PROBABILITY-BASED ANALYSIS FOR MODELING FAILURE MODE INTERACTION PROGRESSIVE DAMAGE IN LAMINATED COMPOSITE STRUCTURES WITH AN INITIAL DELAMINAION

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1 Introduction

This paper presents a failure initiation and progressive damage growth modeling method, including failure mode interaction, for fiber reinforced composite laminates. The present progressive failure analysis (PFA) is targeted at the development of a numerical model for predicting an initial failure mode and consequent damage growth interacting with other failure mechanisms at multiple length scales in the composite structure. The PFA is also coupled with a stochastic analysis tool to account for material variability and manufacturing inconsistencies, thereby quantifying uncertainty and providing rational predictions for margins of safety. The proposed PFA methodology is applied to an axially-compressed composite panel with an initial delamination for validating its capability of predicting the damage progression due to interactive failure mechanisms in the laminated composite.

2 Progressive failure analysis models

2.1 Discrete cohesive zone method for modeling interlaminar behavior

The discrete cohesive zone model (DCZM) in [1] is employed here to analyze delamination growth in a laminated composite structure. The DCZM element models the decohesion process through point-wise discrete traction laws associated with each degree of freedom. The traction separation law is a modular component of DCZM, so that users can have flexibility in controlling different aspects of the cohesive model for their own purposes [2]. Thus, the DCZM element is capable of simulating separation between surfaces in a finite element (FE) framework. Incorporation of these DCZM elements into FE models also enriches the PFA function to simultaneously track various failure modes (material degradation, local and/or global buckling, and etc.) to capture any potential interaction between such failure mechanisms.

2.2 Modeling of progressive microdamage at lamina level using Schapery theory

Fiber reinforced laminates are affected by the growth of matrix microcracking, distributed throughout the quasi-brittle matrix phase of a composite at micro-length scales [3]. Progressive evolution of the microdamage is the primary cause of gradual reduction in the stiffness of the resin until its effects are superseded by larger damage mechanisms, such as transverse cracking. Schapery [4] developed a thermodynamics-based work potential model for the microdamage mechanisms to predict the degradation of matrix properties at lamina scale. Basu et al. extended Schapery theory (ST) to consider the state of the lamina beyond the first failure in the fiber direction to achieve the successful progressive failure analysis schemes for compressive loading conditions [5]. In this presentation, extended ST (EST) combined with DCZM is implemented into the commercial FE software package, ABAQUS, through user subroutines to model and predict delamination initiation and growth dominated by local stiffness degradation due to matrix microcracking interacting with local buckling deformations.

2.3 Probabilistic analysis for uncertainty quantification using NESSUS software

Numerous modeling parameters are involved in the PFA methodology at multiple length scales with various failure mechanisms. Thus, the present PFA implements a probabilistic approach to account for uncertainty in those modeling parameters such as material variability, manufacturing inconsistencies, and so on. The role of probabilistic modeling and analysis is to quantify the variations and uncertainties in predicted damage of composites due to load, material, and manufacturing variations. The probabilistic modeling tool enables comparison of model predictions against experimental results for detailed model validation purposes and for assessing margins of safety. The probabilistic tool also allows designers to account for variations during the design process by providing a rational approach to determine margins of safety and identify important parameters affecting the reliability of the design. The PFA proposed in this paper utilizes NESSUS software [6] for the probabilistic finite element analysis (FEA).

3 PFA applications - Composite laminate panel with an initial delamination

In this section, the numerical framework combining DCZM and EST is demonstrated against experimental data available in literature to show its capability of predicting interfacial behavior as well as material degradation in a fiber reinforced composite laminate. Reeder et al. [8] experimentally studied progressive delamination growth in composite plates subjected to axial compression loading. They examined delamination growth patterns of the composite panels with three different curvatures, while the panel sizes remain the same. In this paper, the flat panel configuration is considered to verify the PFA methodology. Fig. 1 illustrates the configuration of the flat composite panel with the loading and boundary conditions. The plate is 9.0 in. long and 4.5 in. wide and has the circular delamination at the center with the radius of 1.25 in. The plate is axially compressed from the top while the bottom is fixed. Side edges of the plate are simply supported. The panel is made of an AS4/3501-6 graphite/epoxy composite material system with the lamination stacking sequence of $[(\mp 45/90/0)_2/\mp 60/\mp 15]_S$. In the experiment, the initial delamination was introduced by inserting a circular Teflon sheet at the center between the 4th and 5th layers (between 0° and -45°, denoted as Interface 1) and between the 5th and 6th plies (between -45° and 45°, denoted as Interface 2). The material properties of the AS4/3501-6 are summarized in Table 1.

The FE model of the composite panel is composed of four parts; an upper sublaminate, a zero thickness DCZM layer, a circular Teflon sheet, and a lower sublaminate, as shown in Fig. 2. The upper sublaminate models the first four or five layers prior to the delamination layer and the lower sublaminate represents the rest of the plies. Standard 4-node shell elements with reduced integration are used to mesh two laminates. Finer meshes are created around the circular boundary of the initial delamination. The Teflon layer is also modeled with shell elements.

Property	Value
E_{11} (msi)	18.25
E_{22} (msi)	1.35
G_{12} (msi)	0.74
ν_{12}	0.329
Ply thickness (in.)	0.005315

Table 1: Properties for AS4/3501-6 graphite/epoxy material

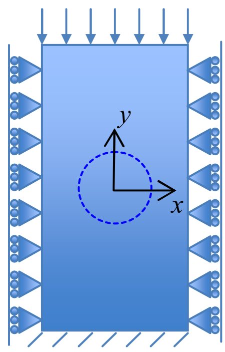


Fig. 1: Composite plate with an initial circular delamination subjected to axial compression [8]

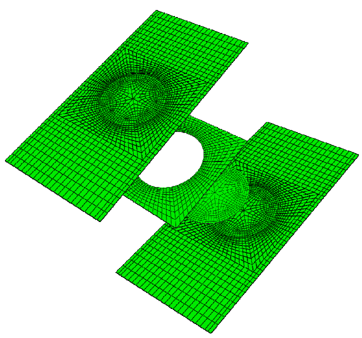


Fig. 2: Finite element model of the composite panel with the initial delamination

3.1 Probabilistic analysis

Linear buckling analysis coupled with the probabilistic analysis is first performed to identify key modeling parameters affecting the structural performance of the composite panels. The DCZM elements play no role in this determination since bifurcation buckling is an eigenvalue problem. Although the progressive damage growth is the main concern of this paper, this probabilistic buckling analysis is carried out to provide preliminary results for the uncertainty quantification associated with various modeling parameters. Additionally, the buckling modes obtained here will be used to perturb the initial geometry of the composite panels for the PFA models to account for initial geometric imperfections. Table 2 lists the variability of modeling parameters that can be characterized with mean values, standard deviation values, and distribution types. NESSUS software coupled with ABAQUS is utilized to perform the probabilistic analysis.

Fig. 3 shows the probability of buckling load for Interface 1 and Interface 2 FE models when uncertainty in the modeling parameters is accounted for. The response of the composite panels is obtained over a wide range of these parameters as can be seen in Fig. 3, indicating that the variabilities greatly affect the structural performance of the plates. Fig. 4 shows the importance level of each modeling parameter. The probabilistic importance factor, α_i, is defined as a measure of the contribution of each parameter to the probability [7]. As can be expected, the fiber direction stiffness is the most important factor to define the buckling response. It is interesting to note that the size of the initial delamination and its location along x-direction are as important as the transverse and shear moduli while the vertical location of the circular delamination has little influence on the buckling load.

3.2 Progressive failure analysis

DCZM and EST are implemented into the commercial FEA software package, ABAQUS, through user subroutines to simulate progressive damage growth in the composite panels under axial compression. The DCZM elements are employed to predict the delamination onset and its growth in the region of interest as shown in Fig. 2. A triangular traction-separation cohesive law is imposed on the DCZM elements to model the interface behavior. Table 3 lists the fracture toughness and cohesive strength values used for the traction-separation law. The FE model is compressed using the displacement-controlled loading until the axial displacement of the top edge reaches 0.04 in.

Parameter	Mean	STD	Type
E_{11} (msi)	18.25	1.83	Lognormal
E_{22} (msi)	1.35	0.3	Lognormal
G_{12} (msi)	0.74	0.3	Lognormal
radius (in)	1.25	0.1	Normal
x_{center} (in)	0.0	0.05	Normal
y_{center} (in)	0.0	0.05	Normal

Table 2: Mean value, standard deviation (STD) value, and distribution type of the variable parameters

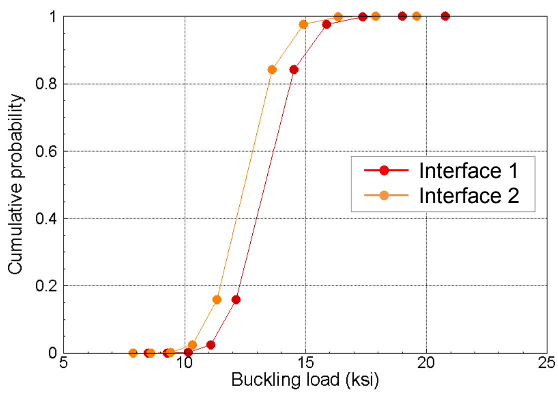


Fig. 3: Cumulative probability distribution for buckling load of Interface 1 and Interface 2 models

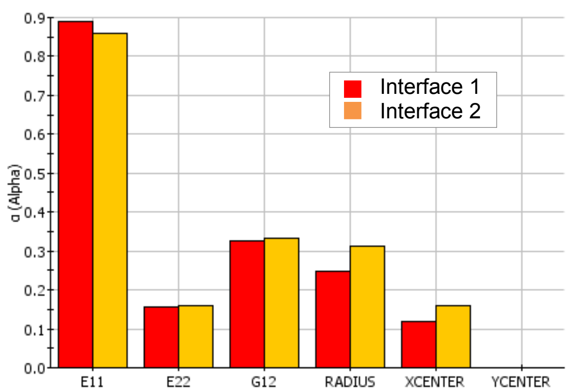


Fig. 4: Importance levels of modeling parameters on buckling load

Although Reeder et al. also performed numerical studies, material degradation was not considered in their work. In this paper, EST is employed to account for the transverse and shear stiffnesses degradation affected by the matrix micocracking accumulation during compression. ST describes the degradation functions for E_{22} and G_{12} as functions of the internal state variables.

$$E_{22}(s) = E_{22}^{0}(e_0 + e_1 \cdot s + e_2 \cdot s^2 + e_3 \cdot s^3 + e_4 \cdot s^4) \quad (1)$$

$$G_{12}(s) = G_{12}^{0}(g_0 + g_1 \cdot s + g_2 \cdot s^2 + g_3 \cdot s^3 + g_4 \cdot s^4) \quad (2)$$

where E_{22}^{0} and G_{22}^{0} are the virgin properties as listed in Table 1, and the coefficients, e_i and g_i, are listed in Table 4 [9]. ST assumes that the structural changes, which result from microdamage, are dependent on the internal state variable, s, only. Experimentally, it has been determined that s behaves as ε^3 [9]. The fiber direction modulus, E_{11}, is assumed to be independent of such microdamage as observed from lamina level coupon tests in [3].

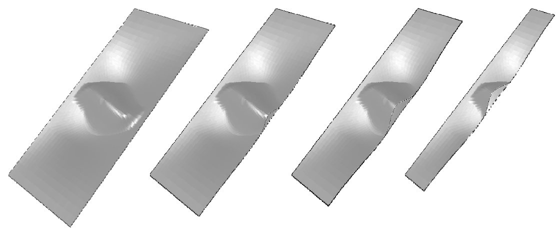
FE results show similar progressive failure behavior for the Interface 1 and Interface 2 models, as similarly observed in [8], and thus the results from the Interface 2 model are reported in this paper. Fig. 5 shows the section views of the composite plate at different locations along the width direction. The upper sublaminate first deforms in the bucked shape at the initial defect area and delamination evolution follows. Fig. 6 shows the delamination pattern, depicted using the Von Mises stress distribution. The delamination pattern predicted by the present PFA reasonably agrees well with the experimental observations reported by Reeder et al. as shown in Fig. 7. ST is capable of predicting material degradation due to microdamage in the matrix constituent. Fig. 8 shows the distribution of the degraded shear stiffness at the upper and lower interface. Since the upper sublaminate has weaker compressive strength than the lower one because of the fewer number of plies, the upper sublaminate experiences comparably severe deformation during the compression. As a result, the shear stiffness degradation progresses significantly near the circular delamination region, leading to the large mismatch of the shear stiffness values between the upper and lower sublaminates as shown in Fig. 8. In the lower sublaminate, the degradation of the shear stiffness is not as obvious as that of the upper sublaminate. It is interesting to note that the region of the most degraded shear stiffness values coincides with the delamination front as shown in Fig. 6.

Property	Value
G_{1C} (lb/in)	0.46863
G_{2C} (lb/in)	3.171825
G_{3C} (lb/in)	3.171825
σ_{1C} (psi)	20
σ_{2C} (psi)	120
σ_{3C} (psi)	120

Table 3: Modeling input for the fracture toughness and cohesive strength values of the AS4/3501-6 graphite/epoxy material.

E_{22}	Tension	Compression	G_{12}	Values
e_0	1.00000	1.00000	g_0	1.00000
e_1	-0.05458	-0.03640	g_1	-0.06827
e_2	0.08088	-0.00997	g_2	-0.04285
e_3	-0.02359	-0.00171	g_3	0.00966
e_4	0.00191	0.00033	g_4	-0.00074

Table 4 Microdamage function coefficients



(a) (b) (c) (d)

Fig. 5: Section views for typical delamination pattern (a) full view (b) cut at 3/4 (c) cut at 1/2 (d) cut at 1/4 along the width direction

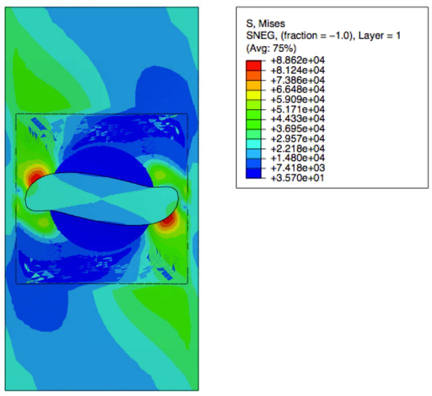


Fig. 6: Delamination pattern with Von Mises stress distribution of Interface 2 model

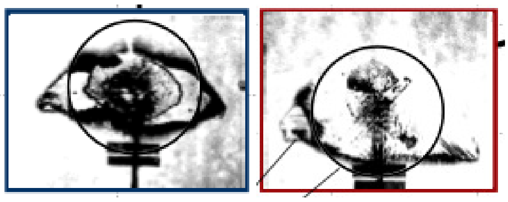
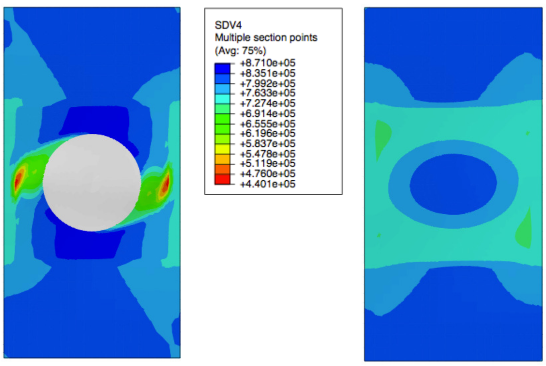


Fig. 7: X-ray photographs of the final delamination pattern (images cropped from Fig. 10 of [8])



(a) (b)

Fig. 8: Distribution of degraded shear modulus (a) at 5th layer and (b) at 6th layer of Interface 2 FE model

4. Concluding remarks

A progressive failure analysis methodology with failure mode interaction is demonstrated for the first time by implementing a matrix microcracking damage model based on Schapery theory coupled with the discrete cohesive zone model for interfacial failure. The methodology is applied for progressive failure analysis for typical laminated composite panels that have initial defects. The method presented here shows that it is capable of predicting the interaction between out-of-plane failure and in-plane failure with material degradation accounted for. Probabilistic analysis is also performed to identify the important modeling parameters for the overall structural performance of the composite plate with the initial delamination. Probabilistic approach incorporated with the current PFA is expected to provide reliability-based failure indicators when material variability and manufacturing inconsistencies are considered.

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