Tensile Damage Analysis Method for Composite Laminates Using a Quasi-3-Dimensional Model*

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Measurement of the strength for laminated composites is very difficult because their failure processes involve various failure modes, which are, for example, interlaminar delamination, destruction of the matrix and interfacial fracture between the fiber and matrix. However, their strength is one of the most important characteristics in structural design using laminated composites. Hence we attempted to develop a fractural progress analysis of laminated composites using a quasi-3-dimensional analysis method under a tensile load. The quasi-3-dimensional model is constructed of shell elements and beam elements which represent the fiber and matrix, respectively. The fractural progress analyses of the laminated composites are carried out to evaluate this proposed model, and are compared with experimental results. Therefore we confirm that this proposed model can simulate a transverse crack and interlaminar delamination independently.

Key Words: Laminated Construction, Finite-Element Method, Delamination, Quasi-3-Dimensional Model, Transverse Crack, Hole

1. Introduction

There is increasing interest presently in many industries in the use of carbon-reinforced plastics as substitutes for conventional metallic materials. This is because of the benefits of high specific strength and specific stiffness. Other advantages such as high corrosion resistance and design flexibility are added attractions. Particularly, a laminated composite fabricated from unidirectional reinforced prepregs is widely used because its stiffness can be easily changed by varying its fiber orientation, and its specific stiffness and specific strength are very high as compared with other materials such as conventional metals. Therefore many reports have been published for the

experimental estimation of their characteristics. The estimation of the tensile strength, considered to be one of the most important factors in structural design, is very difficult. Also, it is more difficult in experiments to consider the damage progress, and the effects of fiber, matrix and interface on the damage progress, because this progress implies various failure modes, which are interlaminar delamination, destruction of the matrix and interfacial fracture between the fiber and matrix. Moreover the estimation of a critical tensile load for the laminated composite with a hole is more difficult because of its stress concentration in the vicinity of the hole⁽¹⁾⁻⁽³⁾. Accordingly the consideration for the tensile fractural mechanism using the finite-element method is an important guide in the design of structures with laminated composites. The use of 3-dimensional solid elements is considered to be the most appropriate for the simulation of the behaviors of laminated composites since the behaviors have complex 3-dimensional deformations with Poisson's effect. Therefore the simulation of the fractural process of the laminated composites using 3-dimensional elements require a very large number of very small elements as compared with a model for the

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Fig. 1 Basic concept for quasi-3-dimensional model

estimation of stiffnesses, because the fractural process consists of above mentioned local failures. However the solution time of these 3-dimensional analyses is too long for usual computer performances⁽⁴⁾⁻⁽⁷⁾. On the other hand, the laminated composite is sometimes assumed to be a single equivalent stiffness plate by means of classical lamination theory⁽⁸⁾⁻⁽¹⁰⁾. However this method cannot simulate the in-layer fracture and the interlaminar delamination independently. Accordingly we need to consider the new numerical model by constructing shell and beam elements which represent the fiber and matrix, respectively. We call this model the quasi-3-dimensional model. We reported that the quasi-3-dimensional model is effective for the estimation of various static stiffness and eigen frequencies of the virgin laminated composite⁽¹¹⁾. Moreover we confirmed that the quasi-3-dimensional model was valid for damaged laminates with interlaminar delamination to simulate the eigen frequencies and buckling strengths by eliminating beam elements on the delaminated positions⁽¹²⁾. We also confirmed that the total solution time of the quasi-3-dimensional analysis is much shorter than that of the conventional 3-dimensional analysis. In this study we attempt to develop the estimation of tensile strengths for four types of quasi-isotropic CFRP plates. We also investigate the estimation of the strength for CFRP plates with holes.

2. Quasi-3-Dimensional Model

As already mentioned, in the case of the construction of our new numerical model, our mainpoint is that we deal with the laminated composite as a heterogeneous material. That is, our proposed model is constructed of orthotropic shell elements and isotropic beam elements, which represent the fiber and matrix, respectively.

Figure 1(a) shows a sketch of the three-layered laminated composite. Each layer is usually modeled as a homogeneous material. However, according to our concept, these layers are considered to be heterogeneous, as shown in Fig. 1(b). Namely, we divide each layer into a fiber area and two resin areas. In the fiber area of Fig. 1(b), we assume that the array of

Fig. 2 Top view of quasi-3-dimensional model

fibers is hexagonal. Under this assumption, the fiber fraction V_f is

$$V_f = \frac{\pi}{2\sqrt{3}} \left(\frac{r}{R} \right)^2, \quad (1)$$

where $2R$ is the distance between fibers, and $2r$ is the diameter of a fiber. When R is equal to r in Eq. (1), the fiber volume fraction V_f becomes the maximum value $V_{f_{\max}}$, which is equal to 0.907⁽¹³⁾. Thus we model the fiber area as orthotropic shell elements whose V_f is 0.907 and the resin area to isotropic beam elements whose V_f is 0. In this case the thickness of shell elements in the individual plies h_1 is

$$h_1 = h_0 \times \frac{V_{f_0}}{0.907}, \quad (2)$$

where h_0 is the thickness of the ply, and V_{f_0} is its fiber volume fraction. The material properties of the shell and the beam elements used in our proposed model are obtained by means of Tsai's equation⁽¹⁴⁾ and from a handbook⁽¹⁵⁾, respectively. Figure 1(c) shows our proposed model called the quasi-3-dimensional model. In Fig. 1(c), the distance between plies is equal to the thickness of each ply h_0 because the shell elements are placed on the neutral surface of each ply. Then we connect the shell elements with beam elements along the thickness direction in order to represent interlamina. The material properties of these beam elements correspond to the resin used.

Figure 2 shows a top view of the quasi-3-dimensional model. As shown in Fig. 2, beam elements have various cross sections, which are considered to reflect their positions. Using a quasi-3-dimensional model, we hope that the calculation time will be much shorter

Table 1 Stacking sequence

	Type A	Type B	Type C	Type D
8th layer	0 deg.	90 deg.	45 deg.	45 deg.
7th layer	90 deg.	0 deg.	-45 deg.	-45 deg.
6th layer	45 deg.	45 deg.	0 deg.	90 deg.
5th layer	-45 deg.	-45 deg.	90 deg.	0 deg.
4th layer	-45 deg.	-45 deg.	90 deg.	0 deg.
3rd layer	45 deg.	45 deg.	0 deg.	90 deg.
2nd layer	90 deg.	0 deg.	-45 deg.	-45 deg.
1st layer	0 deg.	90 deg.	45 deg.	45 deg.

Fig. 3 Mesh division of virgin laminate

Fig. 4 Analytical result for type A

than that of the 3-dimensional analysis because the quasi-3-dimensional model hardly needs to consider the aspect ratio.

3. Tensile Damage Analysis for Virgin Laminates

3.1 Analysis Procedure

The CFRP plates analyzed in this study are set up to form an 8-layer quasi-isotropic plate. The stacking sequences are 4 kinds as shown in Table 1. The overall length of the model is 100 mm, width is 15 mm and the thickness is 1 mm. Furthermore, we perform an experiment in order to investigate the propriety of our quasi-3-dimensional analyses. The specimens tested were fabricated from unidirectional prepreps which were supplied by Toho-Rayon and consisted of

HTA-7 carbon fiber embedded in common epoxy resin #114. The fiber volume fraction V_f was constant 57%.

Figure 3 shows the quasi-3-dimensional model of the virgin laminated composite used in this study. Here X-, Y- and Z-axes show the loading, width and thickness directions, respectively. The load condition is that outermost layers (1st and 8th layers) are tensioned by a load incremental method. We calculate the components of normal and shear stresses separately for every load increment. Figure 4 shows the analytical results for A-type laminated composite. Two kinds of failure appear in the quasi-3-dimensional model with increase of the tensile load. At first, when a transverse stress value σ_T on 90 deg layers reaches the transverse strength F_T with $V_f=90.7\%$ (point A in Fig. 4)⁽¹³⁾, a failure called 'transverse crack' appears. This point is usually called the 'knee-point'. We define the tensile stress at point A as the "1st analytical failure stress". We consider that the redistribution of the stress field in the laminated composite is caused by the transverse crack. Accordingly, after the tensile stress reaches the 1st failure stress, we continue the analysis by reducing the transverse elastic modulus on 90 deg layers, E_T^{90} to the resin elastic modulus E_m . As the tensile load increases further, beam elements represented interlamina begin to yield (point B in Fig. 4). Here, we apply the Von Mises law to the yield condition of beam elements⁽¹⁶⁾. When the first beam element yields, we define that tensile stress as the "2nd analytical failure stress". Moreover, we investigate the yielding progress of beam elements after the 2nd failure stress. Furthermore, we perform a tensile experiment in order to evaluate the propriety of the above analytical method. For the experiment, we use an INSTRON testing machine controlled by a computer, and we carry out acoustic emission measurement with a 40 dB threshold at the same time. For the AE results, we measure cumulative hit counts of low amplitude (40-60 dB), middle amplitude (60-80 dB) and high amplitude (80-100 dB).

3.2 Results and Discussion

Figure 5 shows both analytical and experimental results. In Fig. 5, reasonable agreement is evidenced between both the results for stress-strain relationships, and the 1st analytical failure stresses are in accord with experimental positions of the knee point for all 4 types. They are also in accord with the start of the low-amplitude events in the AE measurements. These events indicate the occurrences of micro cracks in the resin region⁽¹⁷⁾. We conclude that the transverse crack appears at the 1st analytical failure stress level, because of the agreement between the start of low-

Fig. 5 Comparison of analytical and experimental results for virgin laminate

Fig. 6 Yield progress for virgin laminate type A

amplitude events and the 1st analytical failure stress level. For types A - D, we confirm that the 1st analytical failure stress values are almost constant at 131.0, 120.0, 128.1 and 128.5 MPa, respectively. Hence the occurrences of the middle-amplitude events appear at the 2nd analytical failure stress for all 4 types. These events indicate interlaminar delamination⁽¹⁷⁾. Accordingly, we confirm that the yielding of beam elements corresponds to interlaminar delamination because of the agreement between the events and the 2nd analytical failure stress levels. Table 2 shows stress values of the first yielded beam elements and the positions of their beam elements under the 2nd analytical failure stress level. Judging from Table 2, the yielding of beam elements is controlled by shear stress and the position of yielding is the interlamina connected with 90 deg layers for all types. Figure 6 shows a series of features of beam elements in a yielding progress in four stages for type A. Judging from Fig. 6, the yielding starts at the edge of 90/45 interlamina, then yielding spreads in the same interlamina in proportion to the tensile stress increases. Moreover, the evaluation of in-plane stress components, σ_L , σ_T and τ_{LT} in every layer as carried out for this tensile simulation. Here σ_L , σ_T and τ_{LT} shows the fiber direction stress, transverse stress and shear stress, respectively. Figures 7 (a), (b) and (c) show the above stress components plotted against the tensile stress for type A. For Fig. 7 (a), σ_L on the 0 deg layer (σ_L^0) is much larger than σ_L on the

45 deg and -45 deg layers (σ_L^{45} and σ_L^{-45}), whereas σ_L on the 90 deg layer (σ_L^{90}) always has negative values. For Fig. 7 (b), σ_T^{90} drops suddenly at the 1st analytical failure stress. Similarly, σ_T^{45} and σ_T^{-45} drop suddenly with the occurrence of transverse cracks on 45 deg and -45 deg layers, respectively. Also, σ_T^0 is always zero. On the other hand, σ_L^{45} and σ_T^{45} are the same as σ_L^{-45} and σ_T^{-45} , respectively. Figure 7 (c) shows that τ_{LT}^0 and τ_{LT}^{90} are always equal to zero, and that the absolute value of τ_{LT}^{45} is always equal to that of τ_{LT}^{-45} . By modeling of the fiber and matrix separately using the quasi-3-dimensional model, we confirm that different fractural phenomena such as the transverse crack and interlaminar delamination can be simulated at the same time. On the other hand, the separation of the different fractural phenomena may be impossible using the conventional solid elements because their use implies that the laminated composite is assumed to be homogeneous. Therefore we firmly believe that the application of the quasi-3-dimensional model to the tensile damage analyses is effective.

4. Tensile Damage Analysis for Laminate with Hole

As previously mentioned, we could simulate the transverse crack and interlaminar delamination for

Table 2 Stress values of yielded beam elements at 2nd analytical failure stress

TYPE	Position of the 1st yielded beam	σ_z [MPa]	τ_{xz} [MPa]
A	45/90 interlamina	-1.16	14.12
B	90/0 interlamina	-1.14	14.13
C	0/90 interlamina	-5.40	13.80
D	-45/90 interlamina	-3.21	14.02

Fig. 8 Mesh division of laminate with hole

Fig. 7 Stress components on each layer plotted against tensile load for virgin type A

virgin laminates using the quasi-3-dimensional model. In this section, we attempt to apply this model to a laminate with a hole whose strength measurement is more difficult than that of the virgin laminate, because the laminate with a hole has variable stress values in

each layer. The objects for analysis are the same laminated composites as shown in Table 1 with a $\phi=6$ mm center hole. The quasi-3-dimensional model of the laminate with a hole is shown in Fig. 8. Figure 9 shows both the analytical and experimental results.

Fig. 9 Comparison of analytical and experimental results for laminate with hole

Fig. 10 Yield progress for type A with hole

For laminates with holes, reasonable agreement is evidenced between both the results for the stress-strain relationship. Moreover we confirm that the 1st and 2nd analytical fractural stress levels are interrelated with the experimental occurrences of knee point and middle-amplitude AE events, respectively. Figure 10 shows a series of beam elements in a yielding progress in three stages for type A. Judging from Fig. 10, we confirm that beam element yielding starts at an edge of the center hole along the direction transverse to the loading in 90/45 interlamina. Then, as the tensile load increased further, yielding propagates along the loading direction. At the 2nd analytical fractural stress level, the start of beam element yielding is in 90/45, 90/0, 0/90 and $-45/90$ interlaminas for types A - D, respectively. These interlaminar positions are the same as those for virgin laminates. Judging from the above results, we confirm that the quasi-3-dimensional model is effective for the estimation of damage progressions for laminates with holes with a stress concentration.

5. Conclusion

Using the quasi-3-dimensional model we performed tensile analyses, and both the analytical and experimental results were compared. We obtained the following results.

(1) We could simulate the stress-strain relationship to the 2nd analytical fractural stress level for CFRP virgin laminates. The transverse crack, interlaminar delamination and interlaminar damage propagation could also be estimated.

(2) For the CFRP laminates with holes with a stress concentration, the same characteristics can be simulated.

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