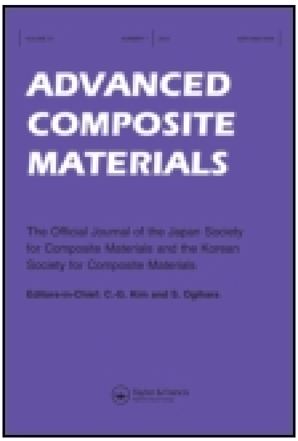

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Edge effect on the damage development of CFRP

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Abstract—The damage process of transverse cracks in quasi-isotropic CFRP laminates under quasi-static loading is studied. It is necessary to investigate the damage process of transverse cracks in order to apply CFRP composites to cryogenic fuel tanks of a Reusable Launch Vehicle (RLV). To investigate edge and specimen configuration effects on transverse cracks, coupon specimens with a range of specimen widths and transverse ply thicknesses are tested under tensile loads. Measurements of edge crack density and detailed observations of transverse crack propagation across the specimen width are made. The results suggest that transverse cracks initiate from free-edges and transverse ply thickness has significant effect on transverse crack propagation.

Keywords: Damage; CFRP; transverse cracking; free-edge effect.

1. INTRODUCTION

Composite materials are now common in many different kinds of structures. However, the damage process is very complicated. When CFRP coupon specimens are tested under tensile loads, different kinds of damage, such as transverse cracks, delaminations and fiber fractures develop before the final failure. Transverse cracking is often the first observed damage mode. Although this damage mode is not critical from a final fracture point of view, it induces more severe damage. Moreover, transverse cracking is a critical design factor for the cryogenic composite fuel tank of a Reusable Launch Vehicle (RLV). This is why it is important to investigate the development of transverse cracks.

Transverse cracking due to mechanical and thermal loads has been extensively studied, and crack initiation can be predicted very well. However, transverse crack propagation is related not only to the cracking stress state but also the distributive initial flaws, so the analytical models cannot predict the crack propagation very well.

Therefore, a probabilistic method has been employed. Xu [1] proposed a probabilistic analytical method, the Characteristic Curve Method (CCM), to correlate initial flaws with transverse crack densities. The concepts of the 'equivalent applied loading' and the 'equivalent crack density' are introduced to reveal the physical essence of the damage process. It is shown that the characteristic curves for laminates of the same material under the same cure process are approximately the same. Specimen configuration has significant effect on transverse crack initiation and propagation. Boniface *et al.* [2] conducted tensile tests of cross-ply coupon laminates with a range of transverse ply thicknesses. In laminates with thick plies, all cracks span the full thickness and width of the transverse plies, whereas for laminates with thin plies, part-width cracks exist over appreciable strain range. Pagano *et al.* [3] also showed the same trend.

In recent toughened CFRP laminates, transverse cracks are less susceptible to initiation or propagation. In this study, quasi-isotropic coupon specimens of toughened CFRP are tested under quasi-static tensile loads in order to investigate edge and width effect on transverse crack initiation. The widths of coupons are 15 mm, 30 mm and 50 mm. The process of crack growth is studied by observing edge cracks with an optical microscope and grown cracks by X-ray radiography. A parallel study is also carried out using coupons with thin transverse plies to investigate thickness effect on crack initiation and propagation.

2. EXPERIMENTAL

The material systems used in this study are IM600/Q133, intermediate modulus carbon fiber and toughened epoxy systems. The specimen configurations are summarized in Table 1. Edges of coupon specimens are polished by diamond hand stones. Specimens are checked for defects that may be introduced during the cure process by an optical microscope before testing. All tensile tests are carried out using an Instron 8501 (hydraulic driven) machine at slow cross-head speed (approximately 0.2 mm/min) at room temperature. Coupon specimens are instrumented with an extensometer and an acoustic emission sensor, and are initially loaded until the first acoustic event occurs. For damage inspection by X-ray radiography and edge observation using an optical microscope, coupons are removed from the machine after the penetrant is applied to coupon edges. Then these specimens are loaded to the next applied strain level. In this way, the density of part-width or full width transverse cracks can be obtained.

Table 1.
Specimen configuration

Type	Stacking sequence	Width (mm)	Thickness (mm)	Gauge length (mm)
Coupon E	$[45/0/-45/90]_S$	15, 30, 50	1.1	80
Coupon F	$[45/0/-45/90/-45/0/45]$	15, 30, 50	1.0	80

3. RESULTS

Figure 1 shows a micrograph and an X-radiograph of cracks in a [45/0/− 45/90] laminate at applied mechanical strain of 0.62%. By edge observation, many cracks can be seen, but few cracks propagate into the inner region. Some specimens are cut and examined for inner damage. There is no crack in the inner region at relatively low strain level. These results suggest that transverse cracks initiate from free-edges and propagate into the inner region. At higher strain level, transverse crack propagation and delaminations at free-edges can be observed. Figure 2 shows the damage process of these laminates; (a) edge cracks appear at the resin-rich region in 90° layers; (b) edge cracks are developed and almost saturated only in the edge region; (c) the cracks propagate into the inner region and edge delaminations initiate. In laminates with thin transverse ply thicknesses, transverse cracks are less susceptible to initiation or propagation. However, damage growth process of both laminates is almost the same. In coupon laminates, there seems to be no specimen width nor transverse ply thickness effect on this damage process within the qualitative meaning.

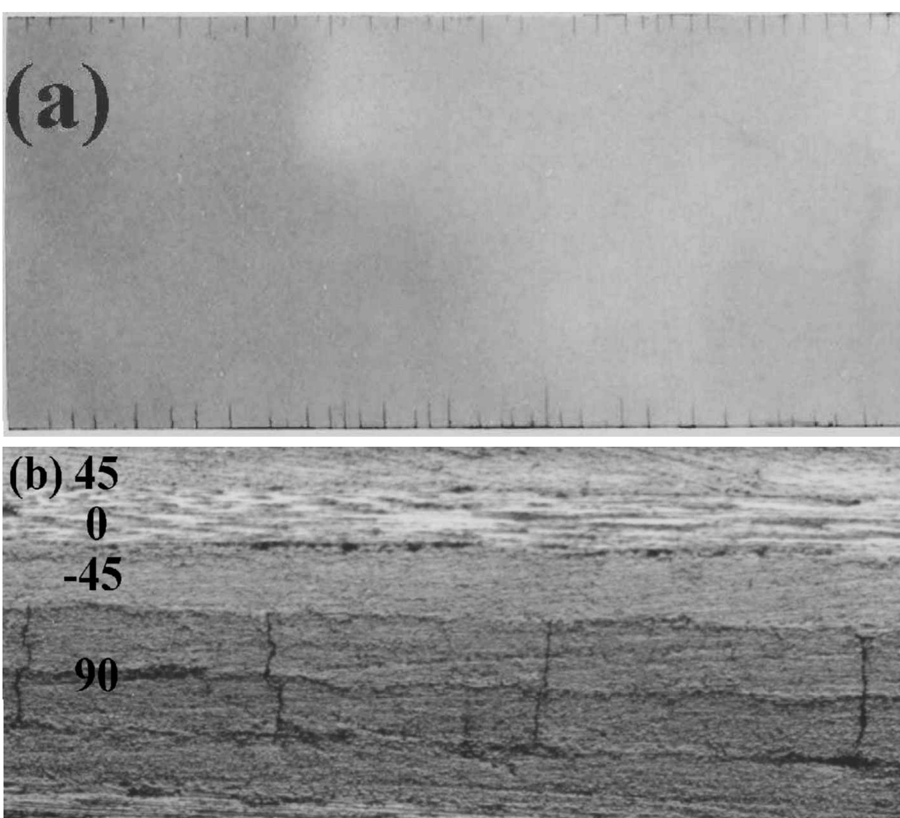


Figure 1. Edge cracks: (a) X-ray radiography; (b) edge observation $\varepsilon = 0.62\%$.

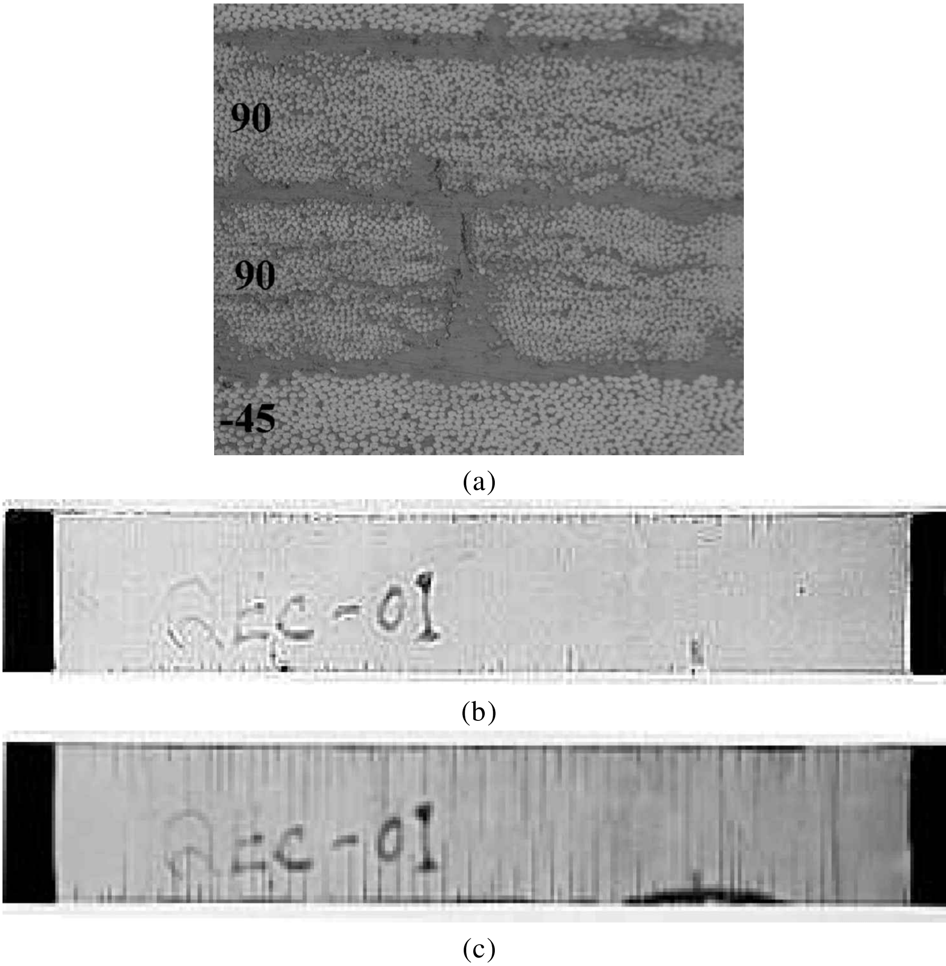
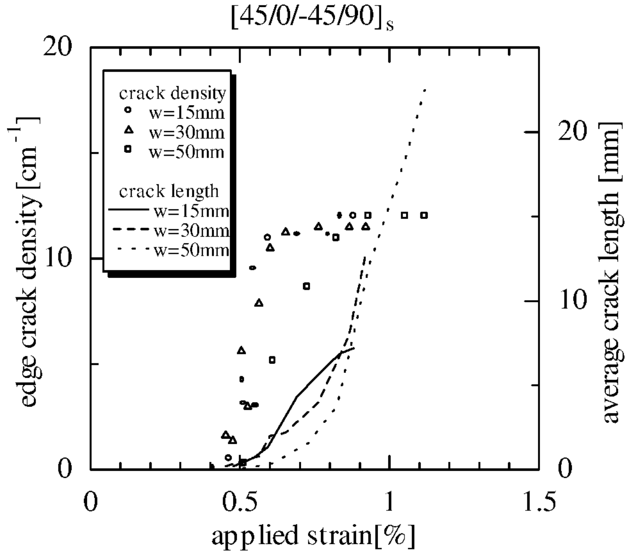


Figure 2. Transverse crack propagation process: (a) edge crack initiation in resin-rich region ($\varepsilon = 0.47\%$); (b) edge crack saturation ($\varepsilon = 0.61\%$); and (c) crack propagation across the specimen width ($\varepsilon = 0.72\%$).

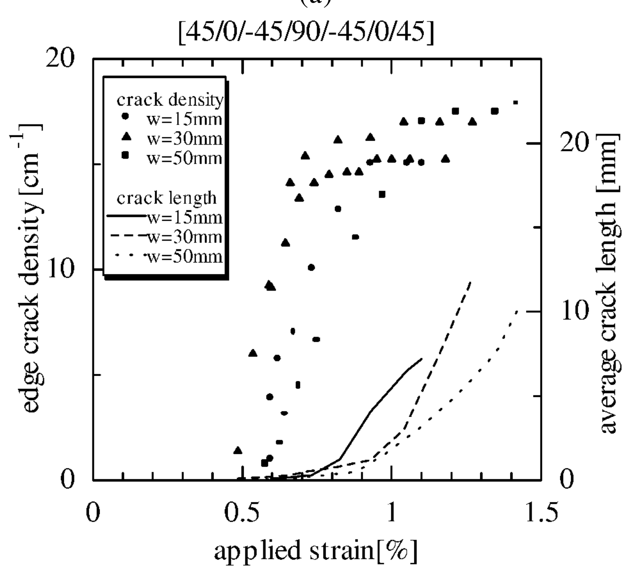
3.1. Edge cracks

Figure 3 shows the relationship between the applied tensile strain and edge crack density measured by edge observation. The circle, triangle, and square marks represent the edge crack densities of the specimen with 15 mm, 30 mm, and 50 mm width respectively. In 90_2 plies, edge cracks seem to initiate at lower strain level than in 90 ply. In conjunction with load increase, the numbers of edge cracks rapidly grow and saturate in both laminates. However, the saturation density of edge cracks in 90 ply is higher than in 90_2 plies. These trends coincide with the conventional results and analyses of transverse full width cracks.

There is a little difference between the laminates with a range of specimen widths about the initiation and growth process of edge cracks. However, this difference



(a)



(b)

Figure 3. Edge crack density and average crack length as a function of applied mechanical strain.

is probably caused by edge conditions, not by specimen width. Kitano *et al.* [4] showed an edge condition effect on the transverse cracks. As edge cracks may be considerably influenced by edge conditions, further investigation is needed.

In recent toughened CFRP laminates, the edge crack density is not equal to the density of transverse full width cracks, so damage inspection of the inner region is needed. Edge crack length along the specimen width is too short to be observed by only X-ray radiography, especially at edge crack initiation. This is why both edge observation and X-ray inspection are conducted.

3.2. Transverse crack propagation

By X-ray radiography, transverse crack length from free-edges along the specimen width can be obtained, as shown in Fig. 3. The full, chain, and dotted lines show the average crack length of the specimen with 15 mm, 30 mm, and 50 mm width respectively. Although observed values of crack length from free-edges have variation to some degree, the lengths of the majority of the cracks are almost the same. The average values of measured cracks lengths are used in this study. Full width cracks are regarded as two half-width cracks. The cracks barely propagate in the edge crack growth process, and after edge crack saturation, crack propagation into the inner region accelerates. From Fig. 3, transverse cracks seem to be less susceptible to propagating through the width in the specimens with thinner 90° plies. There seems to be little effect of specimen width on transverse crack propagation.

4. ANALYSIS

The edge crack growth process seems to be dependent on edge conditions. In this analysis, transverse cracks are supposed to grow from the distributed initial defects at free-edges. According to Wang's 'effective flaw hypothesis' [5], the defects in matrix can be simulated by a distribution of the effective flaws. These flaws may form *situ* transverse crack density. He defined the 'equivalent applied loading' as:

$$\varepsilon_{\mathrm{EQ}} \approx \frac{\varepsilon_{\mathrm{CI}}}{\varepsilon_{\mathrm{CS}}}\sqrt{\frac{\varepsilon_{\mathrm{CS}}^2-\varepsilon^2}{\varepsilon^2-\varepsilon_{\mathrm{CI}}^2}}, \tag{1}$$

where CI and CS represent the crack initiation and the crack saturation state respectively. The equivalent crack density, $D_{\mathrm{EQ}} = D/D_{\mathrm{CS}}$, is derived as:

$$D_{\mathrm{EQ}} = 1 - F_{\varepsilon}(\varepsilon_{\mathrm{EQ}}), \tag{2}$$

where $F_{\varepsilon}(\varepsilon_{\mathrm{EQ}})$ is the distribution function of the equivalent applied loading. In this study, $F_{\varepsilon}(\varepsilon_{\mathrm{EQ}})$ can be described by the Weibull distribution function, i.e.

$$F_{\varepsilon}(\varepsilon_{\mathrm{EQ}}) = 1 - \exp\Big[-\big(\varepsilon_{\mathrm{EQ}}/\omega\big)^{K}\Big], \qquad D_{\mathrm{EQ}} = \exp\Big[-\big(\varepsilon_{\mathrm{EQ}}/\omega\big)^{K}\Big], \tag{3}$$

where ω and K are parameters.

To predict edge crack growth, the crack initiation and the final saturation crack density should be predicted first. Many models can be applied to the prediction of the crack initiation, and the crack saturation loading should be measured in experiments. The parameters ω and K are obtained from a fitted curve of experimental data.

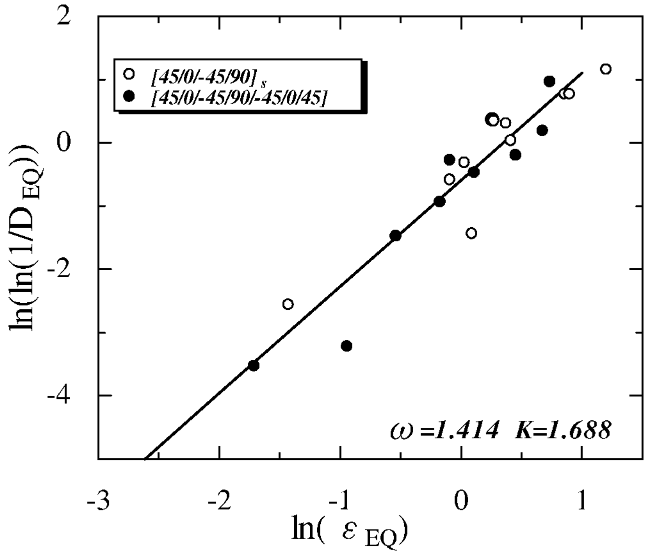


Figure 4. The relationship between the equivalent loading and the equivalent crack density.

The relationship between the equivalent applied loading and the equivalent edge crack density of both laminates with 15 mm width is shown in Fig. 4. By linear regression, the edge crack growth parameters are obtained. The obtained values of ω and K are 1.414 and 1.688 respectively. Figure 4 also shows that the distribution function can be described as the Weibull distribution function very well. By using these parameters, analytical predictions of edge crack density are carried out. Figure 5 shows the experimental data and analytical predictions of edge crack density in 90 plies of both laminates with 15 mm width. According to Fig. 5, edge crack growth processes of $[45/0/-45/90]_s$ and $[45/0/-45/90/-45/0/45]$ laminates seem to be different. However, the fitting parameters obtained from Fig. 4 may be regarded as the material properties and not depend on the laminate layups [1]. By using these obtained parameters, edge crack growth can be predicted very well, as shown in Fig. 5.

5. CONCLUSIONS

Detailed observations of transverse cracks confirm that transverse cracks initiate from free-edges, and that there is a three-stage process of edge crack initiation, edge crack saturation, and crack propagation across the width. The existence of free-edges has significant effect on *in situ* transverse cracking. Data of edge crack density show that edge crack growth process is similar to the conventional full width cracking. A probabilistic-analytical method can be applied to the prediction of edge crack growth. By linear regression, edge crack growth parameters are obtained. Edge crack density of $[45/0/-45/90]_s$ and $[45/0/-45/90/-45/0/45]$ laminates

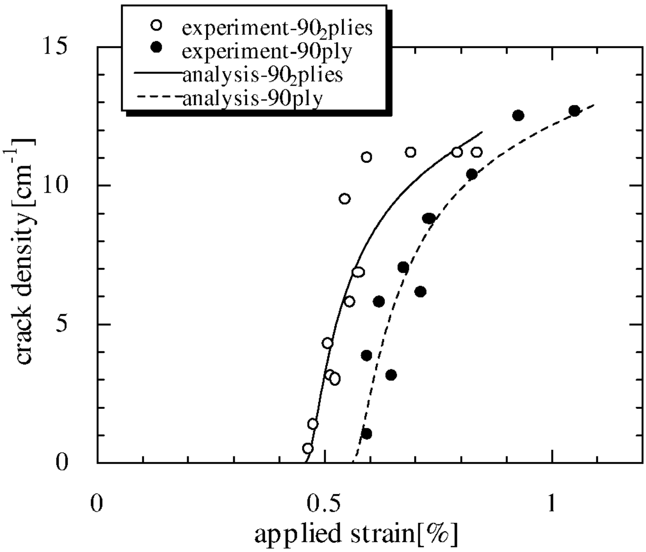


Figure 5. Experimental data and prediction of edge crack growth.

are predicted very well. There is no relation between the specimen width and edge crack growth.

Measurements of crack length from free-edges suggest that the thickness of transverse plies influences crack propagation. Transverse cracks are less susceptible to propagating in thinner 90° plies. Useful information for cryogenic composite fuel tanks of an RLV is obtained. Further work to analyze free-edge stresses and investigate transverse ply thickness effect on transverse cracks is needed.

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