Composite Structures 116 (2014) 432–440

Contents lists available at ScienceDirect

Composite Structures

journal homepage: www.elsevier.com/locate/compstruct

Multiscale reliability analysis of a composite stiffened panel

Venkata M.K. Akula *

Dassault Systémes Simulia Corp., 190 Civic Circle, Lewisville, TX 75067, United States

ARTICLE INFO

Article history:
Available online 11 June 2014

Keywords:
Reliability analysis
Stiffened panel
Composite structures
Finite element analysis

ABSTRACT

A method for performing reliability analysis of a composite stiffened panel subjected to axial compression using the finite element method is discussed. Three-dimensional shell and brick element models are utilized for baseline response prediction, and comparison with experimental results. Owing to the multiscale nature of composite materials, microscale and macroscale design parameters are identified for the panel. The microscale parameters consist of fiber\matrix properties and the volume fraction. The macroscale parameters consist of structural dimensions, layup definition, and an imperfection scale factor. The fiber and matrix properties are estimated utilizing a micromechanics model in conjunction with an optimization method. Thereafter, parameterized finite element models are used to generate an approximation model. Utilizing the Monte Carlo method, design parameters were subject to variation and the variation in response was predicted using the approximation model along with the probability of failure measured against experimental results and baseline finite element responses.

1. Introduction

Owing to the multiscale architecture of composite materials, structural design and analysis requires configuring additional variables. At the macroscale, a laminated structure requires a layup definition in addition to specifying the geometry and boundary conditions. A layup definition constitutes of a stacking sequence in which laminae (or plies) are stacked upon each other at different orientations, to achieve the desired stiffness characteristics. Further, at the microscale, a lamina consists of fibers embedded in a matrix material. Therefore, structural design of composite components requires configuring macroscopic variables such as the layup, and microscopic variables which consist of the fiber\matrix (or constituent) properties, and the fiber volume fraction.

The multiscale design parameters available with composite structures allow for exploring the design space for alternative solutions. For example, by modifying the ply orientations in a layup definition, the stiffness properties of a composite panel can be optimized [1]. However, the additional variables have to be accounted for when measuring the reliability of a design. More specifically, design parameters are prone to variation which can introduce a variation in the component stiffness properties and consequently the structural response. Considering the multiscale characteristics of composite materials, to ensure design reliability, the effect of varying macroscale and microscale design parameters on the structural response of a composite component must be examined.

In this research, we study the influence of the variation in multiscale design parameters on the structural response of a composite stiffened panel subjected to axial compression. Considering the different laminate configurations possible, numerical testing using the finite element method is considered. Using a finite element model of the stiffened panel, an initial baseline force–displacement response is estimated, and compared with experimental results. Thereafter, macroscale and microscale variables are modified and the variation in force–displacement response is estimated. Thereafter, reliability, defined as the probability of satisfying response limits, of the initial design is measured.

2. Literature review

The objective of a reliability analysis is to quantify the uncertainty in structural response due to an uncertainty in design parameters. Sriramulu and Chryssanthopoulos [2] presented a formal classification of uncertainty for composite structures, in terms of variation of design parameters. The parameters were characterized as macroscale variables and microscale variables, in accordance with the material architecture. Furthermore, a detailed literature review was performed, and for a majority of analyses, a Normal distribution or a Weibull distribution was utilized to define the variation of design parameters.

Chiachio et al. [3] also performed an extensive literature review on reliability analysis for composite structures. The discussion was

* Tel.: +1 469 240 7488; fax: +1 469 713 2832.
E-mail address: vmkakula@gmail.com

http://dx.doi.org/10.1016/j.compstruct.2014.06.001
0263-8223/

presented based on the essential components of reliability analysis; the parameters subject to variation, the output variables subject to change, and the reliability analysis method for predicting the probability of failure. Further, the probability of failure of a design is determined based on the concept of failure. For unidirectional laminates this can be the first-ply failure load obtained by measuring the stress state in plies against failure criteria such as Tsai–Wu, Maximum stress, etc.

A variety of methods are available for performing reliability analysis. However, the Monte Carlo simulation (MCS), the First-order reliability method (FORM), and the Second-order reliability method (SORM) are the common methods utilized for this purpose [2–4]. Jeong and Shenoi [5] utilized the MCS method for performing probabilistic strength analysis of rectangular plates made up of T300/epoxy plies. Thereafter, Normal and Weibull distribution functions were used to define the variation in material properties for use in the reliability analysis of the plates. The first-ply failure loads based on six different failure criteria, namely, the Maximum stress, Maximum strain, Tsai–Hill, Hoffman, Tsai–Wu, and the Azzi–Tsai–Hill, were estimated using closed form solutions for the displacement field. The authors concluded that E_{11} had a positive correlation whereas E_{22} had a negative correlation with the reliability of cross-ply and angle-ply laminates considered in the analysis.

Similar to Jeong and Shenoi [5], Frangopol and Recek [6] also utilized the MCS method for predicting the reliability of composite plates. The Tsai–Wu criterion was used to predict failure, and the effect of the thickness of the layers, fiber orientation, and the layup on the probability of failure was examined. It was concluded that the layer interaction effects (the influence of one layer on the behavior of another layer) have to be considered in evaluating the reliability of composite structures. This is an important observation that is applicable for both the undamaged and the damaged behavior. For example, for matrix ply cracking, the neighboring plies have a constraining effect on the behavior of the cracked ply influencing the residual load carrying capacity [7].

The MCS method was also utilized by Shaw et al. [8] for performing reliability analysis of a simply supported orthotropic plate considering two load cases. The first load case consists of a uniformly distributed load over the entire top surface of the plate whereas the second load case consists of line-load acting along the center-line of the plate. Closed form solutions for the stress state were used in conjunction with the Tsai–Hill criterion for performing the reliability analysis using MCS, FORM, and SORM methods. Two types of analysis framework were considered. The first framework consisted of assuming a variation in fiber\matrix properties to directly measure their influence on reliability prediction. The second framework consisted of deriving a variation of lamina properties from a variation of fiber\matrix properties, and using the lamina properties and their variation instead of the constituent properties in reliability prediction. For both methods, closed-form solutions for lamina properties, given constituent properties were utilized. The authors reported that both methods yielded similar predictions for the probability of failure.

The MCS method is considered in the current analysis, owing to the simplicity of the method. However, the accuracy of the method depends on the number of simulations, and performing thousands of finite element simulations to improve accuracy in predictions can be computationally expensive. Therefore, approximation models are often employed in lieu of finite element simulations [3]. For instance, Abu-Odeh and Jones [9] utilized the response surface method to construct an approximation model for the displacement response of a square plate with simple supports and a central concentrated transverse load. Linear and quadratic functional forms were considered in generating the response surfaces, and the quality of the response surface was measured based on the relative error between the approximate response and the exact response obtained from finite element simulations. Thereafter, an optimization analysis was performed where the thickness of the T300/N5208 carbon\epoxy plies was to be minimized subject to the constraint that the stress state in each layer did not exceed a limit set by the Tsai–Hill criterion. The research indicated that with the utilization of approximation models, the computational expense can be greatly decreased while maintaining a reasonable accuracy.

For a majority of reliability analyses, listed in the literature [3], only the ply properties and the structural dimensions are modified. In contract, Yang et al. [10] performed reliability analysis of stiffened e-glass/epoxy panels by varying the properties of fiber and matrix material. With the changing fiber and matrix properties, the lamina properties were calculated utilizing closed form solutions. Thereafter, closed form solutions for the deflection of the stiffened panel were used for measuring the variation in response due to a variation in design parameters; the constituent properties and the structural dimensions. The authors concluded that the isotropic modulus of the fiber material had the largest influence on structural response.

In contrast, in this research, the influence of fiber and matrix properties on the structural response of a composite panel is examined. For this purpose, a baseline response of the panel, using finite element models, is first established. This is followed by a discussion of an optimization method to estimate fiber and matrix properties using known composite properties. Thereafter, an approximation model is constructed for use with the MCS method to perform the reliability analysis.

3. Analysis of a stiffened panel

In this research, a blade stiffened composite panel studied by Kong et al. [11] is examined. Figs. 1 and 2 depict the top-view and front-view of the panel respectively, with the dimensions in meters. The panels were manufactured using graphite/epoxy plies, the properties of which are listed in Table 1. Further, the thickness (t) of each ply is 0.125 mm. The skin region of the panel has a $[0/90/45/-45]_S$ layup whereas the layup for the stiffeners is

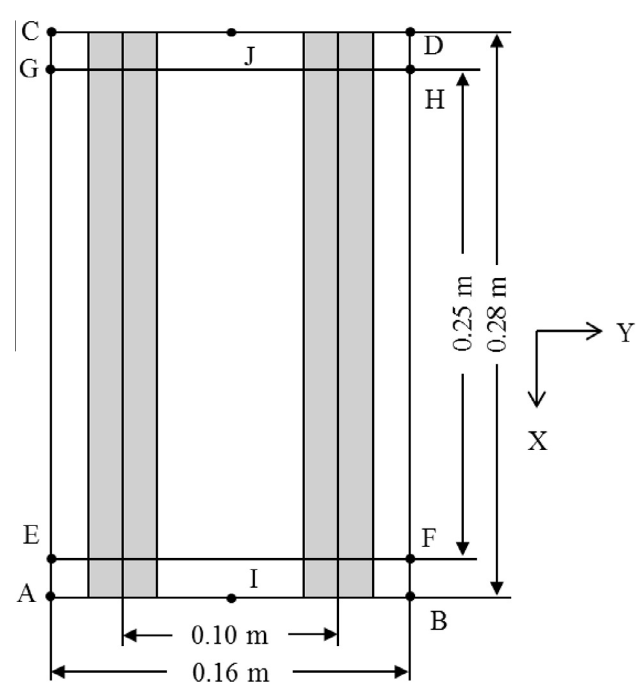

Fig. 1. Top-view of the panel.