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Ultimate Strength of Composite Laminates with Free-Edge Delamination

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The present paper deals with the free edge effect of composite laminates by using a generalized quasi-three dimensional analysis and experimental verification of an analysis performed for laminates with Teflon inserted on interfaces to simulate initial free-edge delamination. We performed tensile tests for laminates $[30_2/-30_2/90]_s$ carbon-epoxy laminates with free-edge delamination under uniaxial tension. The experiment reveals that extensional stiffness of the laminate decreases by the initiation of the delamination, and that strength of the laminate without delamination is smaller than that of the laminates with delamination. Generalized quasi-three dimensional finite element technique, which employs energy release rate and maximum stress criteria, is developed to estimate behavior of the laminate after initial delamination. The numerical result by use of this technique predicts the ultimate strength of the laminates with sufficient accuracy according as the comparison with an experimental stress-strain curve. In the experiment conducted both for the laminate with initial delamination and the laminate without initial delamination, an unexpected results were obtained that is the ultimate load of the laminate without initial delamination was lower than that of the laminate with initial delamination. We presented clear explanation on the phenomenon occurred and developed the method to predict the nonlinear behavior of the laminate with or without initial delamination.

Key Words: Composite Laminates, Free-Edge, Ultimate Strength, Delamination

1. Introduction

The importance of carbon fiber reinforced plastics (CFRP) for an aircraft and a space vehicle which requires the ultimate light weight have been generally recognized. Most of the aircrafts and space vehicles use CFRP as a laminated plate. It is well known that the composite laminates have low fracture toughness and tend to get delamination failure. The behavior of the free-edge is still important subject to study in the future.

Pipes and Pagano(1970) proposed the quasi-three dimensional analysis and showed a stress concentration at the free-edge of the laminates by performing the analysis of symmetric angle-ply laminates. Although their study was remarkable in which they developed a basis methodd for the future study, they clarified the delamination onset by the interlamina stress qualitatively, not quantitatively. On the other hand, O'Brien(1982), Aoki and Kondo(1989) tried to explain the delamination growth by calculating the strain energy release rate at tip of the delamination.

Since they used the quasi-three dimensional analysis to calculate a strain energy release rate, Whitcomb and Raju(1985) pointed out question about applicability of the quasi-three dimensional analysis when the delamination occurred unsymmetrically with respect to the middle surface of laminates. However they have never published an analysis that copes with this problem. Kunoo, Uda, Ono and Onohara(1992) proposed the generalized quasi-three dimensional analysis that deals with bending and twisting of laminates.

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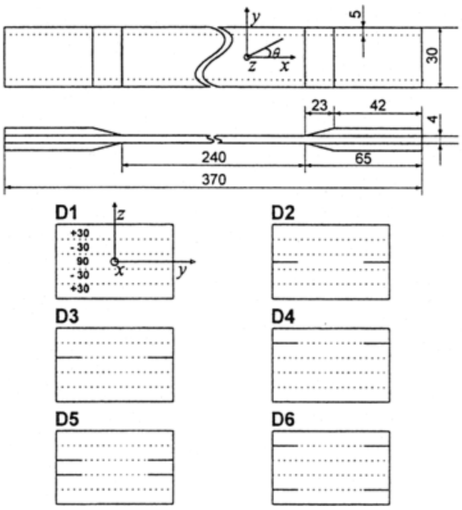


Fig. 1 Test specimen.

They showed that the generalized quasi-three dimensional analysis clearified the difference of rigidity of laminates and strain energy release rate at the tip of delamination depending on bending and twisting constraints. Most of the studies in the past discussed the onset of delamination, but only few papers dealt with behavior of laminates after the onset of delamination.

This paper describes the theoretical and experimintal results on mechanical property of laminates after the onset of delmination.

2. Test Results

Figure 1 shows the CFRP laminates produced with stacking sequence $[30_2/-30_2/90]_s$. The six kinds of specimens named D1~D6 contain Teflon film of 5mm width along the free-edge to simulate interlaminar delamination. Instron 1125 that has loading capacity 100 kN loaded the specimens in tension. Increase of load caused the onset and growth of delamination except specimens D4 and D6.

Figure 2 shows delamination resulted in the specimen D1. Delamination of the specimens D2, D3 and D5 grew in the same plane as the inserted Teflon film. Increase of load caused the final failure after delamination. Table 1 shows the initial stiffness, the stress and the strain of the delamination onset, and the ultimate strength of each specimen in average value.

Table 1 Test results

Specimen	Initial Stiffness (GPa)	Delamination Onset		Ultimate Strength (MPa)
		Stress (MPa)	Strain (μ strain)	
D1	38.8	223	5910	242
D2	35.3	152	4380	274
D3	34.8	210	6300	256
D4	34.1	…*	…*	264
D5	33.7	205	6360	262
D6	29.8	…*	…*	218

* No delamination growth

3. Strength Analysis

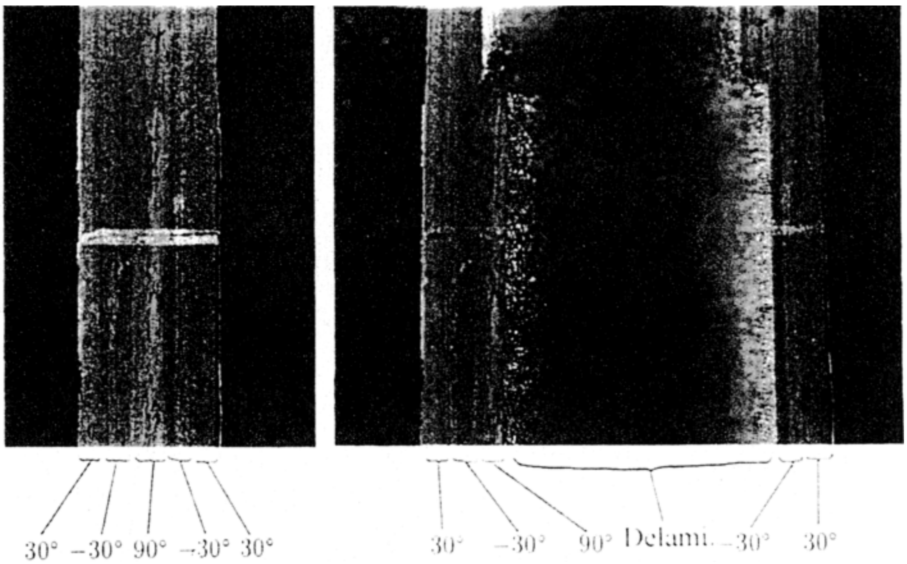
We used the generalized quasi-three dimensional method that evaluated a three dimensional displacement field by calculating the plane of a laminate. In the analysis conducted the combination of the strain energy release rate and the maximum stress criterion evaluated failure of the laminate. Figure 3 shows the procedure of the strength analysis developed in this paper.

At first, initial delamination length of $a_0=5$mm and delamination length $a=a_0+\Delta a$ are calculated by the generalized quasi-three dimensional analysis. On the basis of the computed results before and after delamination, we calculate a strain energy release rate at the tip of delamination by using virtual crack closure technique (Rybicki et al., 1977).

Next, the delamination onset load P_{DEL} is calculated by the following formula,

$$\frac{G_I}{G_{Icr}}+\frac{G_{II}}{G_{IIcr}}+\frac{G_{III}}{G_{IIIcr}}=1 \qquad (1)$$

where G_I, G_{II} and G_{III} are strain energy release rate for mode I, II and III components respectively. G_{Icr}, G_{IIcr}, G_{IIIcr} are fracture toughness for mode I, II and III components respectively. In this paper $G_{Icr}=100$N/m, $G_{IIcr}=G_{IIIcr}=433$ N/m are used (Ramkumar et al., 1985).



(a) Free-edge of no delamination (b) Free-edge after delamination

Fig. 2 Interlaminar delamination in DI.

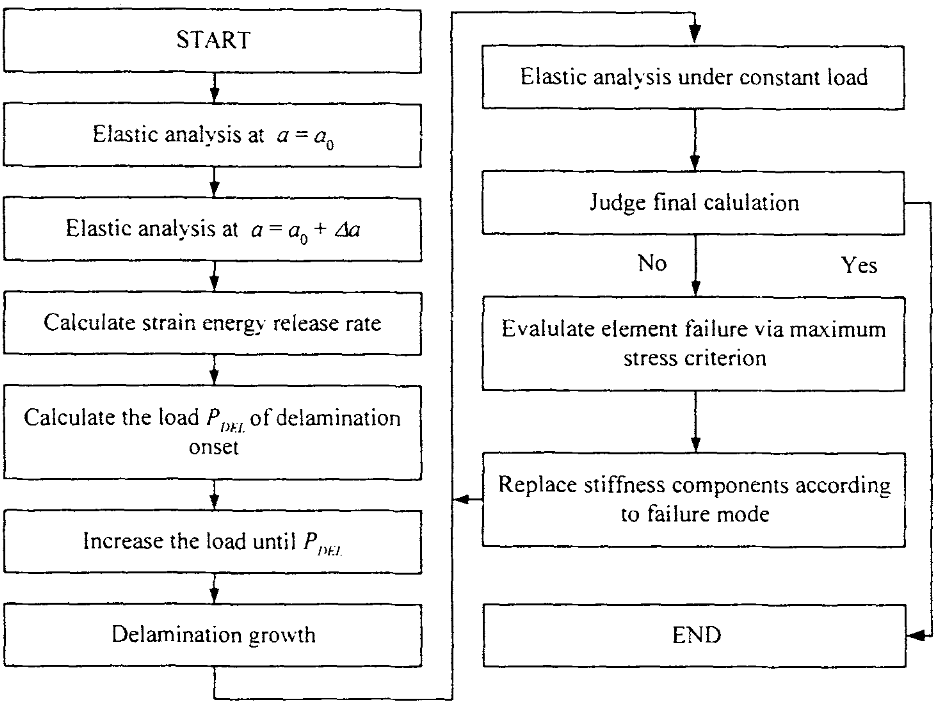


Fig. 3 Strength analysis proceures.

We calculate behavior of the laminate at the load P_{DEL} by assuming that delamination propagates immediately from $a=5$ mm to $a=15$ mm in length at the load P_{DEL}. The finite element procedure realizes immediate propagation of delamination by making twofold nodal points. We evaluate finite element failure by using the maximum stress criterion for calculated stresses.

If there exists a failure element, the stiffness components of the element are replaced with

Table 2 Replacement of stiffness components

Failure Mode	Stiffness Components
F_{1t}, F_{1c}	$Q_{11}=Q_{12}=Q_{13}=Q_{21}$ $=Q_{31}=Q_{55}=Q_{66}=0$
F_{2t}, F_{2c}, F_{12}	$Q_{12}=Q_{21}=Q_{22}=Q_{23}$ $=Q_{32}=Q_{44}=Q_{55}=0$
F_{3t}, F_{3c}, F_{31}	$Q_{13}=Q_{23}=Q_{31}=Q_{32}$ $=Q_{33}=Q_{44}=Q_{55}=0$
F_{23}	$Q_{12}=Q_{21}=Q_{13}=Q_{23}$ $=Q_{31}=Q_{32}=Q_{22}=Q_{33}$ $=Q_{44}=Q_{55}=Q_{66}=0$

those of the value indicated in Table 2 according as the failure mode. The stiffness equation is defined as follows,

$$\begin{Bmatrix}\sigma_1\\ \sigma_2\\ \sigma_3\\ \tau_{23}\\ \tau_{31}\\ \tau_{12}\end{Bmatrix}=\begin{bmatrix}Q_{11} & Q_{12} & Q_{13} & 0 & 0 & 0\\ Q_{21} & Q_{22} & Q_{23} & 0 & 0 & 0\\ Q_{31} & G_{32} & Q_{33} & 0 & 0 & 0\\ 0 & 0 & 0 & Q_{44} & 0 & 0\\ 0 & 0 & 0 & 0 & Q_{55} & 0\\ 0 & 0 & 0 & 0 & 0 & Q_{66}\end{bmatrix}\begin{Bmatrix}\varepsilon_1\\ \varepsilon_2\\ \varepsilon_3\\ \gamma_{23}\\ \gamma_{31}\\ \gamma_{12}\end{Bmatrix} \quad (2)$$

where we use 1-2-3 coordinate system in which 1 indicates the fiber direction of the uniaxial lamina. In the real computation we replace the stiffness of a failed element with 1/100,000 of the actual stiffness instead of zero to avoid singularity of a stiffness equation.

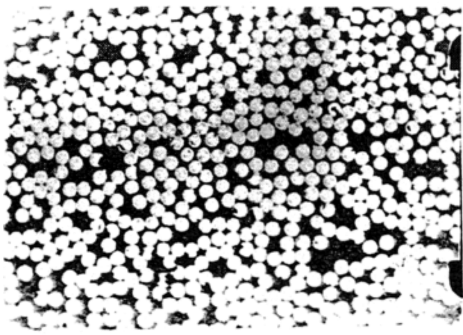
After the replacement of the stiffness, the calculation is repeated under a constant load until no failure occurs. Next step is to increase the load that causes another element failure. The computation is terminated when a strain exceeds 5% or the stiffness matrix becomes singular. In the case of specimen D1, we analyzed the strength only by the maximum stress criterion because of no initial delamination.

4. Material Constants

As material constants of composite laminates depend on fiber volume fraction V_f, we estimated V_f by image processing technique. Figure 4 is a section of 90-degree lamina of D1 coupon and shows circular fibers with epoxy matrix. By using an image processing for Fig. 4, we computed V_f at 56% resulted from ratio of fiber areas to fiber and matrix areas. We adopted the material constants shown in Table 3 according as an estimation formula developed in the reference Okula et al., 1984), Hukutani, 1985), and Hwang et al., 1989).

Table 3 Material constants in the analysis

Elastic Constants	Failure Strength (MPa)
E_1 94.1 GPa	F_{1t} 1230
E_2 5.69 GPa	F_{1c} -1010
E_3 5.69 GPa	F_{2t} 68.0
G_{23} 2.19 GPa	F_{2c} -241.0
G_{31} 2.11 GPa	F_{3t} 68.0
G_{12} 2.11 GPa	F_{3c} -241.0
ν_{23} 0.30	F_{23} 62.1
ν_{31} 0.01995	F_{31} 62.1
ν_{12} 0.33	F_{12} 62.1



$V_f = 56\ \%$

Fig. 4 90-degree section.

5. Computed Results

Table 4 shows the computed results of specimens from D1 to D6 with the finite element procedure based on the generalized quasi-three dimensional analysis. The computed results indicated the lower initial stiffness than the experimental ones. One of the reason is that the elastic constants used in the analysis was lower than the true ones. However the difference is within 10%

Table 4 Computedd results

Specimen	Initial Stiffness (GPa)	Delamination Onset		Ultimate Strength (MPa)
		Stress (MPa)	Strain (μ strain)	
D1	36.3	…*	…*	479**
D2	32.3	102	3170	269
D3	32.1	116	3600	275
D4	32.1	185	5760	286
D5	31.3	153	4870	268
D6	27.5	161	5830	161

* No delamination growth

** Strength analysis via the maximum stress criterion

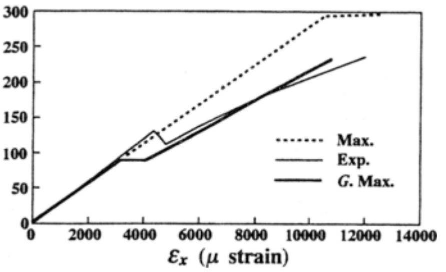


Fig. 5 Stress-strain curve for D2.

that may be considered practically accurate enough. The specimen D1 that has no initial delamination showed the highest initial stiffness among all specimens. Initial stiffness depends on the location of delamination.

We assumed delamination growth for the specimens D4 and D6 in the analysis conducted. However the experiments for these specimens showed no delamination because the final failure occurred near the tab of the specimens. Experiments on delamination growth for the specimens D2, D3 and D5 showed higher load than that of the computed results in the case of delamination onset. The reason for this may be founded on higher fracture toughness than that of the data used for the computation. In fact there is a report (Koizumi et al., 1988) that lower fiber volume fraction gets higher fracture toughness.

Figure 5 shows the stress-strain curve for the specimen D2. In the figure, the solid line with

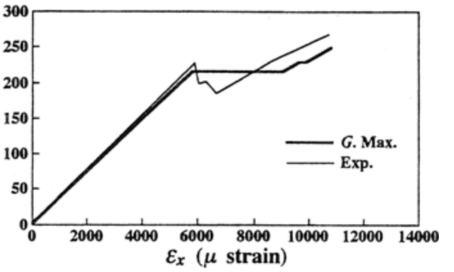


Fig. 6 Stress-strain curve for D1.

Exp. indicates the experimental results. The solid line with G-Max. and the dotted line with Max. show the computed results of the combination of a strain energy release rate and the maximum stress criterion, and the maximum stress criterion only respectively. The computed results of the combination of a strain energy release rate and the maximum stress criterion compare favorably with the experiment.

The stress strain curves for the specimen D1 that has no initial delamination are shown in Fig. 6. Table 1 shows that the ultimate load of D1 was lower than that of D2. And in the case of D1 the computed ultimate load using the maximum stress criterion is 479 MPa that is much higher than the experimental one 242 MPa. We considered that the specimen D1 had short initial flaws. Therefore we assumed short initial delamination in 0.1 mm length and computed the behavior of D1 by using the strain release rate and the maximum stress criterion. The computed results agree well with the experimental results as shown in Fig. 6.

6. Conclusions

We studied the free-edge effect of composite laminates by conducting the generalized quasi-three dimensional analysis and experiment of laminates with Teflon inserted on interfaces to simulate initial free-edge delamination. The following results were obtained,

(1) The extensional stiffness of the laminates with delamination is lower than that of the laminates without delamination. Its magnitude depends on locations of delamination.

(2) The ultimate strength of the laminate with delamination depends on locations of delamina-

tion. The experimental ultimate strength agreed well with the computed result predicted by the strain energy release rate and the maximum stress criterion.

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