Composites Part B 97 (2016) 336–343

Contents lists available at ScienceDirect

Composites Part B

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

# Progressive failure analysis of open-hole composite hoops under radial loading

Yujie Bai*, Xiao-Zhang Zhang

*Department of Engineering Physics, Tsinghua University, Beijing 100084, China*

ARTICLE INFO

*Article history:*
Received 9 July 2015
Received in revised form
22 September 2015
Accepted 10 May 2016
Available online 12 May 2016

*Keywords:*
Layered structure
Strength
Finite element analysis (FEA)
Mechanical testing

ABSTRACT

In this article a finite element-based analysis and experimental study of geometrically non-linear progressive failure analysis of open-hole composite laminated hoops under radial loading is presented. In the finite element analysis the mode-dependent failure criterion Hashin failure criterion and Reddy's sudden material property degradation model are coded using ANSYS-APDL and a progressive failure analysis code is developed. Based on a tensile test machine the experimental fixtures are designed and implemented to apply radial loading on inner surface of the composite hoops. Progressive failure analysis of the sample composite laminated hoops with an open-hole of different diameters subjected to radial loading are performed to study the effect of geometric non-linearity on the failure initiation and propagation. Results show that with large longitudinal strength the circumferential crack is the main failure form because of the shear effect. And, diameters of the open-holes have a significant influence on the initiation and propagation of the failure.



## 1. Introduction

Currently, the carbon fiber reinforced composites have been increasingly employed in various fields such as the high-speed rotating composite laminated cylindrical shells [1], for their advantages like high strength/stiffness-to-weight ratio, excellent resistance to fatigue and corrosion as well as satisfactory durability. With the same geometry a composite cylindrical shell can achieve higher spinning speed and energy density compared with traditional materials. Therefore, a good understanding of the failure characteristics, failure modes and failure propagation of composite laminated shells is essential to develop the full potential of composite materials, especially for already notched structures.

Under a high stress, composite laminates can develop local damages such as matrix failure, fiber breakage, fiber matrix debonding and delamination, which eventually cause the ultimate structure failure. The first three failure modes are called intra-laminar damages and the last is called inter-laminar damage. Especially, local intra-laminar failures can be tolerated much better than inter-laminar failures. To predict these failures, Progressive failure analysis has been proposed. Progressive failure analysis of carbon fiber reinforced composites is a powerful method to determine the capability of composite structures to sustain loads. Over the last three decades, the progressive failure analysis has been studied by many researchers. There are lots of literature on the progressive failure analysis and some key examples are presented below. Chang et al. [2,3] dedicated a lot to establish the progressive failure analysis; they studied the sample laminates plate under tensile and compression loadings with notches and holes, and for the compressively loaded laminates failure loads and damage modes were also predicted. Sleight [4] implemented the progressive failure analysis methodology in the Comet finite element analysis code to predict the failure loads and damage paths in a composite laminate with holes under shear loading. Zabaras [5] performed a 2D finite element progressive failure analysis on composite plates using the higher order shear deformation theory. Reddy and Reddy [6] studied the first ply failure using both linear and non-linear finite element analysis on composite plates under in-plane tension loading and transverse loading. Reddy et al. [7] used the layerwise plate theory to perform the progressive failure analysis with the non-linear geometry taken into consideration. The implementation of progressive failure analysis in commercial finite element software through user-defined subroutines becomes

* Corresponding author.
*E-mail address:* baiyj11@mails.tsinghua.edu.cn (Y. Bai).

http://dx.doi.org/10.1016/j.compositesb.2016.05.029
1359-8368/

popular in many researches to obtain the failure loads, simulate the failure modes and predict the damage path nowadays.

For progressive failure analysis of composite cylindrical shells, Wu [8] studied the stress concentration of isotropic/orthotropic laminated cylinders with an open-hole on the wall under biaxial loading. Gummadi and Palazotto [9] predicted the onset of various failure modes in laminated composite shells based on the total Lagrangian approach with large rotation capability. Spottswood and Palazotto [10] determined the physical response including material failure of a thin, curved composite panel subjected to transverse loading. Zheng and Liu [11] used the classical laminate theory to perform the elastic-plastic stress analysis and damage evolution of Al-carbon fiber/epoxy composite cylindrical laminates under internal pressure and thermal residual stress. Based on the continuum damage mechanics, Liu and Zheng [12] proposed an energy-based stiffness degradation method coded in the finite element software ANSYS-APDL to predict the progressive failure properties of the Al-carbon fiber/epoxy composite cylindrical shells. Associated with the finite element analysis, Perreux et al. [13,14], Doh and Hong [15] Tzeng [16] and Minnetyan et al. [17] also used the continuum damage mechanics and the fracture mechanics to study the damage constitutive relationships and failure strength of composite vessels. Liu et al. [18] performed the progressive failure analysis of composite pressure vessels to predict the failure properties and ultimate burst pressure using a multi-scale damage model by associating the finite element codes ANSYS-APDL with ABAQUS-UMAT. Jayashree Sengupta and Arghya Ghosh [19] used an eight-noded isoparametric shell element to perform the progressive failure analysis of laminated composite cylindrical roofs under transverse uniformly distributed static loadings. However, the numerical convergence problem emerges when the finite element method is employed to predict the limit load-bearing ability of composite structures. So Liu [20] solved the quasi-static progressive failure analysis of composite cylindrical laminated shells using explicit finite element analysis and introduced viscous damping effects into the ill-conditioned finite element equations after the stiffness properties of the failed composite elements are degraded. Many researchers have contributed a lot in the progressive failure analysis of composite laminated cylindrical shells and their work is very brilliant. Yet, progressive failure analysis of composite cylindrical shells with geometrically non-linearity like open-holes and notches is still not enough; and experimental study on this subject also needs to be further discovered. Theoretically distribution of stresses and strains in highly spinning composite cylindrical shells is similar as the laminated vessels; and failure initiation and propagation of the open-hole composite shells under radial loading is also similar to the open-hole laminated plates under tension loading. But in reality some different failure characteristics make it necessary to study the damage of open-hole composite spinning cylindrical shells. It is difficult to study the open-hole spinning shells experimentally, so in this paper an alternative experimental approach is used and the traditional finite element method without considering the convergence problem is also applied.

In this article, a finite element-based progressive failure analysis method is used to study the failure loads, failure modes and damage paths of composite laminated hoops with an open hole under radial loading. Hashin failure criteria are adopted to predict the intra-laminar failure initiation and progression and Reddy's instantaneous material property degradation is implemented. Here, the finite element model, failure criterion and material degradation are all coded in ANSYS-APDL. An experimental facility based on the tensile test machine is also developed to observe the failure process which can transfer axial loadings to radial. The finite element results are compared with those obtained from experiments.

## 2. Progressive failure analysis

The basic process of progressive failure analysis is shown in Fig. 1. In order to obtain final failure results the proper modal preparation for each element, mode dependent or independent failure criteria and material property degradation model will be coded in FE software.

To identify the failed elements and associated failure modes and conduct material property degradation at the ply level of each element from the meshed model, distinct lamination properties with distinct ply of 2D orthotropic materials and failure indices are generated in APDL code. Once obtaining the failure indices of each ply in each element, stiffness reduction is easily implemented on material properties for the failed ply according to the relevant failure mode by referencing the element identification and material identification numbers of the ply. In the developed APDL code there is distinct 2D orthotropic material for every ply in every element. Therefore the lamination is distinct for every element according to pre-defined stacking sequence.

The sequence of lamination property with plies and materials generation steps is present in Fig. 2 for a composite laminated model with four shell elements composed of three layers, respectively. After the material and lamination generations in APDL code, there are four element properties, four composite laminates and twelve 2D orthotropic materials. Here in the FE model of Fig. 4 mat(1,3) and index(1,3,i) stands for the material property and index of the *i*th failure mode of the third ply in the first element.

Following the model preparation, stress and strain distribution is obtained by non-linear solution of FE software ANSYS. Then failure indices are calculated based on the stress or strain distribution according to different failure criteria at the middle plane of every ply of each shell element center. Depending on the failure criteria, whether or not one ply is failed is predicted and at the same

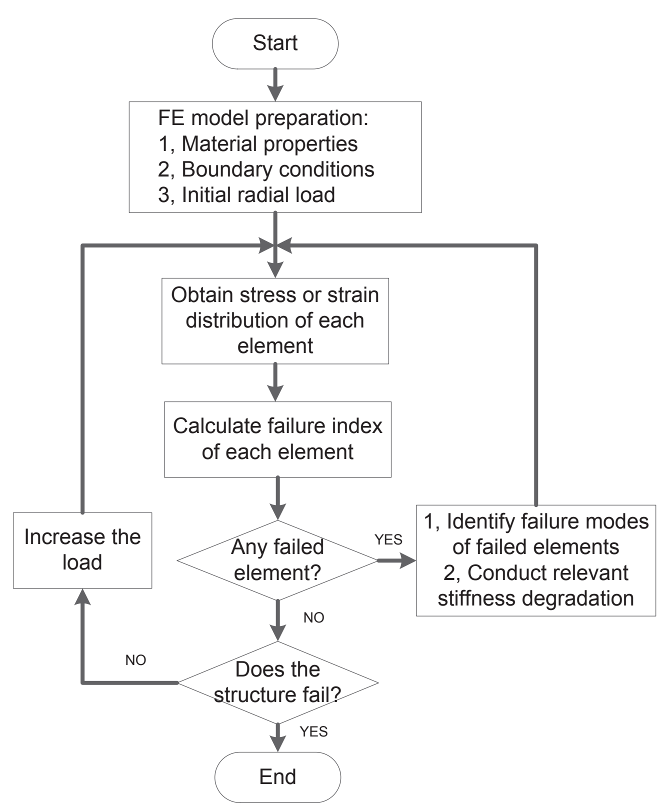


**Fig. 1.** Flow chart of the progressive failure analysis.