PROGRESSIVE DAMAGE ANALYSIS OF OPEN-HOLE COMPOSITE PLATE UNDER COMPRESSION

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1 Introduction

Open-hole composite plate under compressive loading is one of the most studied and tested cases on the fiber reinforced composite laminate. ASTM D6484/D6484M–09 was established to standardize the testing method for obtaining the open hole compressive strength of polymer matrix composite laminates. This open-hole compressive test is sometimes used as a proxy to the compression after impact case which is often used as one of the design criteria for fiber reinforced composite laminate. Prediction of the open-hole compression strength, however, remains a challenge to researchers and designers due to the complexity and variations of the damage modes. In this study, progressive damage simulations using material property degradation method and cohesive elements are used to predict the open-hole compression strength and its damage mode. Parametric study and damage scenario analysis are also performed to study their influence to the strength as well as the damage modes.

2 Problem description

This study is based on experiments by Nettles [1] who performed open-hole compression tests on IM7/977-3 asymmetric $[12.5,-12.5]_8$ by using the four point bend test method proposed by Nettles and Jackson [2] on sandwich beams made of the composite laminate. The tests shows that there are variations in the failure modes, i.e. perpendicular to load micro-buckling (Fig. 1.c) and in plane shear along the fiber direction (Figs. 1.a-1.b). The average open-hole compression strength is 462 MPa.

3 Model description

Finite element models were made and analyzed using Abaqus/Standard. Shell elements were used for the composite lamina and user subroutine UMAT were implemented to model material property (stiffness) degradation based on the Tsai-Wu [3] failure criterion for matrix dominated failure and maximum stress criterion for fiber dominated failure. The analysis includes thermo-mechanical analysis to account for residual stresses due to the curing process, as well as the mechanical load during the compression test. The open hole plate models were 50.8 mm × 50.8 mm square with 6.35 mm diameter hole in the center. Each lamina is 0.127 mm thick.

In addition to the shell models, three-dimensional models using Abaqus continuum shell element and cohesive elements [4] were also used in order to study the influence of delamination between plies. In these 3-D models, the composite laminates were modeled using continuum shell elements while the interfaces were modeled using cohesive elements. Quadratic stress failure criterion [4] was used for the cohesive elements and the elements are assumed to follow exponential energetic softening traction separation law with the Benzeggagh-Kenane [5] mixed mode upon failure. Table 1 and table 2 show the properties used to model the IM7/977-3 lamina and the cohesive elements, respectively. Parametric studies were performed by varying the residual stiffness parameter, the out of plane boundary condition, and initial delamination.

3.1 Stiffness reduction parameters

Material property degradation method (MPDM) typically models damage by reducing the engineering stiffness parameters (the Young's modulus E and the shear modulus G) by a certain ratio. In the case of fiber reinforced composite lamina, the following method can be used to model material failures:

- Transverse stiffness E_2, and shear stiffness G_{12} are reduced by a certain ratio to model matrix dominated failure

- All of the stiffnesses are reduced by a certain ratio when fiber dominated failure occurs.

The residual stiffness in the tensile case can usually be assumed to be close to zero because tensile failure results in the opening of cracks. On the other hand, the residual stiffness for compressive failure cannot be assumed to be zero or close to zero because the there is no crack opening in this failure mode and the failed area can still transfer compressive loads. Thus the residual stiffness ratio has to be assumed and the choice is often arbitrary or empirical at best. To study its influence, two residual fiber direction stiffness (E_1) ratio for fiber dominated compressive failure were used in the analysis, i.e. 14% (following Camanho and Matthews [6]) and 50%, while residual stiffness ratio for other types of failure is assumed to be 0.1%.

3.2 Out of plane boundary condition

Compression tests are usually complicated by out of plane displacement (buckling). Although the amount of this out of plane displacement can be small and may not be able to be noticeable by a naked eye, it is expected to influence the overall stress distribution and damage mode. Thus, two kinds of analysis were performed in this study, i.e. analysis with and without buckling trigger, which is in the form of a very small out of plane force on the circular hole circumference. Both models used shell elements to represent the composite plate.

3.3 Initial delamination

Delamination could occur around the hole due to manufacturing process. This initial delamination could change the damage mode and residual strength. In this study, the initial delamination is assumed to occur on all of the interlaminar interfaces and they are circular in shape. The diameter the delamination is 12.7 mm. 3-D models with Abaqus continuum shell elements and cohesive elements are used in this case to represent the composite lamina and the interfaces, respectively.

4 Results and discussions

Table 3 shows the overall residual strength predicted by the finite element models. The influence of each modeling parameters are discussed in sections 4.1-4.3.

4.1 Stiffness reduction parameters

As expected, stiffness reduction ratio plays an important role in the simulation. Surprisingly, the analysis with lower residual stiffness does not imply lower overall strength of the composite laminate. The in-plane model with residual stiffness ratio of 14% predicts 596 MPa while the model with residual stiffness ratio 50% predicts 508 MPa for the overall strength of the lamina. This is because the first fiber dominated failure in the former case causes large stress redistribution and delays matrix cracking by shear, which causes the major load drop.

4.2 Out of plane boundary condition

The addition of buckling trigger not only decreases the overall strength but also changes the failure pattern (Figs. 1-2). The model with buckling trigger shows unsymmetric shear failure along the -12.5^o direction while the in-plane model has symmetric shear failure pattern along the ±12.5^o direction. These failure patterns are similar to the some of the test results shown in Fig. 1.a. and 1.b.

4.3 Initial delamination

Introduction of initial delamination to the model significantly reduces the residual strength from above 500 MPa to around 350 MPa. The failure mechanism also changes to micro-buckling in the delaminated area followed by fiber failure. The final failure pattern of this model, which is shown in Fig 3, is similar to the experimental result shown in Fig. 1.c., in which the final failure occur by micro-buckling and fiber failure perpendicular to the loading direction which cuts across the hole.

3 Conclusion

Finite element models in this study have shown that damage modes in open-hole compressive test of fiber reinforced composite lamina are strongly influenced by residual compressive stiffness upon fiber dominated compressive failure, out of plane boundary condition (buckling), and initial delamination around the hole. The finite element models, which employ MPDM and cohesive elements to model in-plane failure and delamination, are able to mimic the damage pattern in actual tests, i.e perpendicular to load micro-buckling or in plane shear along the fiber direction. The value of the predicted open-hole compressive strength, however, depends on the three parameters, i.e stiffness reduction ratio upon failure, out of plane boundary condition, and initial delamination, chosen for each model. The difficulty in predicting these parameters complicates the task of predicting this open-hole compressive strength.

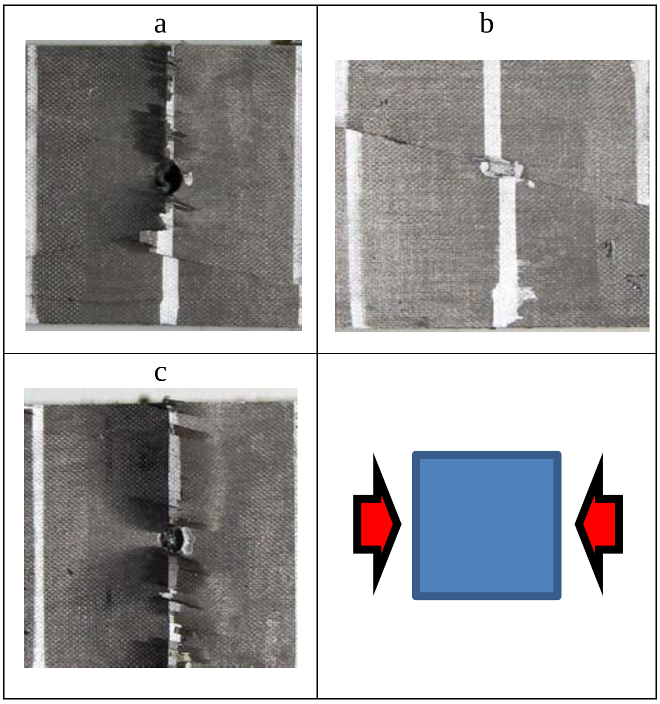

Fig.1 Experimental failure pattern [1]

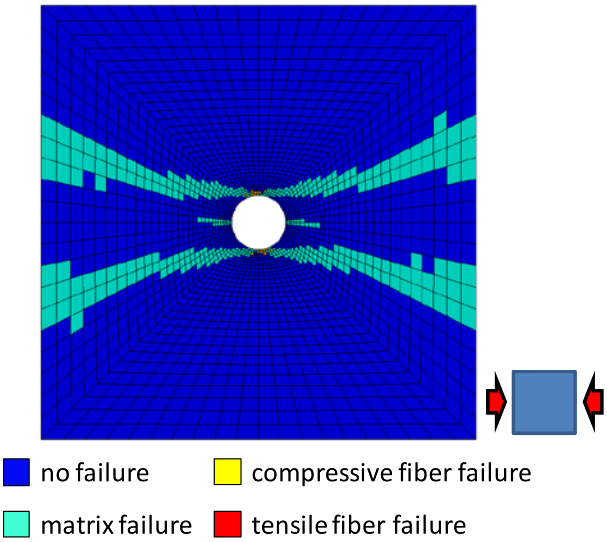

Fig.2 Failure pattern of model without buckling trigger

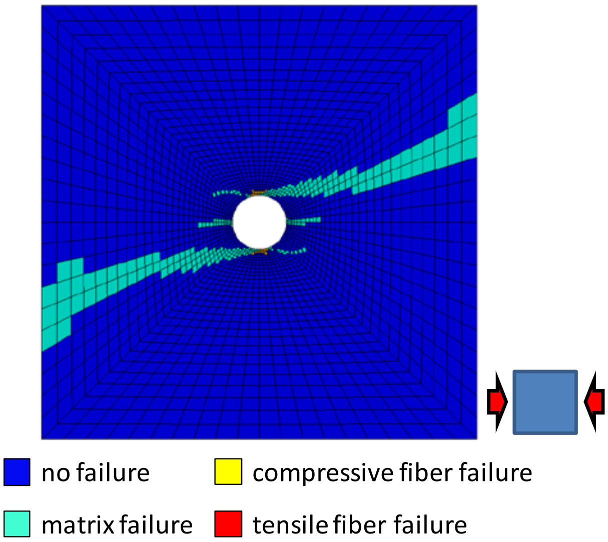

Fig.3 Failure pattern of model with buckling trigger

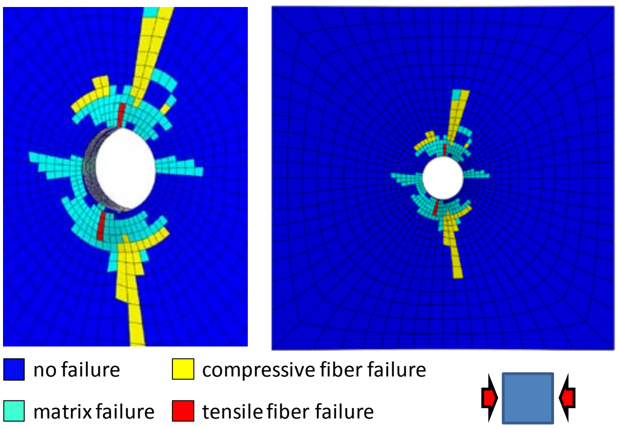

Fig.4 Failure pattern of model with initial delamination

Table 1 Properties of IM7977/3 composite system

Fiber direction stiffness E_1	190 GPa
Transverse stiffness E_2	9.9 GPa
Shear stiffness G_{12}	7.8 GPa
Shear stiffness G_{23}	4 GPa
Poisson's ratio ν_{12}	0.35
Poisson's ratio ν_{23}	0.3
Fiber dir. expansion coeff. α_1	$-0.9 \times 10^{-6}/^{o}C$
Transverse expansion coeff. α_2	$22 \times 10^{-6}/^{o}C$
Fiber direction tensile strength X_t	3250 MPa
Fiber direction compressive strength X_c	1590 MPa
Transverse direction tensile strength Y_t	62 MPa
Transverse direction compressive strength Y_c	200 MPa
Shear strength S	75 MPa

Table 2 Traction-separation properties of cohesive elements

Normal Strength t_n	61 N/mm
Shear Strength $t_s = t_t$	68 N/mm
Mode I fracture toughness G_{Ic}	0.075 kJ/m^2
Mode II fracture toughness G_{IIc}	0.547 kJ/m^2
Benzeggagh-Kenane power	1.45

Table 3 Predicted residual strength

	14 % residual stiffness upon fiber failure	50 % residual stiffness upon fiber failure
in plane model	569 MPa	508 MPa
buckling triggered	554 MPa	504 MPa
with circular delamination	351 Mpa	352 Mpa

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