Composite Structures 184 (2018) 581–590

Contents lists available at ScienceDirect

Composite Structures

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

Failure load analysis of C-shaped composite beams using a cohesive zone model

Viet-Hoai Truong, Khanh-Hung Nguyen, Sang-Seon Park, Jin-Hwe Kweon*

School of Mechanical and Aerospace Engineering, Gyeongsang National University, Jinju, Gyeongnam 52828, Republic of Korea

ARTICLE INFO

Keywords:
Composite
Delamination
Cohesive zone model
Failure load prediction

ABSTRACT

Delamination-based failure is commonly observed in curved composite structures owing to the significant curvature-induced through-thickness stresses present therein. To gain further insights on this failure mode, we investigated the initiation/propagation of delamination in C-shaped composite beams under an opening load and determined their failure load utilizing a three-dimensional finite element simulation based on a cohesive zone model (CZM). Several cohesive parameters (e.g., initial interface stiffness, cohesive zone length, and interface strength) were examined to construct an optimal CZM for the chosen loading conditions, with all parameters except for mode II fracture toughness (directly obtained from end-notched flexure test results) determined by an extensive literature survey. The predicted beam failure loads were compared with experimental results, with the obtained maximum prediction error of 8.4% indicating good agreement. Finally, the predicted position of delamination initiation was found to be heavily dependent on the ratio of the shear strength to the normal strength of the interlayer.

1. Introduction

Composite materials exhibit a broad range of structural applications because they feature excellent mechanical properties such as high specific strength, high specific modulus, and corrosion resistance. However, since the through-thickness strength of these materials is typically lower than their in-plane strength, they commonly suffer from delamination failure induced by factors such as low-velocity impact, stress near free edges, and manufacturing defects. The growth of delamination cracks leads to stiffness and strength losses and may cause a catastrophic failure of composite structures [1,2], making delamination of laminated composites a well-established but challenging issue. In particular, for composite structures featuring curved regions, a large peel stress is easily developed in the thickness direction due to the bending moment at these regions, which often leads to delamination.

An extensive review of composite delamination was performed by Tay [3], who highlighted the importance of the virtual crack closure technique (VCCT) and the cohesive zone model (CZM) as the most common delamination simulation methods. Notably, the former method is based on the assumption that for an infinitesimal crack opening, the released strain energy equals the amount of work required to close the crack.

In contrast to VCCT, CZM additionally allows the prediction of delamination initiation and can be easily implemented into finite element methods, thus being more frequently used than the former method. In particular, Dugdale [4] and Barrenblatt [5] proposed the use of CZM to examine the size of the plastic zone preceding the crack tip in ductile metals.

In CZM, the relation between the opening displacement and stress at the crack tip is described by a traction-separation law and can be visualized by a so-called traction-separation load curve (TSLC), with the area under this curve assumed to equal the critical energy release rate. Various traction-separation laws have been used in Alfano's works [6–8], depending on the TSLC shape. Fig. 1 illustrates a TSLC corresponding to a typical bilinear traction-separation law, with the area under this curve featuring two regions, namely the elastic region I and the softening region II.

Since fracture behavior is usually dependent on the loading direction, the three common delamination failure modes can be classified as pure opening (mode I), pure in-plane shearing (mode II), out-of-plane shearing (mode III), and/or combinations thereof. The mode I and I/II delamination behavior of laminated composites is commonly examined using the double cantilever beam (DCB) and mixed-mode bending (MMB) tests, respectively, with mode II delamination evaluated using methods such as end load split (ELS), end-notched flexure (ENF), and four-point bend end-notched flexure (4ENF) tests.

Several researchers have utilized CZM to investigate the delamination of composite structures [6–11]. For instance, Alfano [6] applied

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

http://dx.doi.org/10.1016/j.compstruct.2017.10.035
Received 10 October 2017; Accepted 12 October 2017
Available online 14 October 2017
0263-8223/

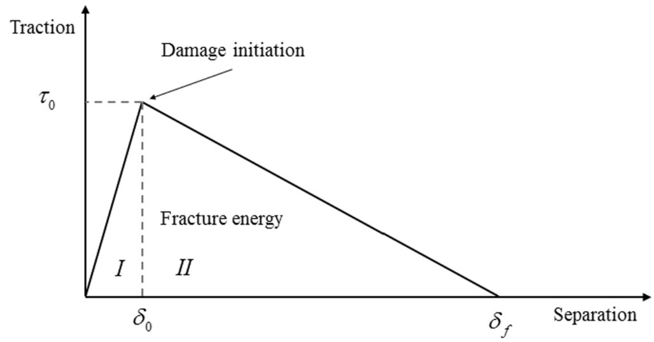

Fig. 1. Graph illustrating the bilinear traction-separation law.

this method to numerically investigate the influence of the interface law shape (bilinear, linear-parabolic, exponential, and trapezoidal) on debonding, concluding that the exponential law was most optimal in terms of finite element approximation, whereas the bilinear law represented the best compromise between computational cost and approximation quality. Peng et al. [7] considered the effect of cohesive parameters on mode I and II composite delamination, providing a guideline for selecting optimal cohesive parameters to obtain accurate numerical results. Recently, Liu et al. [8] have also considered the effect of cohesive parameters on the postbuckling and delamination of compressed composite laminates comprising initial multiple delaminations, concluding that the cohesive shape did not significantly influence the buckling load, whereas the zero-thickness cohesive element was beneficial for computational efficiency and numerical convergence.

Mixed mode I/II delamination has also been extensively investigated, e.g., Reeder [9] conducted a series of tests to measure mode I/II interlaminar fracture toughnesses of three different composite materials to predict the delamination growth therein. Turon et al. [10] proposed a CZM-based method for predicting the propagation of mixed-mode delamination, correlating interlaminar strength and penalty stiffness to ensure correct energy dissipation upon delamination propagation. Moreover, Liu and Islam [11] simulated mixed-mode delamination using an anisotropic nonlinear cohesive model based on continuum damage mechanics.

C-shaped composite beams are commonly used in aircraft and wind turbine blades in structures such as spars and ribs, where delamination is usually initiated in the curved region connecting the flange and the web. However, although such curved-region delamination is a critical structural design issue, it has not been investigated in sufficient detail. An earlier study on the delamination of curved composite laminates subjected to static and fatigue loads was carried out by Martin et al. [12], who aimed to predict the delamination onset and growth in these curved laminates and utilized closed form analysis, finite element analysis, and other tests to determine the stress distribution in an undamaged curved laminate, with mode I fatigue and fracture toughness data obtained from DCB test results. Kress et al. [13] proposed a new model for calculating interlaminar normal stress in the curved section of the specimen produced by in-plane deformation, whereas Hao et al. [14] conducted a four-point bending test to study the delamination mechanism of curved beams with various curvatures and thicknesses.

Feih and Shercliff [15] studied the delamination of L-shaped composite joints experiencing a bending moment, with failure load and location obtained using a numerically stabilized damage model and validated experimentally. Wimmer et al. [16] predicted the emergence and growth of delamination in an L-shaped laminated composite, using the first ply failure criterion to determine the delamination onset and utilizing VCCT to monitor delamination propagation.

Although several studies on the delamination of composite laminates have been conducted, most of them focused on simple-geometry specimens (e.g., DCB, ENF, and MMB), with the number of studies on

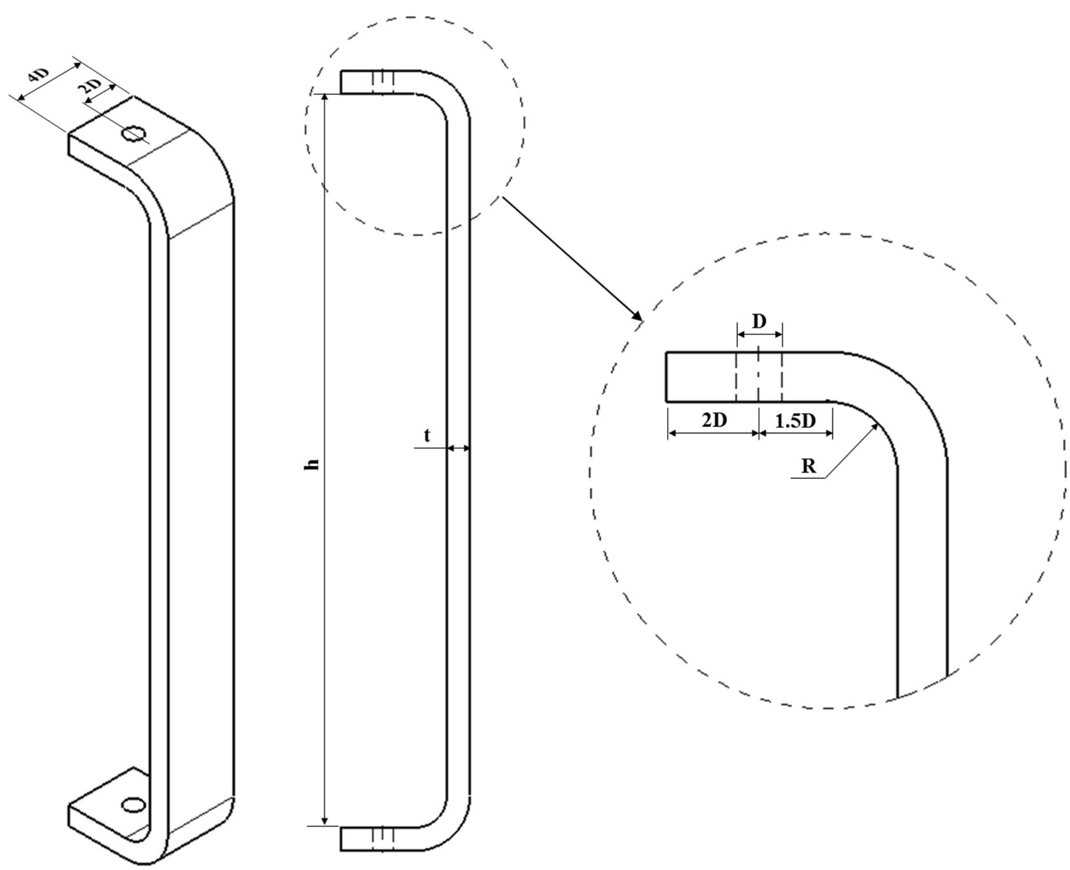

Fig. 2. Schematic configuration of a C-shaped composite specimen used for tensile testing (dimensions not drawn to scale).