EFFECTS OF PROCESS-INDUCED FIBER BUNDLE WAVINESS ON THE MECHANICAL PROPERTIES OF CARBON FIBER REINFORCED THERMOPLASTIC COMPOSITES

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Abstract
This study focuses on the process-induced fiber bundle waviness in carbon fiber reinforced thermoplastic composites (CFRTP). Fiber bundle waviness is often observed in manufactured CFRTPs, which deteriorates the mechanical properties. This study experimentally investigates the quantitative measurement of fiber bundle waviness (e.g. amplitude and wave length of fiber bundle waviness) in unidirectional CFRTP using the optical microscope and the X-ray CT scanning. Flexural mechanical properties are measured in relation to the magnitude of the included fiber waviness. Strength deterioration is experimentally evaluated as a function of the fiber waviness parameter.

1. Introduction

Fiber-reinforced composites have been widely used among the aerospace and the automotive industries because of their high specific stiffness and specific strength. However, initial imperfections (fiber bundle waviness, fiber misalignment, voids, variation of fiber volume fraction, etc. see Fig. 1) are inevitably induced in composites during the manufacturing process, and these imperfections cause the deterioration of mechanical performance of composites [1-5]. Composite manufacturing process generally contains uncertain factors and induces unexpected imperfections in fabricated composites, resulting in large uncertainty of mechanical properties. This situation might require unnecessarily high safety factors for the design of composite structural components, which leads to increase of structural weight. Therefore, it is necessary to clarify the mechanism of induced imperfection and the effect of imperfection on the mechanical properties.

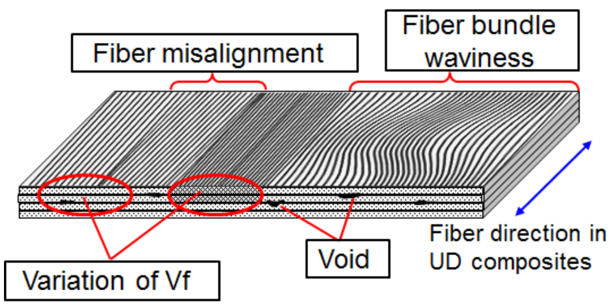

Figure 1. Examples of initial imperfections in unidirectional composites.

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Carbon fiber reinforced thermoplastic composites (CFRTP) are expected to be applied to structural components owing to high productivity and recyclability. Fiber bundle waviness is often observed in unidirectional CFRTP, which is of concern in the present article. This study experimentally investigates the quantitative measurement of fiber bundle waviness (e.g. amplitude and wave length of fiber bundle waviness), and evaluates the flexural mechanical properties of unidirectional CFRTP. Relationship between the mechanical properties and the magnitude of fiber bundle waviness is discussed.

2. Experimental

2.1. Observation of Fiber Bundle Waviness

Unidirectional CFRTPs with thickness of 1-10mm were used for characterization. Fiber bundle waviness could be observed on the surface of specimens as shown in Fig. 2. Fiber bundle waviness is not homogeneously distributed on the surface of fabricated plates, but observed locally and randomly. Fiber waviness parameters are defined in this study in reference to our previous study [6], as shown in Fig 3. The waviness region is divided into two parts; Constant Waviness(CW) region and Transient Waviness(TW) region.

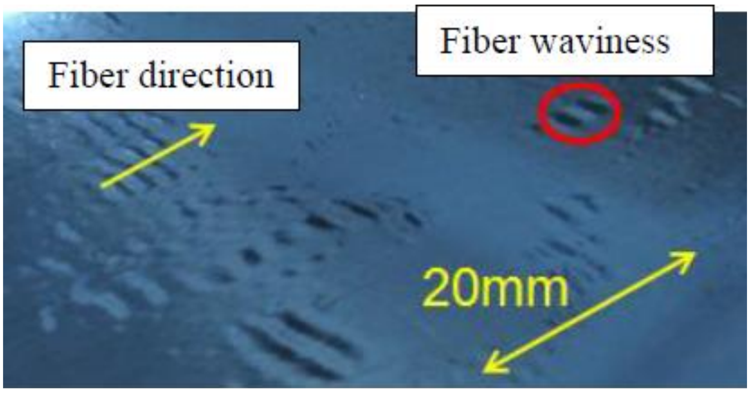

Figure 2. Fiber bundle waviness on the surface of CFRTP.

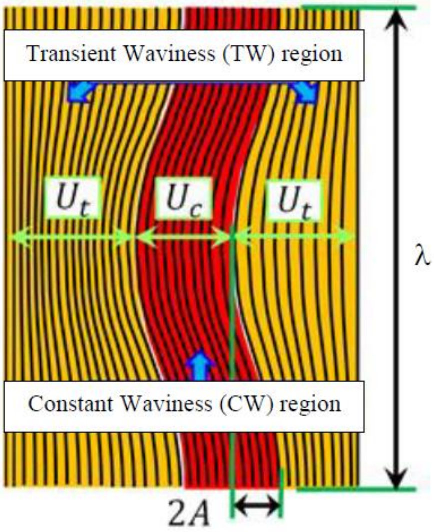

Figure 3. Schematic of fiber bundle waviness and related geometric parameters.

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CW denotes the region where the fiber waviness is uniform with constant amplitude, while TW means the region where the degree of fiber waviness gradually changes. TW exits between CW and perfectly aligned fibers regions. Definitions of four parameters are listed below, although two of them (A and λ) are mainly focused on in the present study.

A : amplitude of the waviness in CW region
λ : wavelength of the waviness in CW region
U_c: width of CW region
U_t : width of TW region

Fiber waviness in CFRTP can be observed on the surface of the specimen. X-ray CT scanning was applied to observe the internal state of fiber waviness in CFRTPs. Examples of X-ray image indicating the internal fiber waviness are shown in Fig. 4.
A number of fiber waviness was observed, and the following results can be derived; only in-plane fiber bundle waviness was observed (no waviness in the out-of-plane direction) within the cases in this study; the amplitude of the fiber waviness, A, decreased in conjunction with the increase of the depth from the surface; no fiber waviness existed in isolation inside the specimen, and all the fiber waviness can be observed from the surface.

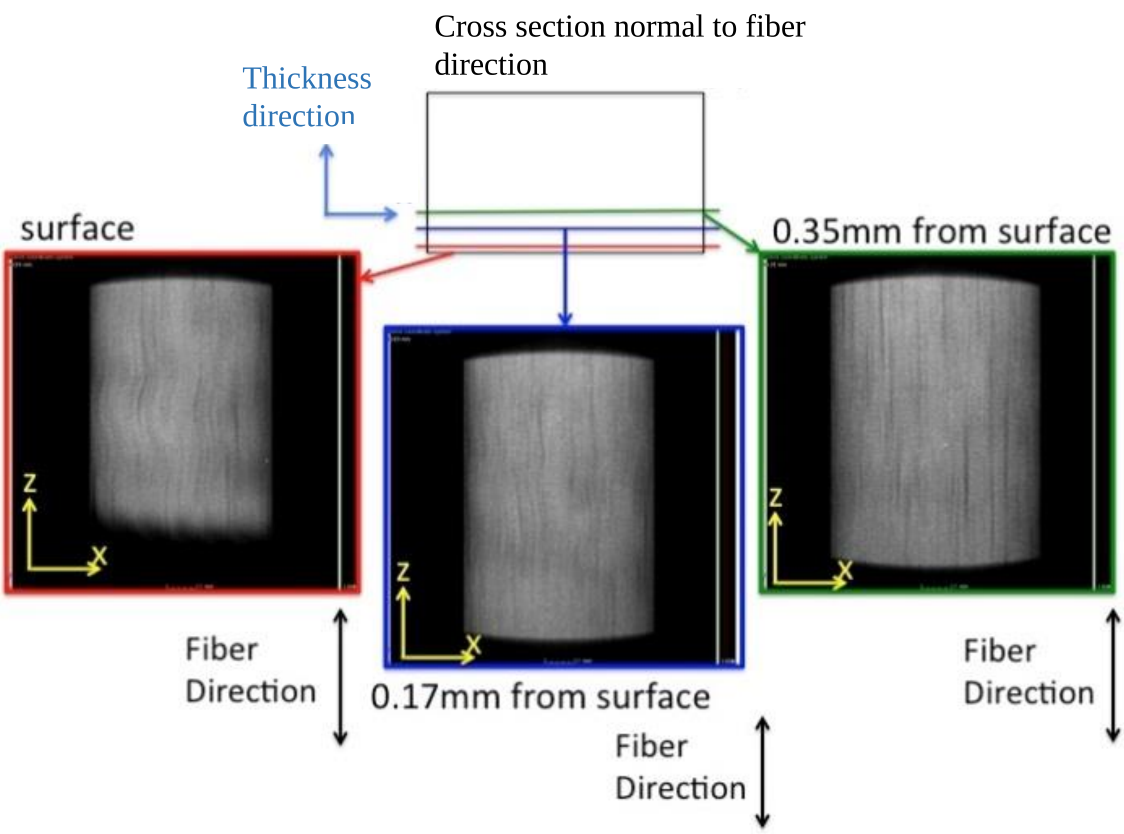

Figure 4. Examples of X-ray CT image of CFRTPs.

2.2. Measurement of Fiber Bundle Waviness Parameters

The previous observation suggested that fiber bundle waviness is most significant on the surface of CFRTPs within the cases in this study. The surface waviness can be easily observed by surface observation using microscopes. A number of fiber bundle waviness was observed, and fiber bundle waviness parameters (A and λ) were measured.

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An optical microscopic image of the surface of CFRTP with a region of fiber bundle waviness is shown in Fig. 5. The relationship between measured A and λ is plotted in Fig. 6.This figure shows that A and λ are distributed around specific values (0.02-0.10mm and 1.0-2.5mm, respectively), suggesting that fiber bundle waviness is induced by buckling phenomenon. It is know that fiber waviness is induced by resin flow, thermal shrinkage, and/or tool-part interaction during manufacturing process. The observation in this study provokes the inference that in-plane fiber bundle waviness results from thermal buckling during manufacturing process.

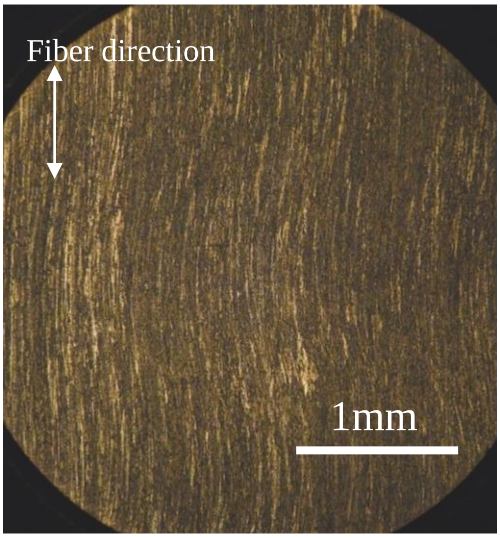

Figure 5. A microscopic image of fiber bundle waviness.

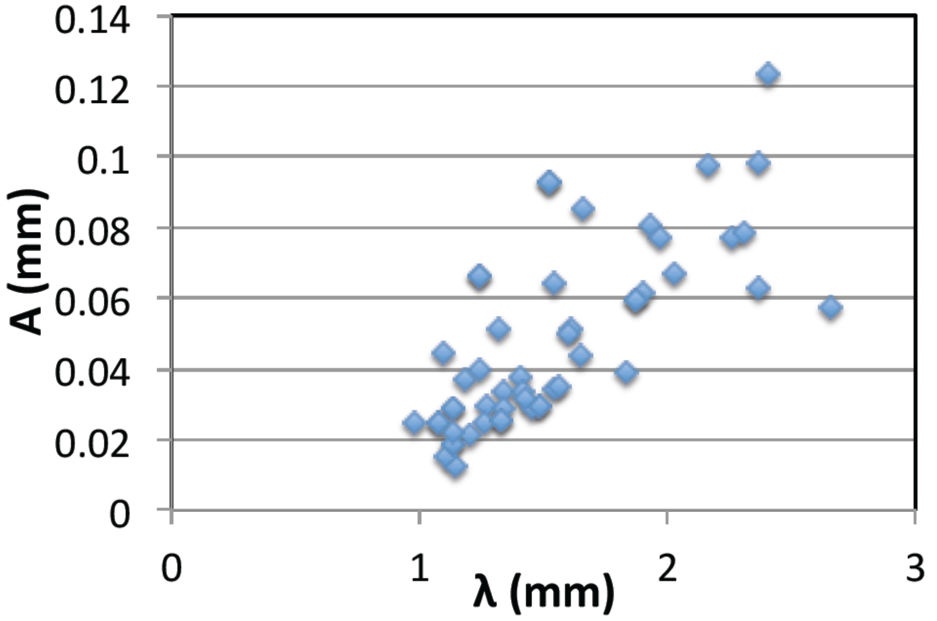

Figure 6. Relationship between the amplitude (A) and the wavelength (λ) of fiber bundle waviness in CFRTP.

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2.3. Measurement of Flexural Properties

Four-point bending tests were perfomed using unidirectional CFRTP with a region of fiber bundle waviness. Fiber bundle waviness parameters in the gauge section (in between the upper loading noses) of flexural specimens were measured using an optical microscope prior to testing. A high speed camera (FASTCAM SA-Z, PHOTRON Inc.) was utilized to capture the failure sequences of the flexure specimens from the surface in the compressive side. The measured flexural strength was summarized as a function of waviness parameter (A/λ) in Fig. 7. This waviness parameter represents the fiber angle inclination in the CW region from the nominal fiber direction. Experimental results indicate that flexural strength decreases with the increase of waviness parameter.

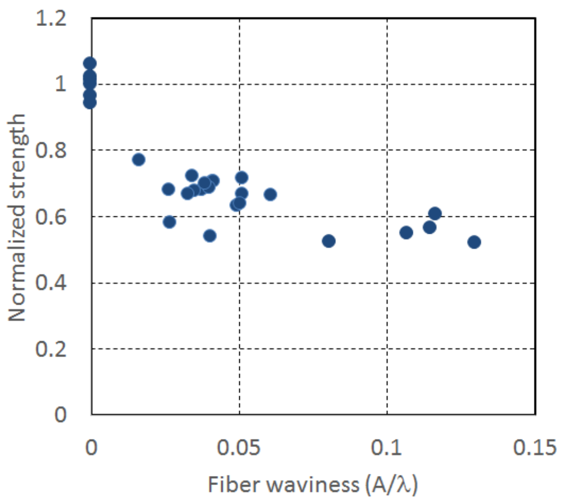

Figure 7. Relationship between the flexural strength and the waviness parameter (A/λ) of unidirectional CFRTP.

The failure sequence of unidirectional CFRTP in flexure is presented in Fig. 8, which indicates the crack formation in the fiber bundle waviness region in the compressive side leding to the complete failure. In the case of CFRTP specimens without fiber bundle waviness, sudden complete failure was observed. The fiber bundle waviness region significantly influences the bending strength properties and the failure process of unidirectional CFRTP.

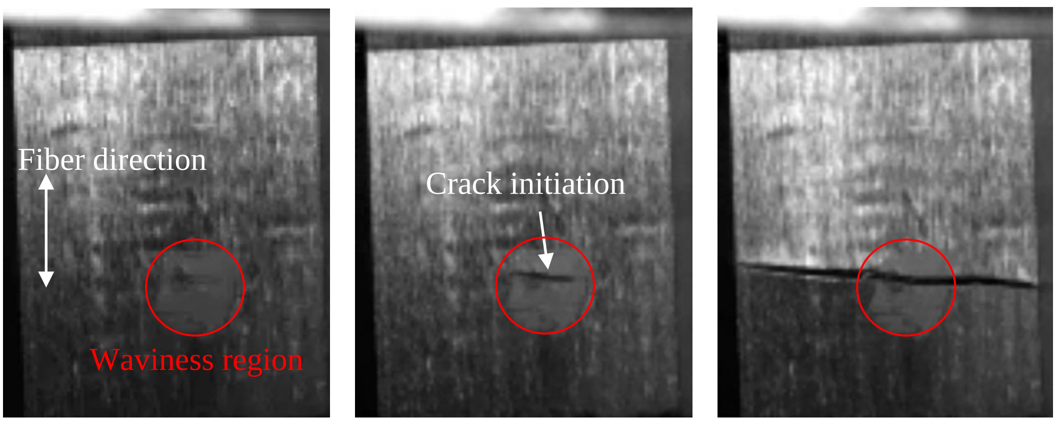

Figure 8. High-speed image of compressive failure of CFRTP with fiber waviness in flexure; before testing (left), crack initiation (middle), final failure (right).

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3. Conclusions

The present report focuses on the process-induced fiber bundle waviness in unidirectional CFRTP. X-ray CT and optical microscopic observation of fiber bundle waviness (e.g. amplitude and wave length of fiber bundle waviness) found that only in-plane fiber bundle waviness was observed, the fiber waviness could be observed from the surface, and fiber bundle waviness had specific geometries within the cases in this study. Flexural mechanical properties were measured in relation to the magnitude of the included fiber waviness. Flexural strength decreased with the increase of fiber bundle waviness parameter. High-speed imaging results suggested that fiber bundle waviness region significantly influences the failure process of unidirectional CFRTP in flexure.

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