EFFECT OF PERIODICAL FIBER WAVING ON TENSILE STRENGTH OF PLAIN WOVEN CFRP LAMINATES

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1 Introduction

Carbon fiber reinforced plastics (CFRP) laminates have often been used for aerospace structure because of their superior specific stiffness and strength. Furthermore, plain woven CFRP laminates are nowadays applied to many industrial products such as leisure items, components of cars, reinforcement of bridge piers and others. Especially, for the transporters, CFRP reduces their weight and cuts the amount of CO^2 exhausted from them due to the light weight and high stiffness of carbon fibers. Therefore, CFRP can achieve the low carbon society and save the progress of the global warming. For the product of plain woven CFRP, it is rare to use plain woven CFRP as laminae and almost used as laminates. Therefore, the necessity of the study about the strength properties of the plain woven CFRP laminates is demanded. Plain woven fabric is interwoven with equally textural pitch, whereas the gap of each lamina is not adjusted on the laminating process. Thus the crimp gap, that is the misalignment of the crimp position on each lamina, arises in plain woven laminates. Naik, et al [1] revealed the effect of crimp gap on Young's modulus of plain woven FRP laminates theoretically. According to their results, an optimum configuration, i.e. symmetry sequence, can give higher elastic moduli and lower Poisson's ratio, as compared to other configurations, but any configuration was defined as an ideal sequence. In this sense, the relationship between the crimp gap and the mechanical properties has not been clarified yet.

It is well known that CFRP laminates fail due to the accumulation of microscopic damages such as transverse cracks, delaminations and fiber breaks. It is estimated that such damages are related to the degree of crimp gap, and finally it might influence the strength of CFRP laminates. Thus, the purpose of this study is experimentally and numerically to clarify the effect of crimp gap on microscopic damage and tensile strength for plain woven CFRP laminates.

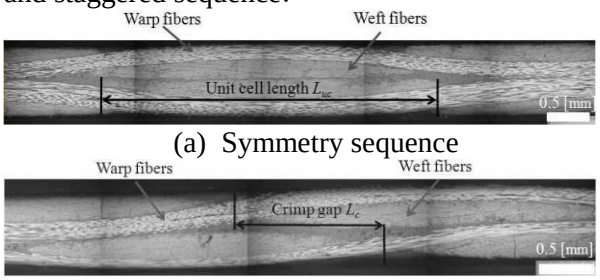
2 Experimental Procedures

2.1 Materials and tensile tests

Plain woven CFRP laminates were prepared in this study. The laminates consist of TR50S carbon fibers (TRK101-12K Mitsubishi Rayon Co., Ltd) and epoxy resin. The stacking sequence of the plain woven CFRP laminates was $[0/90]_2$. These CFRP laminates had different crimp gaps, so that the crimp gaps were measured by optical microscopic photograph on the side faces. The gage length, width and thickness of the specimens were 137, 15 and 0.83 mm, respectively. The tapered GFRP tabs were bonded at the end of specimens. The tensile tests were carried out at 1.5mm/min of the cross head speed by using an Instron-type testing machine (IS-5000, Shimadzu Co., Ltd), following JIS K 7083 (JIS: Japan Industrial Standards).

2.2 Laminates classification of stacking gaps

The crimp gap was observed through an optical microscope on the side faces including warp yarns. Fig. 1 shows the crimp gap for the case of symmetry and staggered sequence.



(a) Symmetry sequence

(b) Staggered sequence

Fig. 1 Side observation of plain woven CFRP laminates.

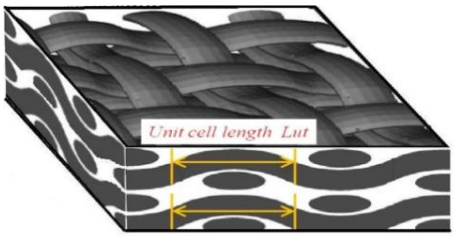
From this crimp gap, we supposed that the shape of the in-plane warp yarns is a sine curve, and we defined the relative phase lag α in the warp direction as the following equation.

$$\alpha = \frac{180^\circ}{L_{uc}} \times L \qquad (1)$$

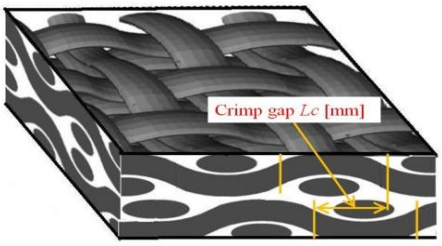
Where, α: phase lag [°], L_{uc}: unit cell length [mm] and L: crimp gap [mm]. Also, we defined α=0° when the waiving of adjacent warp yarns is parallel sequence and α=180° when the waiving of symmetric warp yarns is symmetry sequence. Furthermore, staggered sequence is defined as the range of 0°< α<180°. Figures 2(a), (b) and (c) show the schematic models of laminate configurations as parallel (α=0°), staggered (0°< α<180°) and symmetry (α=180°) sequence, respectively.

2.3 Finite element model

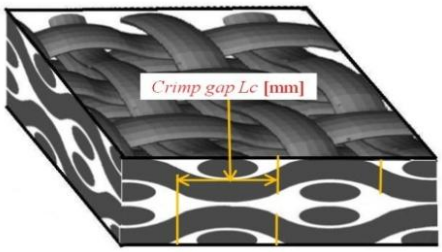
2D finite element model for side face of woven



(a) Parallel sequence (α=0°)



(b) Staggered sequence (0°< α<180°)



(c) Symmetry sequence (α=180°)

Fig. 2 Schematic models of woven fabric lamination.

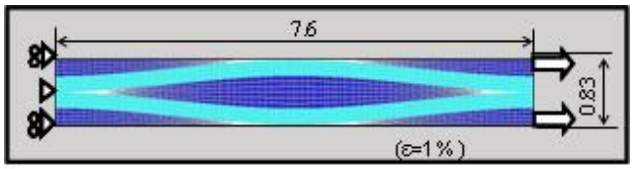


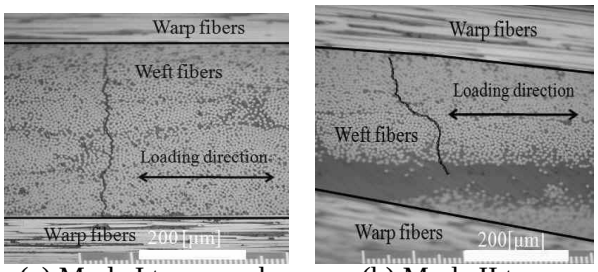
Fig. 3 FEM model for the case of symmetry sequence.

fabric CFRP laminates was conducted in order to investigate the effect of crimp gap on stress distribution near warp yarns, based on the model of Pagea, et al [2]. The FEM model for the case of symmetry sequence was shown in Fig. 3. The boundary conditions were also shown in this figure. It was supposed that the shape of the in-plane warp yarns are sine curves and there are 5 kinds of phase lags. 4-node iso-parametric elements are used as weft and warp elements. The warp elements were defined as anisotropic body with some angles depending on the wave shape. The warp yarn in this model was divided into 14 regions along loading direction. On the other hand, weft elements were defined as isotropic body. In fact, there is the matrix rich region near weft yarns. However, it was reported that the existence of the matrix rich region does not affect on the occurrence of transverse cracks [3]. Thus, the matrix region near weft yarns was ignored in this model. In this model, the number of total nodes is 3696 and the plane strain condition was assumed.

3 Results and Discussion

3.1 Transverse cracks

To investigate the relationship between the phase lag and the transverse crack occurrence in weft yarns, the side in plain woven CFRP laminates was observed through an optical microscope after the tensile test. Figs.4 (a) and (b) show the examples of the observed transverse cracks in weft yarns. In Fig.4 (b), this transverse crack is inclined compared to the transverse crack in Fig.4 (a). It is known that the vertical cracks, as shown in Fig.4 (a), often appear in CFRP, especially cross-ply CFRP laminates. On the other hand, the inclined crack, as shown in Fig.4 (b), is inherent in plain woven CFRP laminates. Thus the vertical cracks and the inclined cracks can be classified into mode I and II type cracks, respectively.



(a) Mode I type crack (b) Mode II type crack

Fig.4 Mode I and II type cracks.

3.2 Effect of the crimp gap on the transverse cracks occurrence

In order to explore the transverse crack occurrence quantitatively, the relationship between the transverse crack density and the phase lag was investigated. The transverse crack density means in this study a number of mode I type cracks or mode II type cracks divided by the observation length. Fig.5 shows the relationship between the transverse crack density and the phase lag. It is found from this figure that the mode II type crack density decreases when α is close to 180°, while mode I type crack density decreases when α is near 45° or 135°.

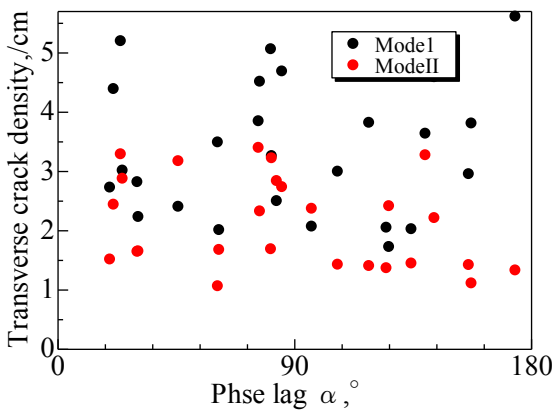


Fig.5Relationship between transverse crack density and phase lag.

3.3 Effect of the crimp gap on the tensile strength

Figure 6 shows the relationship between the tensile strength and the phase lag. It was found from this figure that the tensile strength distribution against the phase lag has a local mimimal values near α=45° and 135° (staggered sequence). In other words, the tensile strength was greatly affected by the phase lag.

Fig.7 shows the relationship between tensile strength and the mode I and II types transverse crack densities. In this figure, the tensile strength increases with increase in mode I type transverse crack density. On the other hand, the tensile strength is not sensitive to mode II type transverse crack density. The correlation coefficients of tensile strength against mode I type and mode II type transverse crack densities were 0.705 and -0.276, respectively. From this result, it is suggested that higher tensile stress is brought by accumulation of the mode I type cracks, and occurrence of mode II type cracks are not related with change in tensile stress. From Figs. 6 and 7, it is implied that there is a range of phase lag which decreases the tensile strength.

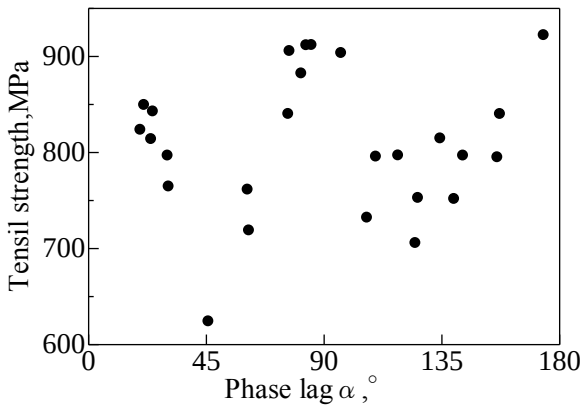


Fig.6 Relationship between the tensile strength and the phase lag.

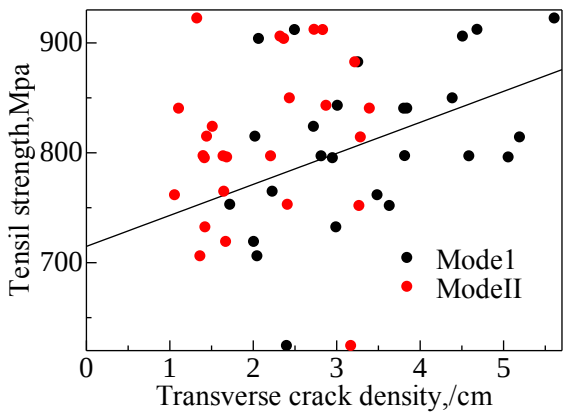
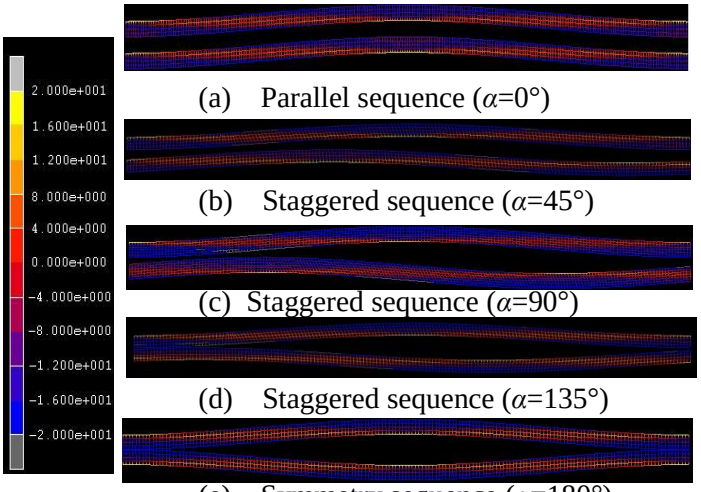


Fig.7 Relationship between tensile strength and mode I and II type crack densities.

3.4 Effect of the crimp gap on the stress distributions

Figures 8 (a) ~ (e) show the σ_{11} component in the warp yarns obtained from FEM analyses. The stress concentrated area at the staggered sequences model increases larger than that at the parallel and symmetry sequences model. The fiber breakages in the warp yarn would occur because of this higher stress concentration.



(a) Parallel sequence (α=0°)

(b) Staggered sequence (α=45°)

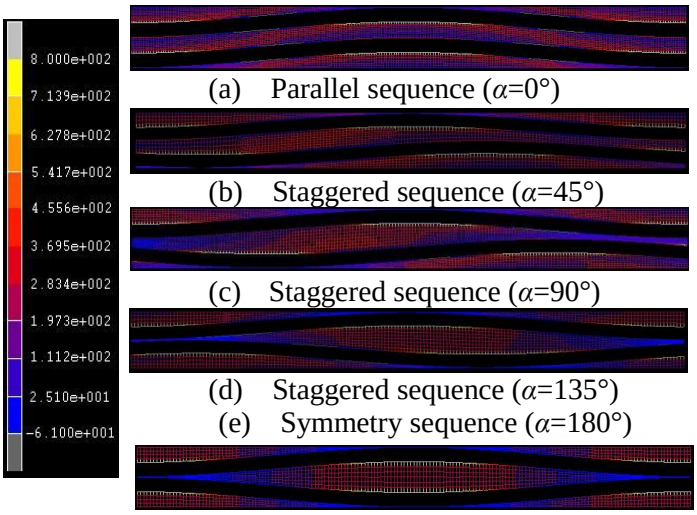
(c) Staggered sequence (α=90°)

(d) Staggered sequence (α=135°)

(e) Symmetry sequence (α=180°)

Fig. 8 σ_{11} stress components in warp yarns.

Figures 9 (a) ~ (e) show the σ_{11} component in the weft yarns obtained from analyses. The high tensile stress area and these values are similar in any case. To investigate the relation between the occurrence of transverse cracks and the distance of these warp yarns is our future work.



(a) Parallel sequence (α=0°)

(b) Staggered sequence (α=45°)

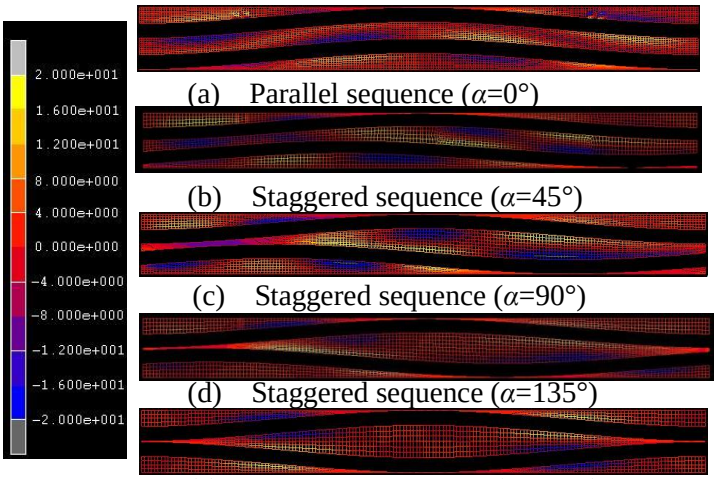
(c) Staggered sequence (α=90°)

(d) Staggered sequence (α=135°)

(e) Symmetry sequence (α=180°)

Fig. 9 σ_{11} stress components in weft yarns.

Moreover, Figures 10 (a) ~ (e) show the τ_{12} component in the weft yarns. From this stress distributions, the high shear stress area decreases as increasing phase lag. Consequently, the occurrence of mode II type crack decrease as phase lag increases, as shown in Fig. 5.



(a) Parallel sequence (α=0°)

(b) Staggered sequence (α=45°)

(c) Staggered sequence (α=90°)

(d) Staggered sequence (α=135°)

(e) Symmetry sequence (α=180°)

Fig. 10 τ_{12} stress components in weft yarns.

4 Conclusions

The relationship between the transverse crack density and the crimp gap in plain woven CFRP laminates was investigated in this study. From the tensile test of the laminates, it was found that the mode I type crack density decreases when the phase lag, i.e. misalignment of the crimp gap, is near 45° or 135°. Thus, the tensile strength was greatly affected by the phase lag. It was implied that accumulation of the mode I type cracks mainly increased the tensile strength.

References

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