Development and Evaluation of Crack Band Model Implemented Progressive Failure Analysis Method for Notched Composite Laminate

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1. Introduction

A crack band model implemented progressive failure analysis (PFA) method was developed. Some energy-based PFA using crack band model were recommended to avoid mesh dependence of analysis. Lapczyk et al. [1] suggested a constitutive model using damage variables obtained from equivalent displacement. The study shows the mesh independent PFA results. Riccio et al. [2] developed crack band model implemented PFA and applied the method to conduct FEA for the stiffened composite panel. In this study, a crack band model implemented PFA was developed and evaluated by comparing with experimental results according to digital image correlation (DIC) method.

2. Progressive Failure Analysis

Progressive failure analysis is performed reducing the stiffness of composite laminate according to damage initiation criterion and evolution law. Some material property degradation models have been proposed; instantaneous unloading, gradual unloading, or constant stress at failure material point. The gradual degradation model was used in this study. The material behavior shows a linear elastic behavior until the damage initiation, and the damage initiation induces the softening behavior. As a composite material is being damaged, the stiffness matrix of material is replaced by damaged stiffness matrix. Eq. (1) shows damaged stiffness matrix, all the 'C' values include damage variable, d, according to its directions.

$$[C_d] = \begin{bmatrix} C_{11} & C_{12} & C_{13} & 0 & 0 & 0 \\ C_{21} & C_{22} & C_{23} & 0 & 0 & 0 \\ C_{31} & C_{32} & C_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & C_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & C_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & C_{66} \end{bmatrix} \quad (1)$$

The damage variables range from 0 to 1. 0 and 1 means undamaged status and complete damage status, respectively. As the failure of material occurred, the damage variables is being closed to 1. Performing progressive failure analysis, failure criteria are checked to detect failure in material in terms of effective stress that reflects the damaged stress status at each analysis increment. The effective stress is as fallows;

$$\{\tilde{\sigma}\} = \begin{bmatrix} \frac{1}{(1-d_f)} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{(1-d_f)} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{(1-d_m)} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{(1-d_s)} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{(1-d_s)} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{(1-d_s)} \end{bmatrix} \{\sigma\} \quad (2)$$

using the effective stress, failure criterion parameter, "f_I" was calculated. The "I" can be replaced by ft, fc, mt, and mc meaning fiber tension, fiber compression, matrix tension, matrix compression failure mode, respectively. Considering the various failure modes, Hashin failure criteria was used in this study. From the FEM calculation, equivalent displacement, and stress can be obtained using strain values at each failure mode. Using the equivalent displacement, and stress, equivalent displacement, and stress at damage initiation can be obtained as follows;

Equivalent displacement at initial state :

$$\delta_{I,eq}^0 = \frac{1}{\sqrt{f_I}} \delta_{I,eq}$$

Equivalent stress at initial state :

$$\sigma_{I,eq}^0 = \frac{1}{\sqrt{f_I}} \sigma_{I,eq} \quad (4)$$

according to the fracture energy relation, following equation was derived;

Equivalent displacement at final failure state :

$$\delta_{I,eq}^f = \frac{2G_I^c}{\sigma_{I,eq}^0} \quad (5)$$

bi-linear damage behavior can be shown in Fig. 1 according to stress-displacement relation. Using the parameters obtained above, the damage variables can be calculated as follows at each failure mode;

$$d_i = \frac{\delta_{I,eq}^f(\delta_{I,eq} - \delta_{I,eq}^0)}{\delta_{I,eq}(\delta_{I,eq}^f - \delta_{I,eq}^0)} \quad (6)$$

PFA is performed using the damage variables to reducing the stiffness matrix according to failure state of material.

3. Test procedures

Open-hole composite specimens were manufactured. One or two holes were introduced to tensile and compressive specimens. [0/+45/-45/90]s and [0/+45/0/-45]s stacking sequences were chosen for the composite specimens as type-1 and type-2. Tests were performed using MTS 810 hydraulic testing machine. Displacement rate was controlled as 1 and 2 mm/min for tensile and compressive test, respectively.

4. Results

4.1 Tensile test results comparison

Fig. 1 shows the results of tensile test and PFA for type-1 specimen. The PFA results indicate the stiffness of the composite material well. The maximum load difference between the experiment and PFA results was only 2.3% and 0.59% for type-1 and type-2 specimens, respectively.

4.2 PFA evaluation with digital image correlation

Figs. 2 and 3 show the strain comparison between PFA result, and DIC result. Near the hole, the only 0.5% difference was observed. Fig. 4 shows the maximum longitudinal strain values obtained from the strain gauge, PFA, and DIC at the same point with type-1 specimens. The point was selected based on the position of the strain gauge. The maximum error was 7.03% in all specimen cases. Only slight differences were observed among the results.

5. Conclusions

In this study, PFA model was developed using a crack band model. Verify the effectiveness of the suggested PFA model, the tensile test results of the open-hole composite laminate were compared with the analysis results. The analysis results were in good agreement with the experimental ones, when the load-displacement behavior and strain distribution of PFA results were compared with the experimental ones. The suggested model is expected to benefit in the designing process of complex composite structures.

References

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[2] A. Riccio, C. D. Costanzo, P. D. Gennaro, A. Sellitto, and A. Raimondo, Intra-laminar progressive failure analysis of composite laminates with a large notch damage. *Engineering Failure Analysis*, 73 (2017) 97-112.

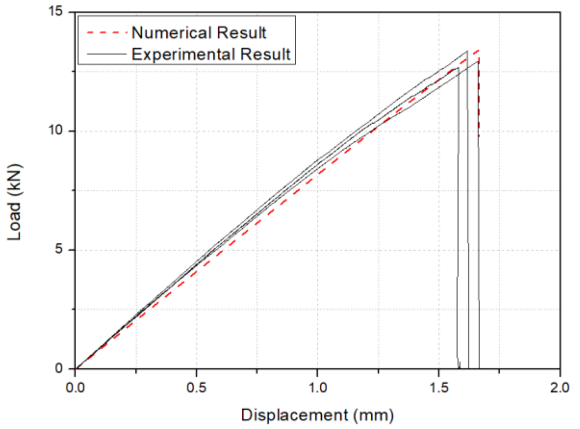

Fig.1 Load-displacement curve comparison

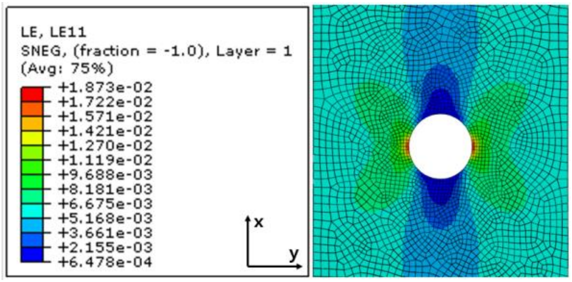

Fig.2 Longitudinal strain (ε_{xx}) contour obtained from PFA.

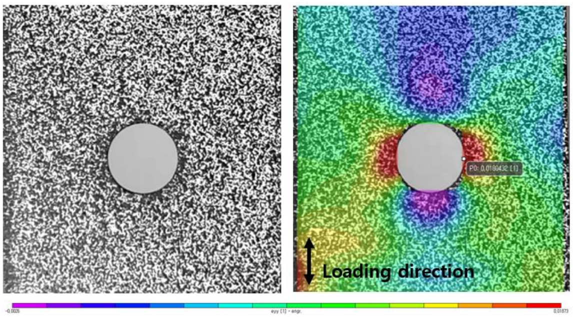

Fig.3 Reference image and longitudinal strain (ε_{xx}) contour obtained from DIC.

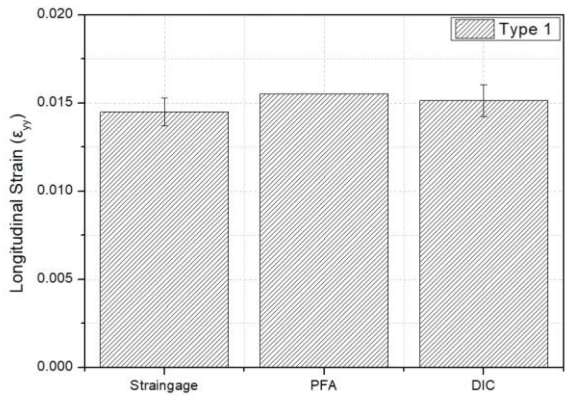

Fig.4 Longitudinal strain (ε_{xx}) value comparison for type-1 stacking sequence.