EXPERIMENTAL INVESTIGATION OF LOAD-SHARING IN CFRP WITH IN-PLANE WAVINESS BY MEASURED LOCAL FIBER STRESS

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Abstract

The objective of this study is to highlight the effect of manufacturing induced fiber waviness defect on load shearing between waved fibers and their neighbor fibers in tensile test. For this purpose, fiber stress distribution along the cross-section perpendicular to loading direction was measured using microscopic Raman spectroscopy. At the same time, FEM model has developed considering the distribution of fiber volume fraction and fiber orientation. The stress distribution was measured at apex and inflection point of the waviness. Experimental results show that the stress relaxation of composites in wavy region, whilst stress concentration in the straight fiber region around the waviness, it was also confirmed that stress relaxed in the inflection point, the numerical result was also evident for experiment result.

1. Introduction

Strong demand for use of composite material is increasing today, because the successful replacement of traditional materials with composite materials is due to their high specific strength and stiffness coupled with low density, are needed to reduce energy consumption in aviation and automotive transport industries. But for composite manufacturing process has a degree of variability that cannot be totally extinguished.

Fiber waviness is one of the manufacturing defects frequently encountered in composite structures, when during the processing phase of composite products, the fibers experience axial load, such as residual thermal stress, while the matrix is unable to provide some level of transverse fiber support. The fiber will deform and waviness will develop. This mechanism was modelled by Bhalerao [1]. Fiber waviness in woven fabric, which is inevitably caused by woven fabric, which is inevitably caused by the woven architecture, is a typical inherent waviness [2]. No matter that it is unintentionally induced or inherent, waviness is generally thought to be disadvantage to properties of composite materials.

Studies on fiber waviness were mostly concentrated on the impacts of out-of-plane fiber waviness on compressive performance. The nonlinear behavior of composites with out-plane fiber waviness under tensile and compressive loading was investigated theoretically by Heoung-Jae Chun et al. [3]. H. M. Hsiao and I. M. Daniel [4] described an investigation of the effect of out-of-plane fiber waviness on stiffness and strength reduction of unidirectional composites under compressive loading by analytical models.

However, influence of in-plane fiber waviness on composite mechanical performance are lack of studies. In many cases, it is assumed to be a secondary effect in the presence of large scale out of plane waviness, the reason for it lies in that: (1) there have been less practical, reliable tools developed in the open literature for characterizing this type of fiber waviness and (2) the studies of in-plane waviness remain at a very basic conceptual level. In view of the above mentioned, Mariana. P [5] evaluated the in-plane fiber waviness influence with regard to initial failure in unidirectional carbon reinforced composite under uniaxial load through finite element analyses. Moreover, Pottavathri [6] develop a model by using the finite element method to predict the effect of in-plane fiber tow waviness on the stress distribution and loss of strength in carbon-reinforced composite materials, the result clearly show that the effect of in-plane fiber tow waviness lead to resin rich area which causes high stress concentrations and decrease in the strength ratio, leading to delamination.

For better understanding numerical finding in [5] [6] by performing experimental simulations that clarify stress distribution alone the cross section perpendicular to loading direction of inflection points and apex of waviness through microscopic analysis, due to very few other methods give in situ information on the distribution of the fiber residual stress and they are often inapplicable(fiber have a small diameter and cleave very easily) [7]. microscopic Raman spectroscopy was most specifically applied to measure it. This study aims to understand how region of waviness induce non-uniformity of load sharing on the composite structure, and thus evaluate influence relate to fiber breakage or fracture. Afterwards, the result of experiment combine with the result of numerical analysis will be discussed. This is important because limited research is available that combines both experimental and numerical approaches to explain the load sharing of these laminates.

2. Experimental work

2.1. Materials and Processing

Prepreg unidirectional carbon fabric (HRX350G110S,) was used in this study. “One mountain” in plane wavy laminate panel was manufactured by inducing a wave with help of hand movement on the central part of laminate panel, and the fibers in the both ends of upper and lower sides are straight (Fig. 1). Initially the specimen were placed on the hot plate at 35℃. Each lamina undergoes the same process before stacking and curing; different wave severities were achieved by changing amplitude rather than changing the wavelength of the defect (due to size limitation for testing and analysis). As shown in the Fig. 2, The two layer ([0°/0°]) panels were prepared with two different wave severity levels (0.046 and 0.053) by using unidirectional fiber. Each panel has an average thickness of 0.14mm. The composite panel fabrication was done using hot press molding. The cure profile employed was 20 min at 140℃, the pressure was 8Mpa. The fiber angle variation was again measured with the help of an optical microscope.

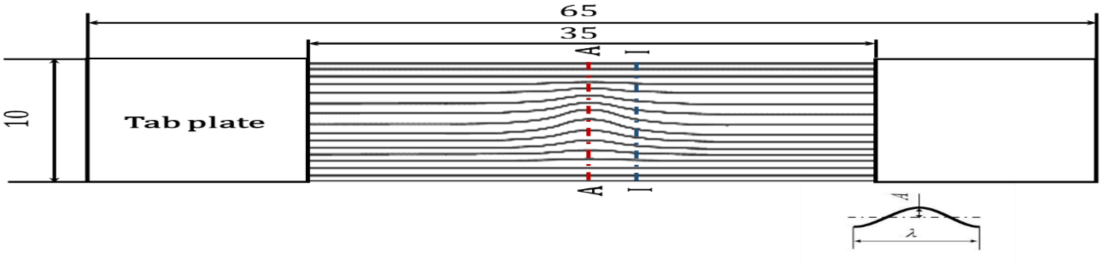
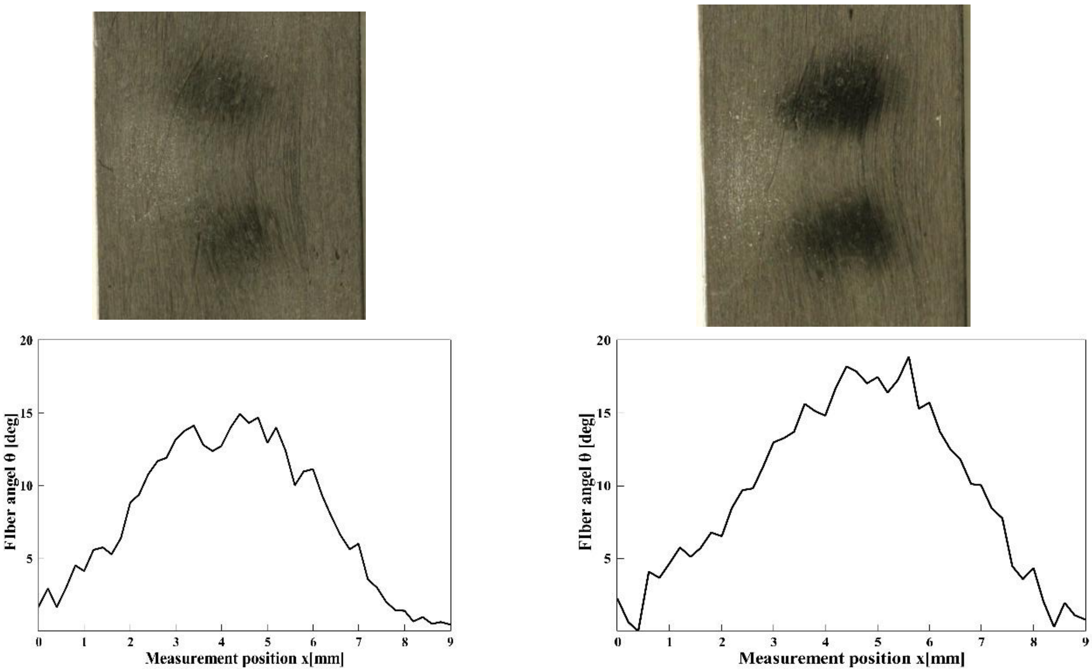


Figure 1. Schematic of specimen with in-plane waviness.



A/λ=0.046 A/λ=0.053

Figure 2. Observation and fiber angle variation at inflection point with different curvature.

2.1. STRESS MEASUREMENT BY A MICROSCOPIC RAMAN SPECTROSCOPY

The microscopic Raman spectroscopy(MRC) were obtained from single carbon fibers both in air and in the microcomposite using a Raman spectrometer system coupled to an optical microscope, and the measurement range was shown as Fig. 1. In order to observe the load sharing of waviness fibers on orthogonal plane of tensile direction, measurements taken at 0.2mm intervals over a length of 9 mm

Step 1 Step 2

Step 4 Step 3

Figure 3. A scheme showing the procedure to fiber stress measurement with microscopic Raman spectroscopy.

along dash line, here line I denotes the inflection points of waviness, and the line A denotes the apex of waviness respectively.

The tensile deformation required were conducted on a universal testing machine (tensile/compression). The experimental data were collected in the form of load and strain directly. As shown in Fig. 3, the strain gage was pasted on the part of straight fiber. The fiber stress measurement with Raman spectroscopy composed by four separate steps: (1) Place specimen on the Raman spectroscopy to measure residual stress. (2) Set up the specimen which was mounted with load cell on the test stand and specimen was loaded in axial tension to 0.22%, stain gage which attached to the straight fiber section was used to monitor deformation in real time. (3) Tighten nut and keep tension of load cell after testing. (4) Measure the fiber stress at same place of initial load frame by Raman spectroscopy, Calculation of fiber stress follow by $\sigma_f = \sigma_4 - \sigma_1$ where σ_1 is the stress of tension test before (step 1), σ_4 is the stress of tension test after (step 4).

3. Finite Element Model (FEM)

3.1. Definition of local stiffness

In order to quantify fiber waviness in the composite, mathematical descriptions of the wave geometry of the waviness was required. For graded waviness, the geometry of the waviness is approximated by:

$$\mathrm{Y(x,y)} = \mathrm{y} + \mathrm{A}\frac{1+\cos\left(\frac{\pi y}{U_t}\right)}{2}\cos\frac{2\pi x}{\lambda}\left(|x| < \frac{\lambda}{2}\right) \tag{1}$$

here the amplitude of the waviness is assumed to decay linearly from a maximum at the mid-surface to zero in the outer surfaces. The intensity of the fiber waviness was defined with a term called fiber wave severity (*Ws*), which is the ratio of *A* to *λ*.

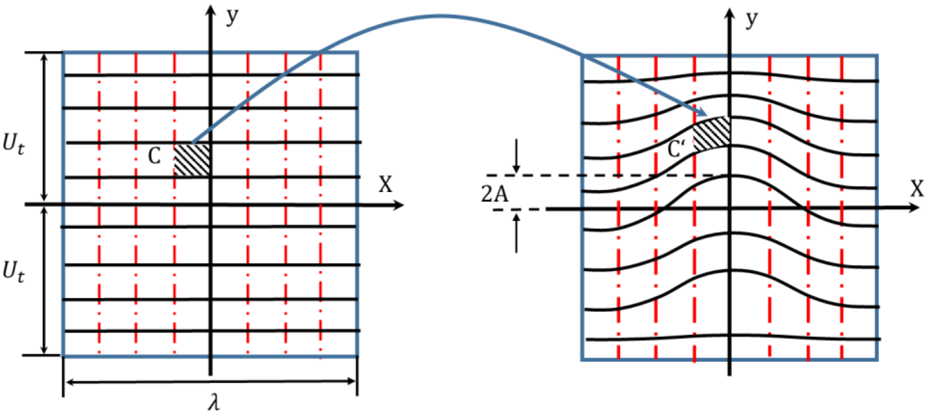


Figure 4. Variation of width between fiber by waviness.

As shown in Fig. 4, the space between the fibers was divided into several evenly spaced unit-cell. Before waviness occurred the area of the unit-cell is *A*, the area of any unit-cell in wavy region becomes *A'*, i.e., due to occurrence of waviness, the area rate of change in unite-cell is inversely proportional to fiber volume fraction. If the fiber volume fraction of straight portion is V_f, the local fiber volume fraction can be expressed as:

$$v_f = \frac{V_f}{(A/A')} \tag{2}$$

Since the local fiber volume fraction at any position in the waviness region has been determined, the local stiffness at an arbitrary position can be obtained using rule of mixture[8], the formula as follow:

$$E_1 = v_f E_{f1} + (1 - v_f) E_m \tag{3}$$

$$\frac{1}{E_2} = \frac{v_f}{E_{f2}} + \frac{1 - v_f}{E_m} - v_f (1 - v_f) \frac{\frac{E_m}{E_{f1}} v_{f12}{}^2 + \frac{E_{f1}}{E_m} v_m{}^2 - 2 v_{f12} v_m}{v_f E_{f1} + (1 - v_f) E_m} \tag{4}$$

$$v_{12} = v_f v_{f12} + (1 - v_f) v_m \tag{5}$$

$$\frac{1}{G_{12}} = \frac{v_f}{G_{f12}} + \frac{1 - v_f}{G_m} \tag{6}$$

Where E is the Young modulus, v is Poisson ratio, G is shear modulus. In addition, the subscripts 1 and 2 are for fiber direction and vertical direction of fiber, f and m represent physical property value of fiber and matrix, the elastic constants of fiber and matrix according experimental material was shown in Table 1.

Table 1. Elastic coefficients of fiber and matrix.

E_{f1} (GPa)	E_{f2} (GPa)	G_f (GPa)	v_{f12}	E_m (GPa)	v_m	V_f
240	18.6	100	0.29	4.6	0.3	0.65

3.2. Modeling approach

A 2D finite element model of the whole experiment specimen was built in Abaqus/Explicit for direct comparison with experimental results. Due to take account of stress components vertical to the plate to be negligible, a plane stress assumption was examined, The piles were built using an Two-dimensional 4-node plane stress shell elements (type CPS4R) were used. The mesh size of 0.1mm was used, the thickness of the element ply was similar to the specimen thickness of 0.14mm and 10mm wide.

The fiber orientation was accomplish by partition in a number of small regions across the weight and assigning each region with a local orientation based on a sinusoidal curve, we use the discrete orientation feature in Abaqus [9], the material orientation was defined continually varying orientation that follow the shape of a curve.

3.3. Boundary condition

In the actual experiment, there was no deformation to the tab materials and the adhesive joint detected, hence, the boundary condition of model was shown in the Fig. 5, the left tap plate was fixed as rigid support, tensile load was applied as prescribed displacements (u) on the reference point opposite to support side which was coupling with the surface nodes of right tap plate.

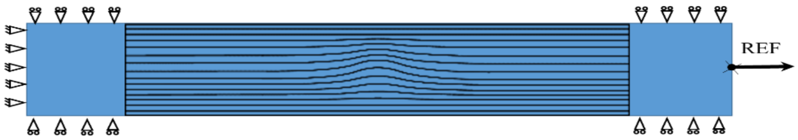


Figure 5. Boundary conditions at both ends of the sample.

4. Result and discussion

4.1 Effect of waviness defect on tensile strength in transvers direction

The stress in fiber of a specimen without waviness was basically in the same shown in Fig.6. In detail, In-plane average stress was approximately about 530MPa, corresponding with a variation of standard deviation about 60MPa. If the stress difference exceeds 60MPa, it can be consider as the result of fiber waviness on the fiber load sharing. Fig.7 illustrates the fiber stress distribution in cross section orthogonal to the load direction. For both instances, with severity of A/λ=0.046 and A/λ=0.053, the reassignment of load sharing was noted between fibers, i.e., the longitudinal stress relaxation in the wavy region is demonstrated, whilst the region of straight fiber around the fiber wavy region presents longitudinal stress concentration. This can be all relate to local load shearing changes induced by fiber curvature.

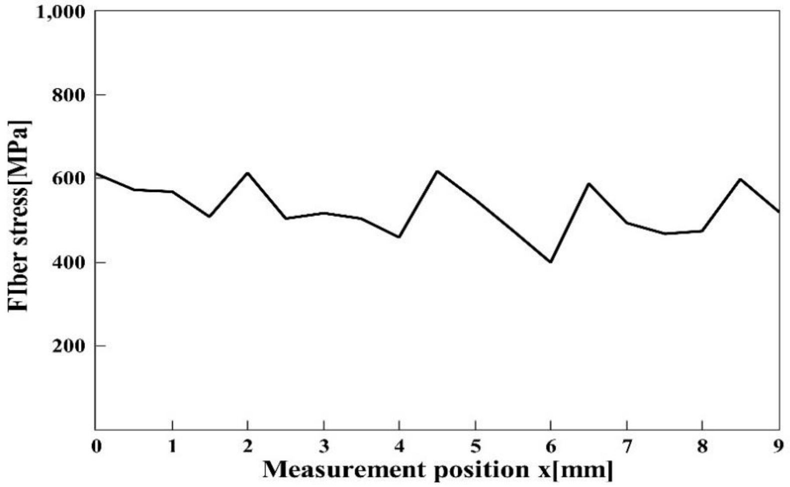
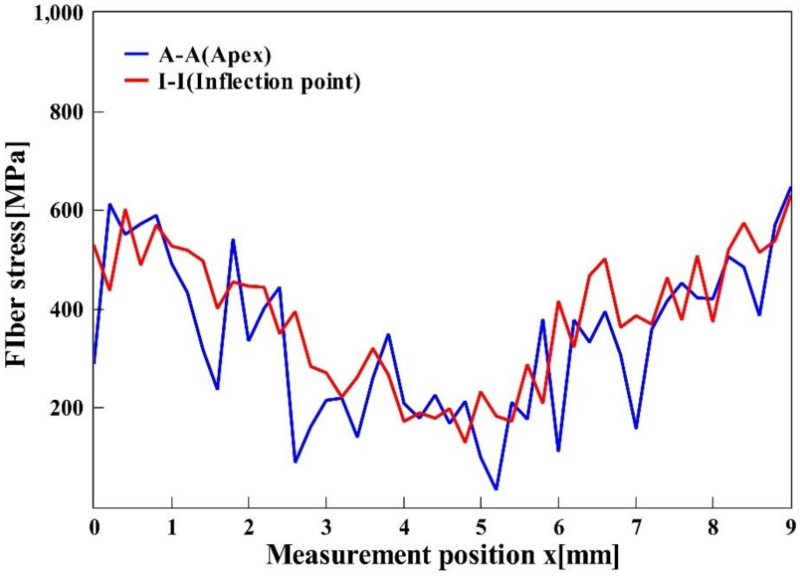
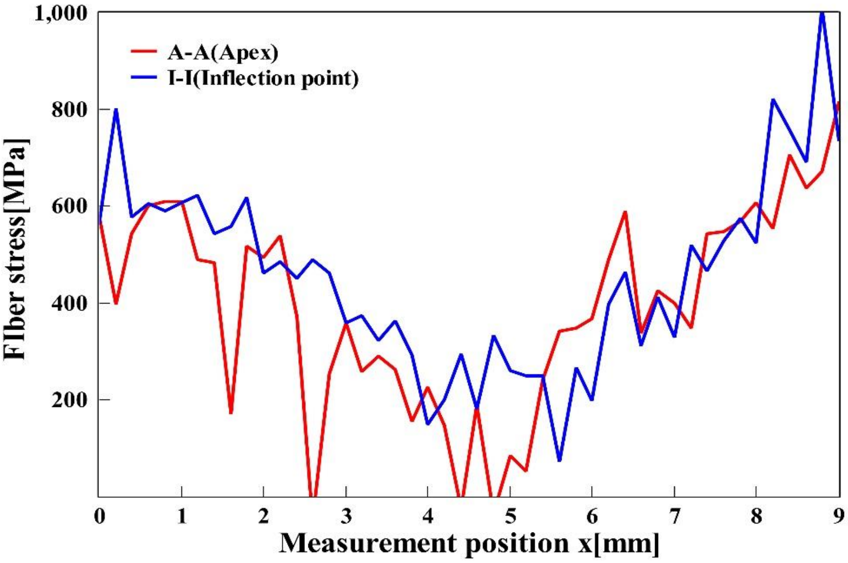


Figure 6. Fiber stress distribution in a specimen without waviness.



(a) A/λ=0.046



(b) *A/λ*=0.053

Figure 7. Fiber stress distribution in specimens with different curvature.

Fig.2 shows typical normalized line of fiber orientation angles on cross section along inflection point I, relative to the loading direction, for prepreg samples. There is an approximately normal distribution of angles which can be characterized by the standard deviation θ in the fiber orientation angle. Values are in the range 0-18°. The crest value of angle for A/λ=0.046 sample and A/λ=0.053 sample are 15° and 18 °, respectively. In addition, it is expected that the fiber stress will be less the path through the apex of waviness. This trend was not observed in Fig.7, and there was almost no difference in the fiber stress distribution between the cross section of apex and the cross section of inflection point.

As a result of the specimens with different waviness curvature, comparing Fig.7 (a) and (b), from the result obtained so far, it seem that the fiber stress distribution varies with the curvature. Hence, the more difference the waviness curvature is, the greater difference stress gradient of fiber is. Therefore, uneven distribution of fiber stress will be formed. As for A/λ=0.046, the stress of maximal value is 1.2 times as much as average stress, and for A/λ=0.053 is 1.5 times, exceeding 800Mpa.

Furthermore, as a geometric change caused by fiber waviness, it is expressed as a change in fiber density (local fiber volume content v_f). Considering at the apex of waviness, fiber density becomes dense on the mountain side and sparse on the valley side. Since the changing of the fiber density occurs within one transverse cross section, Observe the stress distribution on cross section along the apex T in detail Fig.7 (b), the fiber stress on the right side of the specimen (x>4.5 mm) is greater than the corresponding position on left side. This may be because the waviness cause the v_f become smaller on the right side of the specimen, while the fibers need to share more stress to support the same load. Taking into account the above-mentioned stress distribution, the straight portion of the lateral side of the waviness of valley side should have more stress, and stress failure will occur in this portion.

4.1 Experimental observations versus FEM model

As mentioned earlier, a complete specimen model had been build up for direct comparison of experimentally observed DIC outcomes, experimental observation and results fit well with model predictions (Fig.8).

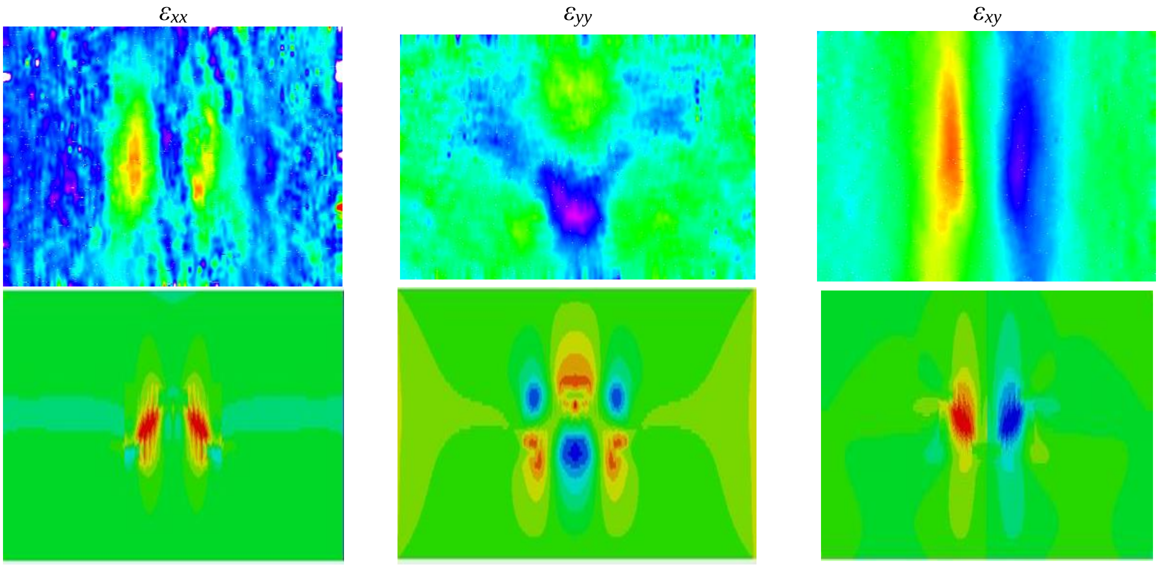


Figure 8. Strain distribution in experimental and numerical test.

In figure, the elements with red and yellow color means both fiber and matrix are strain concentration in this region, oppositely, the blue color represent strain relaxation. The misalignment of fibers and the strain relaxation, a strain concentration analysis has also been conducted, From result, it was found that longitudinal strain concentration exhibited in the part of inflection point of waviness, and in-plane waviness also induce the transverse strain according to the showed pattern, especially, for shear strain cases, it can be identified an alternating positive and negative shear pattern around the peak misalignment angle position, This can be all relate to local stiffness changes induce by fiber curvature.

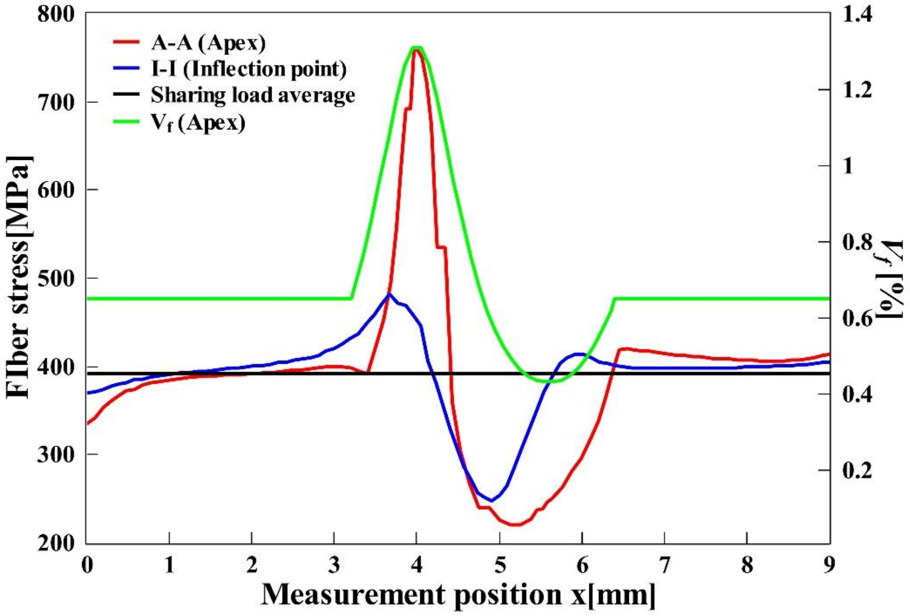


Figure 9. Model predictions of fiber stress distribution in a specimen with waviness.

Based on load shearing result obtained from abaqus model (Fig.9), it is evident that the load sharing reduction has initiate at the waviness region of the gage length, furthermore, the peak of stress concentration initiated in straight fiber region above the peak of central wave, in the same time, due to the stress relaxation in the wavy region, the straight fibers (at the bottom of the waviness) are weak links in the system and the stress concentration diverted towards this areas. Specifically, according to the V_f distribution of the apex, a large amount of fibers gather on the mountain side of the waviness, which leads to an increase in the stiffness constant. On the contrary, the fewer fibers are dispersed on the valley side of the waviness, the stiffness contant becomes smaller. Therefore, in the same deformation of a cross-section, the high-stiffness region (mountain side) will receive a great resistance, while the low-stiffness (valley side) will bear a smaller force. In general, Relative to the load average, the sum of the positive load energy and the negative load energy is nearly to zero. From the model, the load energy are equal to -3.1 and -5.1 in apex and inflection of point, respectively. Hence, we can conclude that the model prediction is reliable.

The abaqus model is a lamina level macro-mechanical mode, and the drop in the stiffness properties of laminate purely depends on the element stiffness. Hence a change in element orientation and fiber volume content bring about the variety of elastic modulus in local area of the model. However in the experiment, the fiber stress was measured one by one. It can be seen how the fiber stress at the measurement point fluctuates on the microscopic scale, and how the waviness fibers influences the stress response of the straight fibers near the waviness fiber. this is a reason for the great fluctuations of the stress distribution observed in numerical result when compared to the experiment. Unlike the experimental data, the abaqus model failed to predicted fiber stress in micro scale. In the future, the finite element model considered developing by fiber element and matrix element individually.

5. Conclusions

Tensile tests were performed on unidirectional CFRP laminated with induced one mountain in plane waviness defects, and the fiber stress distributions along cross section perpendicular to loading direction were measured by using microscopic Raman spectroscopy, it was noted that a redistribution of load sharing between the fibers caused by waviness. The stress generated in the waviness region is smaller than the average stress. Oppositely the region around waviness generated higher stress than average stress, on the other hand, the cross-sectional stress distribution which path through apex point of waviness is almost same as the one which path through inflection point. In addition, the fiber stress distribution is affected by waviness curvature, the greater curvature there is, the greater non-uniform stress distribution occurred.

And the finite element model based on the distribution of fiber volume fraction and fiber orientation had been developed, which agrees well with the experimental response in the case of waviness defect containing samples. Compared to experiment result, the current model was successfully predicted the failure of waviness induced samples under tensile load conditions, it confirmed that stress relaxation of wavy region leading to fiber concentration of straight fiber region above the peak of central wave and the bottom of waviness.

Acknowledgments

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