformation reversed in all fiber orientation angles when CF/PPS and GF/PPS laminates were reversed up and down. This cause is a segregation of the resin matrix contained on the surface of these laminates. Also, the amount of Z-displacement (δ_{TC}) increases in the vicinity of glass-transition temperature (T=80ºC).

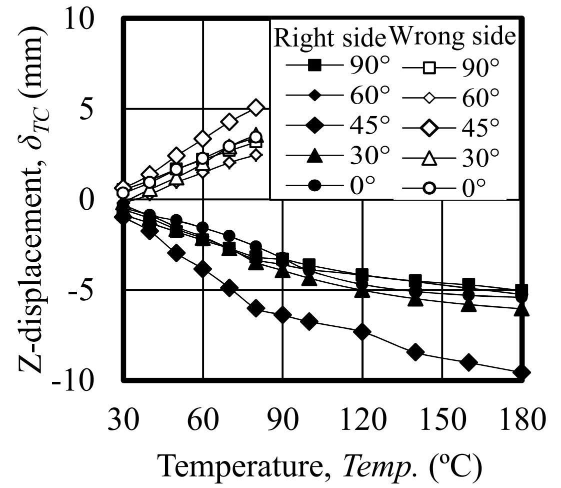
Fig.8 shows the profiles of Z-displacement in width direction (δ_T) of CF/Ep laminates. The profile of δ_T shows left-right asymmetry at the center of test specimens when the fiber orientation angle is not at θ=0° and θ=90°. This is because the edge of fiber direction is not fixed by the fasting device. The unfixed area increases with increasing the fiber orientation angles.



(a) CF/Ep laminates



(b) CF/PPS laminates



(c) GF/PPS laminates

Fig.7 Effects of fiber orientation angle on Z-displacement (δ_{TC}) under various temperatures.

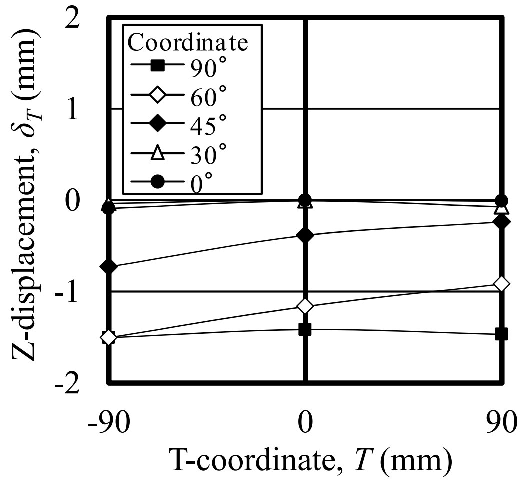


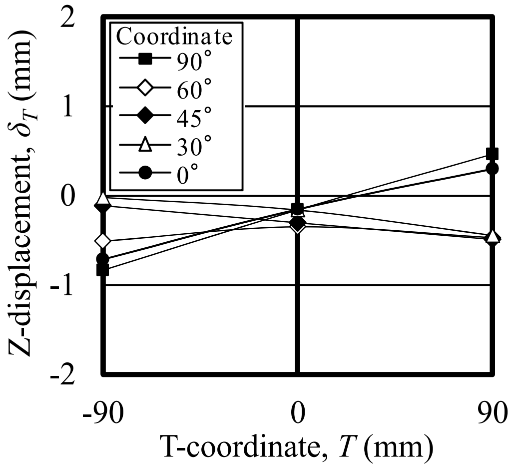
Fig.8 Effects of fiber orientation angle on Z-displacement in width direction (δ_T) of CF/Ep laminates.

Fig.9 shows the profiles of Z-displacement in width direction (δ_T) of CF/PPS laminates with various fiber orientation angles. The thermal deformation behavior is similar at θ=0° and θ=90° in both sides. In addition, the profile of δ_T shows left-right asymmetry at the center of test specimens. These complex behaviors are caused by segregation of resin matrix and mismatched fiber in test specimens. In addition, the results for GF/PPS laminates are obtained as similar to CF/PPS ones. However, GF/PPS laminates do not show the thermal deformation behavior such CF/PPS laminates at θ=0° and θ=90°. Moreover, the values of Z-displacement (δ_T) are larger in GF/PPS compared to CF/PPS, because the elastic modulus of GF/PPS laminates is lower than CF/PPS ones.

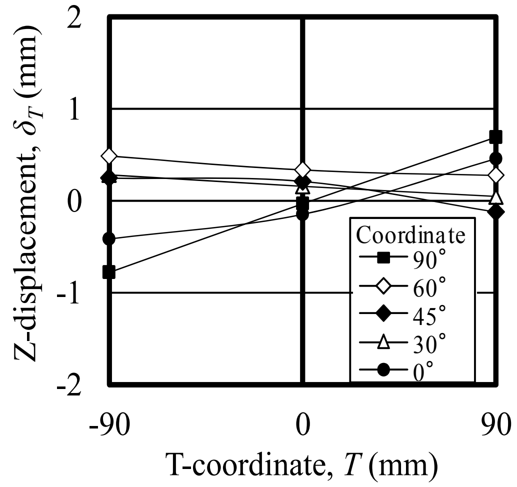
3.3 Effects of matrix resin distribution

Fig.10 shows cross-sectional SEM image of CF/PPS laminates polished at θ=0°. There is matrix resin segregation of approximately t_R=200µm in the right side layer. As for the wring side layer, the resin matrix layer is about t_W=50µm.
Fig.11 shows the resin distribution on the uncut CF/PPS laminates measured by the image analysis. This distribution chart shows that the ratio of the resin matrix distribution is high with increasing the brightness. The matrix resin segregation arises especially at both ends of the wrap yarn direction on the uncut laminates result from roll forming processes. Also, the distribution of the matrix resin

changes by the cutting out position of test specimens. Thus, it is considered that the profiles of Z-displacement of CF/PPS and GF/PPS laminates showed complex thermal deformation behavior.



(a) Right side



(b) Wrong side

Fig.9 Effects of fiber orientation angle on Z-displacement in width direction (δ_T) of CF/PPS laminates at T=80ºC.

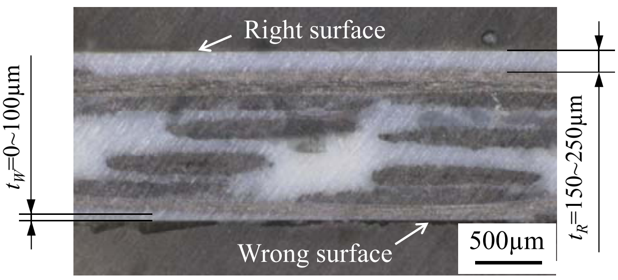
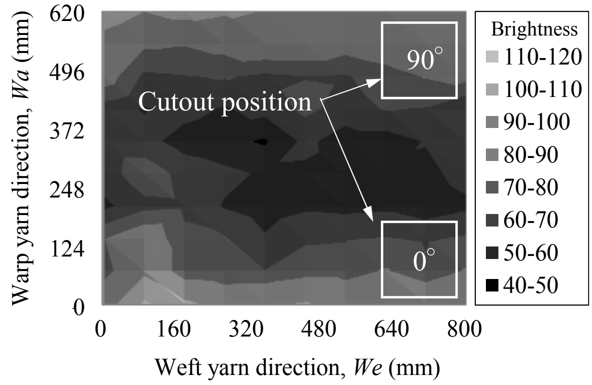
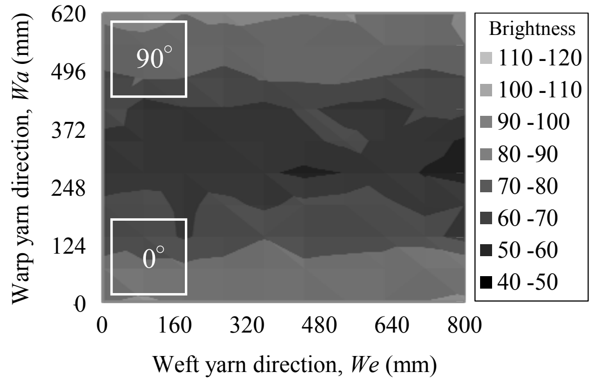


Fig.10 Cross-sectional image of CF/PPS laminates polished at 0°.



(a) Right side



(b) Wrong side

Fig.11 Resin matrix distribution on the uncut CF/PPS laminates.

4 Conclusions

In this study, the anisotropic behavior in bending deformation of unidirectional carbon fiber reinforced epoxy thermosetting-plastic and woven carbon or glass fabrics reinforced PPS thermoplastic laminated composites with various fiber orientation angles under a concentrated and thermal loading was mainly investigated by coordinate measurements. Two parameters for anisotropic evaluation of the bending deformation such as the amount of torsion and degree of anisotropy were used. As for unidirectional CF/Epoxy laminates, a reasonable result on the anisotropic behavior in bending deformation was obtained excepting a slight difference in experiment and FEA. On the other hand, the anisotropic behavior in bending deformation of woven fabric thermoplastic laminated composites under thermal load was affected strongly by matrix resin segregation on the surface of laminates.