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Statistical methodology for assessing manufacturing quality related to transverse cracking in cross ply laminates

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ABSTRACT

We present a statistical analysis based methodology for making assessment of the manufacturing quality of cross ply composite laminates as it relates to its effect on transverse cracking evolution. Assuming a two-parameter Weibull distribution of tensile strength of the transverse plies to represent randomly distributed manufacturing defects, multiple crack formation in the plies is simulated in the non-interactive and interactive regimes of cracking using the local stress fields calculated by a variational analysis. The statistical methodology is demonstrated on crack density evolution in cross ply laminates manufactured by four different processing routes and loaded in monotonic tension in the axial direction. The differences in the crack density evolution, supposedly due to different defect population induced by the four manufacturing conditions, could be described by the proposed statistical simulation method.

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1. Introduction

In recent years, there has been a steady growth of the applications of fiber-reinforced composite materials not only for the aerospace industry, but also for some emerging fields such as the automotive, marine, and renewable energy industries. The different applications sometimes mean quite different design methodologies, manufacturing processes, service environment, maintenance, and recycle strategies. Some applications of composite materials outside of the aerospace industry are often more sensitive to the manufacturing cost. The tradeoff between the performance and cost usually yields low-cost composite structures with more severe state of manufacturing-induced defects compared to high quality composites used for aerospace structures. A reliable and optimal design for low-cost composite structures needs to pay more attention to the manufacturing defects and their effects on performance.

Manufacturing-induced defects exist in most fiber-reinforced polymeric composites though their severity varies with the manufacturing process. The most common manufacturing defects in composite laminates are: (1) matrix defects, e.g. voids, porosity, resin rich area, and uncured matrix; (2) defects associated with fiber, e.g. fiber misalignment, unimpregnated fibers, and broken fibers, and (3) interface defects, e.g. fiber/matrix debonding, and delamination between layers. A classical approach to treating manufacturing defects correlates the severity of defects to the macroscopic properties such as stiffness and strength, and acceptance criteria are then set based on the correlations. For example, quantitative relationships between the void content and certain mechanical properties of composite laminates such as the interlaminar shear strength, transverse tensile strength and fatigue life, have been developed in the literature and threshold values of the void content have been proposed as acceptance criteria [1,2]. For composite structures manufactured by low-cost processes, the defects induced have often large variation in size, shape and location. Several recent studies have indicated that the void content by itself may not suffice to describe the effects on stiffness [3], strain energy release rate [4], fatigue life [5], and delamination buckling growth [6], for instance. Thus, specific information concerning the defect size, shape and location must be accounted for, explicitly or implicitly, into a performance assessment strategy for cost reduction. Such a strategy was proposed as an outcome of a new field coined as defect damage mechanics by Talreja [7]. The work presented here is along the lines of the proposed strategy.

We take the problem of the transverse cracking evolution in cross ply laminates under axial tension as an example to illustrate the effect of manufacturing defects. Composite laminate plates are produced under different manufacturing conditions to

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intentionally introduce defects, and then investigate the consequence on the cracking evolution. A statistical model is developed to describe the crack density increase with axial stress. The cracking evolution occurs in two phases, the first phase where the stress fields perturbed by cracks do not interact, followed by the interactive regime. The statistical model treats these two phases separately and provides a basis for assessment of the manufacturing quality.

2. Materials and testing

2.1. Materials

Composite laminate plates were manufactured in the cross ply configuration [0/90]s using the autoclave molding process. The material was unidirectional carbon/epoxy prepreg (HexPly M10/38%/UD300/CHS). The curing process consisted of a standard, supplier recommended cure cycle; heatup rate of 3 °C/min, followed by a 60 min hold at 120 °C at 3 bars and −0.95 bar vacuum. The purpose of applying pressure in addition to the atmosphere pressure is to consolidate the layup and remove air and excessive resin. Vacuum is applied to additionally draw out air, which otherwise can remain entrapped in the laminate.

For the purpose of the study conducted here, the manufacturing process was intentionally varied from the standard one to simulate the conditions that could be present in actual manufacturing, in particular where the cost must be reduced. Thus, the pressure and/or vacuum may not be applied sufficiently in such cases. For large structures, such as wind turbine blades, the vacuum may not be fully effective away from the vacuum ports. In the case of manufacturing by resin infusion, the pressure is usually not applied. Assuming the temperature is properly controlled, we study the consequences on transverse cracking of deficiencies in pressure and vacuum during the manufacturing process. These two variables are varied in the three composite plates as follows.

Plate 1: Cured without applying vacuum and pressure (NV_NP).
Plate 2: Cured without vacuum, but with 3 bars of pressure (NV_P).
Plate 3: Cured with vacuum, but no pressure (V_NP).

Finally, Plate 4 was made by following the standard cure cycle, i.e. with vacuum and pressure (V_P).

2.2. Measurement of the cracking evolution under static tension

The thickness of plates, summarized in Table 1, varies due to the different manufacturing processes. The manufactured laminate plates were cut into specimens for tensile testing. The dimensions of all specimens were 210 × 10 mm with the thickness given in Table 1. The axial tensile load was applied along the fiber direction in 0° plies. Under this loading, transverse cracks form in the 90° plies with their planes in the ply thickness direction. After growing through the 90° ply thickness, the cracks are arrested at the 0/90 ply interfaces. With the neighboring 0° plies sharing the load shed by the 90° plies, the laminate does not fail catastrophically, if the 0° plies can sustain the additional load. Instead, multiplication of transverse cracks occurs under increased loading. To track this cracking evolution, the edges of the specimens were polished for microscopy observation. The loading was applied to different increasing levels and subsequent to each loading, the cracks were observed. The maximum strain levels corresponding to each loading level were: 0.35%, 0.5%, 0.65%, 0.8% and 1.05%. The cracks were observed and their positions along the specimen edge were recorded over the gauge length of 70 mm. For first several specimens, both edges were observed to assure that the cracks were indeed continuous through the specimen width.

Table 1
Average thickness for different plates.

	Thickness	St. dev.
Plate 1 (NV_NP)	1.281	0.037
Plate 2 (NV_P)	1.506	0.072
Plate 3 (V_NP)	1.273	0.06
Plate 4 (V_P)	1.204	0.062

Fig. 1 shows an example of the location of the cracks, plotting them as straight lines along the specimen width. The random distribution of crack location (spacing) is presumably due to randomly distributed defects in the 90° plies. Fig. 1(a) illustrates an early part of the cracking evolution where the cracks are relatively far apart and have unequal spacing. This is a consequence of crack formation from defects in the 90° plies which are randomly distributed within the volume of the plies. The later stage of cracking evolution, at higher applied load, is illustrated by Fig. 1(b), where the crack spacing is reduced and is more uniform than in the early stage of evolution. Here the stress fields associated with cracks interact and the crack formation is influenced by defects as well as by the stress variation. Fig. 2 shows two images taken at applied strains of 0.6% and 0.85% illustrating crack formation from a void. Other types of defect induced by manufacturing will presumably also have influence on crack formation.

Crack density, defined as the number of fully developed transverse cracks per unit axial distance, averaged over a specimen gauge length, is usually used to characterize the cracking evolution. Such information is given in Fig. 3 for the four laminate plates described above. As seen in the figure, the crack density at a given applied strain is different depending on the manufacturing condition. Plate 1 which was produced by not applying vacuum and pressure achieves the most cracks, while the standard curing cycle used for plate 4 results in the least cracking.

3. Statistical simulation of cracking evolution

There are basically two approaches that can be taken to analyze evolution of transverse cracking in cross ply laminates [9]. One is by assuming that cracks form when the local stress reaches the material strength, and the other is by assuming that a pre-existing crack (or flaw) of certain size grows unstably when the energy release rate at the crack front reaches the local fracture toughness of the material. For analyzing the effects of manufacturing defects, whose size and distribution are not known, the strength-based approach is more suited. We will take this approach here.

3.1. Statistical distribution of static transverse strength

As Fig. 4 shows, the 90° plies are discretized into elements. The element size l_0 satisfies the following criteria: (1) it must be large enough to contain typical manufacturing defects critical for cracking, and (2) it must be small enough so that the stress level may be assumed constant within each element. If these two requirements are satisfied, then each element can be assumed to possess a single static transverse strength, and can accommodate only one crack.

The static transverse strength of each element is affected by the local defects. It is assumed that this strength follows the Weibull distribution that will reflect the random material property to resist crack formation, given by

$$P_s(\sigma_s \leqslant \sigma) = 1 - \exp\left(-\left(\frac{\sigma}{\sigma_0}\right)^m\right) \quad (1)$$

where σ_0 and m are the two Weibull parameters called the characteristic strength and distribution shape constant, respectively. The