INEXPENSIVE DAMAGE PROPAGATION ANALYSIS FOR COMPOSITE LAMINATES BY USING FEM WITH PLANE ELEMENTS

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SUMMARY: Recently, applications of integrated composite structures have been attempted to many structures of vehicles. To improve the cost performance and reliability, it is necessary to judge the structural integrity of the composite structures with damage. For the judgement, we have developed a simple and inexpensive simulation method using finite element method with two-dimensional plane stress elements. The simulation method includes both intralaminar and interlaminar fracture mechanisms. Analytical damage propagation and stiffness degradation of CF/epoxy laminate with an open hole were compared with experimental results. As a result, it is shown that the proposed simulation method can roughly predict the damage propagation and stiffness degradation of composite laminates.

KEYWORDS: Damage, Finite element method, Delamination, Simulation

INTRODUCTION

Recently, applications of integrated large composite structures have been attempted to many structures of vehicles. To improve the cost performance and reliability of the integrated composite structures, it is necessary to judge the structural integrity of the composite structures with defects that were found by nondestructive inspection. For the judgement, we need fracture simulation techniques of composite structures. Many researches on the fracture simulation method using FEM have been reported by now. The main objective in the studies, however, is to predict fracture strength of structures, and damage propagation of composite laminates has not been investigated in detail. Most of the researches carried out simulations considering only intralaminar fracture mechanisms, and did not consider delamination. Several papers have reported the delamination simulation [1][2][3][4], but all these reports require three-dimensional elements or quasi three-dimensional elements for FEM analysis. The analyses are very expensive and time-consuming.

In order to analyze damage propagation of composite laminates inexpensively, we have developed a fracture simulation technique using FEM with plane stress elements that includes both intralaminar and interlaminar fracture mechanisms. For the intralaminar fractures, i.e. matrix cracking and fiber breaking, stiffness degradation of laminae is applied to the fractured laminae, and stress-strain matrices of elements are calculated based on the classical lamination theory. For the interlaminar fracture, i.e. delamination, stiffness degradation of elements based on improved lamination theory is applied to the delaminated elements. This approach does not require thickness-direction analysis. Analytical damage propagation and stiffness degradation of CF/epoxy laminate with an open hole were compared with experimental results. As a result, it is shown that proposed simulation method can roughly predict the damage propagation and stiffness degradation of composite laminates.

SIMULATION PROCEDURE

Judgement of Intralaminar Fractures

Tsai-Hill criterion was adopted as a fracture criterion of intralaminar fractures.

$$\left(\frac{\sigma_L}{F_{Lt}}\right)^2 - \frac{\sigma_L \sigma_T}{F_{Lt}^2} + \left(\frac{\sigma_T}{F_{Tt}}\right)^2 + \left(\frac{\sigma_{LT}}{F_{LT}}\right)^2 = 1 \tag{1}$$

where σ_L, σ_T, σ_{LT} are longitudinal stress, transverse stress and shear stress, respectively, and F_{Lt}, F_{Tt} and F_{LT} are longitudinal tension strength, transverse tension strength and shear strength, respectively. If compressive stress components are involved, the corresponding compressive strength should be used.

Fiber breaking of the lamina is judged if $\sigma_L \geq F_{Lt}$ *or* $\sigma_L \leq F_{Lc}$, and matrix cracking of the lamina is judged if $F_{Lc} \leq \sigma_L \leq F_{Lt}$, where F_{Lc} is longitudinal compress strength. Stiffness degradation of the lamina that was judged as intralaminar fractures is as follows.

$$\begin{aligned} &\text{Matrix cracking}: E_T^* = \frac{1}{100} E_T, G_{LT}^* = \frac{1}{100} G_{LT} \\ &\text{Fiber breaking}: E_L^* = \frac{1}{100} E_L, E_T^* = \frac{1}{100} E_T, G_{LT}^* = \frac{1}{100} G_{LT}, \nu_{LT}^* = \frac{1}{100} \nu_{LT}, \end{aligned} \tag{2}$$

where E_L, E_T, G_{LT}, ν_{LT} are longitudinal modulus, transverse modulus, shear modulus and major Poisson ratio, respectively, and superscript * means degraded modulus.

Judgement of Interlaminar Fractures

In the present approach, delamination is regarded as stiffness degradation of plane stress elements of FEM. By dividing the difference between total strain energy before and after delamination by the element area, we can obtain the total strain energy release rate G of the elements due to delamination. If strain components $\{\varepsilon_1\ \varepsilon_2\ \varepsilon_6\}$ are unchanged before and after delamination, the total strain energy release rate G is expressed as

$$G = \left(\frac{1}{2}\varepsilon^T D_{lam}\varepsilon - \frac{1}{2}\varepsilon^T D_{delam}\varepsilon\right) \cdot St \Big/ S \tag{3}$$

where D_{lam} and D_{delam} are stress-strain matrices of the laminate without and with delamination, respectively, and S, t are the element area, element thickness, respectively [5]. It is assumed that longitudinal moduli of X direction and Y direction are calculated independently by using Whitcomb & Raju's method [6].

A criterion of delamination onset is described as

$$G > G_C \tag{4}$$

where G_C is the critical energy release rate.

Simulation Procedure

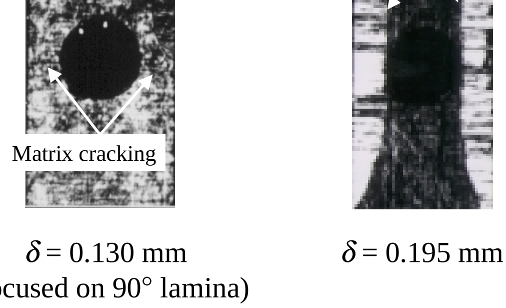
The simulation procedure is described as follows.
(1) The D matrix is calculated based on the classical lamination theory.
(2) Strain components of each element are determined by FEM analysis with 2-dimensional plane stress elements.
(3) A fractured lamina or a delaminated element is estimated one by one according to Yamada's method [7].
(4) Degradation of stiffness is applied to the fractured lamina or the delaminated element.
(5) The above process is repeated until a given displacement is achieved.

In the simulation, triangle plane stress elements are adopted. In each element, an additional fracture is not judged after delamination for simplicity of calculation.

EXPERIMENTAL AND ANALYTICAL RESULTS

Using CFRP laminates of stacking sequence $[30_2/\text{-}30_2/0_2/90_2]_S$ with an open hole, static tension tests were conducted under a displacement control. An extensiometer was mounted on the specimens to measure a displacement over 50mm-gauge length. In order to observe delamination and matrix cracking, applied load was held at several steps and then unloaded. Ultrasonic inspection method (Hitachi AT5000) was used for the observation.

Damage propagation results obtained experimentally are shown in Fig. 1. In the first step, matrix cracking in 90° lamina emanated from the hole edges where the stress concentration occurred. Further increase of the displacement brought delamination between 0° lamina and 90° lamina. The delamination propagated into loading direction from the ligaments of the specimen.



δ = 0.130 mm (Focused on 90° lamina) δ = 0.195 mm

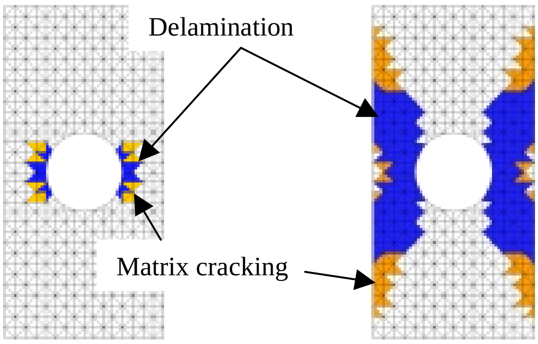
Figure 1: Experimental damage propagation in $[30_2/\text{-}30_2/0_2/90_2]_S$ laminate

Damage propagation analysis of the laminate with an open hole was conducted by using the proposed simulation method. In the analysis, a mesh division of 524 nodes and 928 elements was adopted, and a displacement was given at the upper edge of the mesh division. Material properties used in the analysis are listed in Table 1. In Table 1, subscripts L and T denote longitudinal and transverse, respectively.

Table 1: Material properties of CFRP

Longitudinal modulus, E_L	161.7 GPa
Transverse modulus, E_T	9.43 GPa
Shear modulus, G_{LT}	5.06 GPa
Major Poisson ratio, ν_{LT}	0.32
Longitudinal tension strength, F_{Lt}	2000 MPa
Transverse tension strength, F_{Tt}	30 MPa
Shear strength, FL_T	550 MPa
Longitudinal compress strength, F_{Lc}	160 MPa
Transverse compress strength, F_{Tc}	60 MPa
Critical energy release rate, G_C	294 J/m^2

The results obtained from the analysis are shown in Fig. 2. Dark elements represent matrix cracking, and black elements represent delamination. Matrix cracking occurred 90° lamina form hole edges, and delamination occurred between 0° lamina and 90° lamina from the hole edges. Further increase of the displacement brought delamination from free edges, and it propagated in the same way as the experimental results. The profile of the analytical damage propagation agrees with the experimental one.



δ = 0.125 mm δ = 0.200 mm

Figure 2: Analytical damage propagation in $[30_2/\text{-}30_2/0_2/90_2]_S$ laminate

Load versus displacement curves are shown in Fig. 3. Solid line represents an experimental result and broken line represents an analytical result. Since delamination propagated beyond the mounted points of the extensiometer when the displacement reached at δ = 0.24 mm and excessive stiffness degradation was observed in the experimental result, we show the load-displacement relationship until δ = 0.24 mm. The analytical result shows a good agreement with the experimental result.

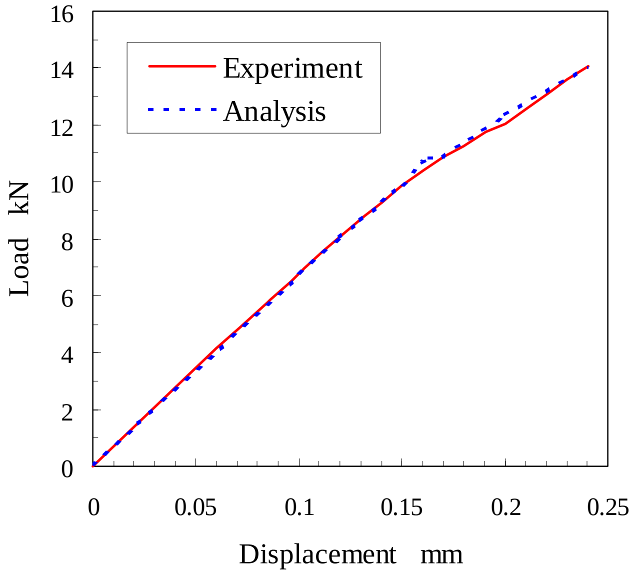


Figure 3: Load versus displacement curves

Increase of delamination area in according with the displacement is shown in Fig. 4. Vertical axis means delamination area normalized by the analyzed area. Open circles mean experimental results and open squares mean analytical results. Rapidly increase of delamination area after δ = 0.13 mm was reproduced by the analysis. As a result, it is shown that the simulation method can roughly predict damage propagation and stiffness degradation of composite laminates.

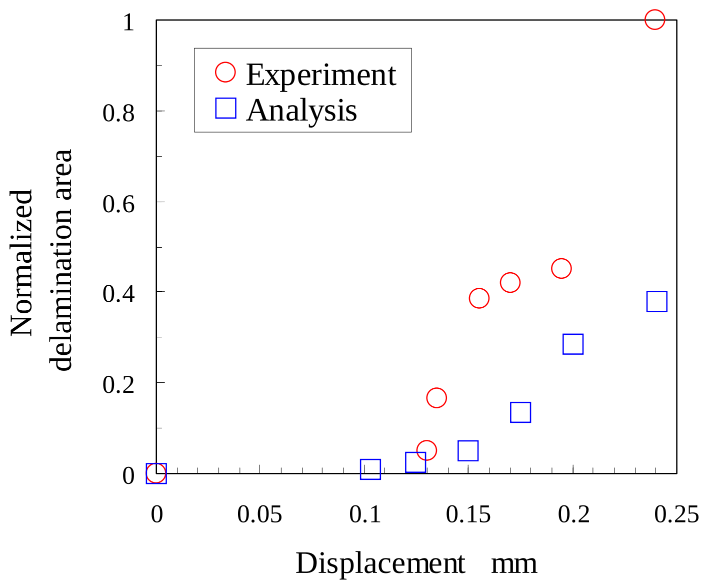


Figure 4: Increase of delamination area

CONCLUSIONS

A FEM simulation method of damage propagation for composite laminates was proposed, and analytical results were compared with experimental results. As a result, it is shown that the simulation method can roughly predict damage propagation and stiffness degradation of composite laminates.

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