Composite Structures xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Composite Structures

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

Delamination analysis of multi-angle composite curved beams using an out-of-autoclave material

Khanh-Hung Nguyen, Hyun-Woo Ju, Viet-Hoai Truong, Jin-Hwe Kweon *

School of Mechanical and Aerospace Engineering, Gyeongsang National University, Jinju, Gyeongnam 660-701, South Korea

ARTICLE INFO

Article history:
Received 31 January 2017
Revised 21 March 2017
Accepted 22 March 2017
Available online xxxx

Keywords:
Double cantilever beam
Curved laminate
Cohesive elements
Delamination
Out-of-autoclave

ABSTRACT

Corners of composite curved beams can easily experience delamination under opening or closing bending moments. Existing literature on the delamination of curved laminated beams, however, is limited to unidirectional and cross-ply laminates with 0° and 90° layers and two-dimensional (2D) plane strain finite element analysis. This study experimentally and analytically investigates the failure behaviors of curved composite structures under four-point bending. Multiangle laminates manufactured using an out-of-autoclave prepreg were examined. A three-dimensional (3D) finite element model was created and analyzed with cohesive elements at the interfaces of adjacent plies. In the experiments, delamination dominated the failure of the curved laminates with several opening cracks. Multiple delamination positions were predicted in the analyses. Double cantilever beam specimens were tested and analyzed for a reference point for selecting cohesive parameters. Several cohesive parameters were selected and discussed. Predicted failure loads matched the experimental results well with 5.8% error when the model simulated a sufficient number of factors of the real test.

1. Introduction

Composite materials have a high specific strength and specific stiffness and are widely used in aerospace vehicles, automobile, ship structures, etc., for which weight reduction is the main concern [1,2]. Among the main structures of an aircraft, the wing spars play an important role in resisting shear loading. The flanges and web of a spar meet at curved corners; the radii of these corners can affect the interlaminar stresses inside these areas. Delamination at the corner is one of the typical failure modes of such composite material spars. In this work, the behavior of the corners of spar-like components is investigated through experiments and analyses of curved laminates to understand the failure phenomenon of the structure.

Delamination research has mostly dealt with the initiation and growth of delamination. Initiation can be predicted using stress-based criteria with some characteristic lengths [3]. Methods using fracture mechanics were developed for simulating delamination growth successfully. Another approach for the numerical simulation of delamination is the cohesive zone method (CZM), in which the framework of damage mechanics and softening is employed. A thin layer of matrix material is assumed to exist between plies. Delamination is interpreted as the creation of a cohesive damage zone in front of the delamination front, separating the adjacent plies. The CZM can handle delamination onset and growth [4].

Cohesive zone models, which employ cohesive elements or interface elements, have generally shown potential applications in basic structures such as double cantilever beams (DCBs) and end-notched flexures (ENFs), as proved by the works of Camanho et al. [3], Alfano and Crisfield [4], Turon et al. [5], Peng et al. [6], and so on. Camanho et al. [3] developed a method for simulating progressive delamination on single-mode and mixed-mode delamination test specimens with pre-existing cracks. The authors investigated the effects of several parameters of cohesive zone models. The method was indicated to be useful for specimens without pre-existing cracks.

Researchers used cohesive elements for simulating the debonding of highly complex composite parts. Davila and Camanho [7] numerically investigated the debonding of skin/stiffener specimens under tensile loading using cohesive elements. The skin and the stiffener were bonded using a film adhesive by the secondary bonding method. The interface properties were based on the properties of composite lamina. Li et al. [8] modeled the adhesive layer in single lap bonded joints using cohesive elements. The strength and deformations were described reasonably well. In addition to bonded joints, bolted joints were investigated through finite element analysis by using cohesive elements by Atas and

* Corresponding author.
E-mail address: jhkweon@gnu.ac.kr (J.-H. Kweon).

http://dx.doi.org/10.1016/j.compstruct.2017.03.078
0263-8223/

Please cite this article in press as: Nguyen K-H et al. Delamination analysis of multi-angle composite curved beams using an out-of-autoclave material. Compos Struct (2017), http://dx.doi.org/10.1016/j.compstruct.2017.03.078

Soutis [9]. Cohesive elements were used to model the subcritical damage modes that simulate the initiation and growth of the damage between predefined crack surfaces. Davies et al. [10] developed a cohesive model to predict delamination and debonding in aerospace structures, including DCBs, ENFs, a Tee stiffener, flat plates with internal delamination, and a two-crack model. Wager and Balzani [11] examined delamination and skin-stringer separation in the framework of the finite element method. Instead of using general cohesive elements, they developed a solid-like interface element, which was based on the formulation of a standard hexahedral isoparametric solid element but was only subjected to interlaminar stresses. Three other stresses were set to zero a priori. Numerical examples showed that the elements could be used to predict the delamination in laminates and the separation of composite structures. Cohesive elements were also used to simulate the impact phenomenon of composite laminates. Aymerich et al. [12] used cohesive elements to predict the matrix failure and delamination of laminates under impact by a dropped mass. The interfaces between (0°/90°) and on the symmetry planes of the quarter model were modeled with cohesive elements to predict delamination and tensile failures of plies. The model accurately predicted the force-time curve and correctly simulated the delamination dimensions and sequence of damage events.

Curved structures were investigated through analytical solutions in the works of Kedward et al. [13] and Cui et al. [14], for example, for interlaminar normal and shear stresses in a curved region. An early numerical work of Wisnom [15] investigated the stress distribution of a curved beam during bending through three-dimensional (3D) finite element analysis. Stress variation was found along the width of the beam, indicating the necessity of 3D analysis. Other researches on stress variation based on different evaluation methods can be found in other works [16–19].

In addition to the evaluation of interlaminar stresses in curved regions, the prediction of delamination is also a major concern. Wimmer et al. [20] investigated delamination phenomenon in L-shaped laminates through an experimental and numerical study. In their two-dimensional (2D) numerical model, a simple and computationally efficient semi-analytical approach was used to predict delamination growth. The predicted strength of the laminates agreed well with the experimental results, in particular, in the case of laminates with initially existing cracks. Gözlüklü and Coker [21] modeled the dynamic delamination of L-shaped laminated composites subjected to quasi-static loading parallel to the arm. A pre-crack was intentionally created in the laminate. Further, 2D cohesive elements were inserted at the centerline of the laminates for predicting delamination propagation. Several aspects were investigated well numerically through explicit finite element analysis. A limitation of the research was the lack of experimental works for validation.

In another study, Gözlüklü et al. [22] investigated dynamic delamination in curved composite laminates. The specimen was tested until a sudden load drop occurred at the maximum load. Failure occurred with a loud breaking sound associated with instantaneous delamination. Matrix cracking was noticed during the test, with a low cracking sound at 60–70% of the final load. Single and multiple delaminations were observed along the whole specimens after the test. In addition, a 2D finite element model was created and analyzed. The cohesive elements were inputted at all interfaces between two adjacent layers. The analysis results agreed well with the experimental results at the macroscopic scale in terms of load-displacement behavior and at the mesoscale in terms of crack-tip speeds and delamination behavior. However, in the analysis, only one crack was predicted by the model. While the failure was initiated and propagated with single or multiple delaminations, as noted by the authors, the model could not predict multiple cracks, which partly existed in the test.

The above discussions clarify that although curved structures have been investigated from the perspectives of stress evaluation and failure prediction, the research is still limited. To the best of the authors' knowledge, considered ply angles other than 0° and 90° have not been considered in the studies on curved laminates; the analyses were mostly based on the plane strain elements; and 3D effects were ignored. The load-displacement behavior of specimens was predicted well, but multiple cracks were not observed in the analyses results. At present, out-of-autoclave curing methods, instead of traditional autoclave methods, are being increasingly used to manufacture composite structures, and therefore, more research on these method and the prepreg types is necessary.

In this study, multi-angle curved laminates were manufactured using an out-of-autoclave prepreg and were tested to investigate the failure behavior of the structure under four-point bending. In addition, 3D finite element models with cohesive elements were created and analyzed. Several methods to select cohesive parameters were used and discussed in the simulation of four-point bending and double cantilever beam specimens. The predicted results were then compared with test values.

2. Specimens and test

Curved laminated specimens were prepared using Cycom 5320-1 epoxy resin with IM7 fiber system prepreg, which was designed for out-of-autoclave application. A curved panel was first made and cured using a chamber at AnH Structures Ltd. for 10 h according to the manufacturer's guide. Curved laminates were manufactured using an outer mold, and then they were cut into several small specimens with a constant width of 25.4 mm (1 in.) after curing. A schematic configuration of the test is showed in Fig. 1. The test was chosen mainly to create the delamination failure mode in the curved region. Therefore, we selected the four-point bending test.

The specimens had a stacking sequence of $[45/0/-45/90]_{3S}$ and an average thickness of 3.288 mm. The test was modified from ASTM D6415-06a to fit the facilities available in the lab. The upper two steel pins were pushed downward with a controlled displacement δ_Z, as shown in Fig. 1. The test was aimed to create an area with a dominant bending moment between the two upper pins. The testing speed was set at 1.5 mm/min. Consequently, the delamination was expected to be the only failure mode in this area.

Six specimens, denoted as B1 to B6 in Table 1, were manufactured and tested. The first three specimens were obtained from one batch, and the remaining three were from the second batch. Tests were performed and then stopped automatically when 80% load was reduced during the test by the testing machine, Instron 5582. A side face of each curved composite specimen was painted

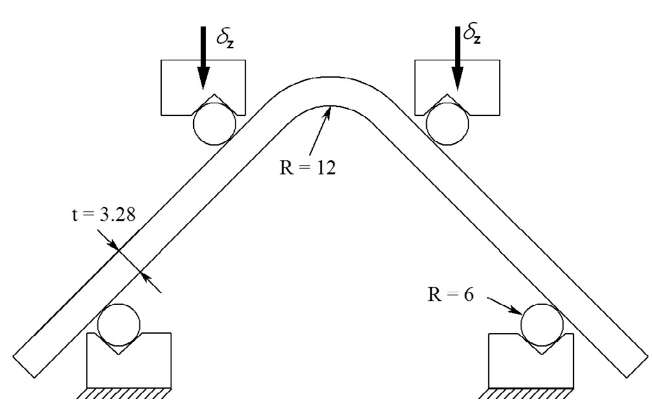

Fig. 1. Schematic configuration of the test.

Please cite this article in press as: Nguyen K-H et al. Delamination analysis of multi-angle composite curved beams using an out-of-autoclave material. Compos Struct (2017), http://dx.doi.org/10.1016/j.compstruct.2017.03.078