Composite Structures 184 (2018) 512–522

Contents lists available at ScienceDirect

Composite Structures

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

A blended continuum damage and fracture mechanics method for progressive damage analysis of composite structures using XFEM

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ARTICLE INFO

Keywords:
Composites
Finite element analysis
Damage mechanics
XFEM
Cohesive zone modeling

ABSTRACT

Progressive damage analysis of composite structures remains problematic, holding back the full potential of these materials. Widely used continuum damage models feature a heuristical stiffness reduction to reflect damage, resulting in an unrealistic representation of damage patterns. To the end of a more realistic failure representation, this paper proposes a blended methodology for progressive damage analysis of such structures implemented in ABAQUS, combining continuum damage models with a more physically based approach from a fracture mechanics perspective. Matrix cracks are modelled through the eXtended Finite Element Method and delaminations through a cohesive zone model. Validation of the blend on an experimental campaign of open-hole tensile tests shows remarkable predictive capability, in good conformance to experimental failure loads, digital image correlation and acoustic emission measurements - particularly yielding more realistic damage patterns than state-of-the-art continuum damage model implementations.

1. Introduction

Propelled by advantages in structural efficiency, performance, versatility and cost, fibre-Reinforced Polymers (FRPs) have made a mark in numerous industries, aerospace industry being a leading party. The full potential offered by FRPs is held back, however, by an overall lack of understanding and inability to accurately predict failure [1,2]. Composite anisotropy and heterogeneity complicate mechanical behaviour. These complications are particularly pronounced in Progressive Damage Analysis (PDA), exemplified by The World-Wide Failure Exercises [2,3] reflecting an overall lack of prediction accuracy amongst leading failure theories.

Driven by the need for accurate failure prediction, great strides have been made in the development and implementation of failure theories for FRPs. These strides have mostly focused on isolated application of Continuum Damage Models (CDMs) on one hand and fracture mechanics on the other hand. CDMs, operating on the principle of damage initiation on the basis of the local stress-strain state [4,5] and subsequent stiffness degradation to reflect damage [6], have found widespread application. Fracture mechanics approaches have been used most widely in the modelling of delaminations and to a limited extent matrix cracking. Fracture mechanics based approaches typically employ either the Virtual Crack Closure Technique (VCCT) or Cohesive Zone Models (CZMs).

Contrary to many of these past attempts, focusing on isolated application of these approaches, this paper presents a blended model combining both approaches for Progressive Damage Analysis (PDA) of FRPs. To this end, the paper commences with an abridged overview of CDMs and fracture mechanics approaches to PDA of FRPs. This is followed upon by the numerical implementation in ABAQUS. Thereafter, validation is presented with respect to an experimental campaign. Lastly, conclusions and recommendations are given.

2. Continuum damage models

CDMs operate on the basis of damage initiation criteria evaluating the local stress-strain state [4,5], and propagation models, or Material Degradation Models (MDMs), that degrade material stiffnesses upon damage initiation [6]. Common to CDMs is a lacking strong physical basis, instead posed more on a heuristical basis – in particular for MDMs. Still, remarkable advancements have been made leading to the failure theories discussed briefly hereafter.

For the case at hand, the LaRC05 criteria are used to guide damage initiation from a stress and strain based methodology, complemented by the bilinear softening law formulated by Lapczyk and Hurtado [7] and extended to three dimensions by Zhang et al. [8]. This selection follows from a precursor study [9], to which the reader is referred for more details.

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http://dx.doi.org/10.1016/j.compstruct.2017.10.007
Received 13 June 2017; Received in revised form 2 September 2017; Accepted 2 October 2017

2.1. Initiation criteria

Initiation criteria find their origin in the Tsai-Hill failure criterion [10,11], proposed on the basis of the Von Mises yield criterion extended to anisotropic metals [12]. A fundamental flaw herein is overlooking composite heterogeneity, transferring to many mode-independent criteria in its wake (e.g. Hoffman [13], Chamis [14], Tsai and Wu [11] and Sandhu [15] criteria).

This deficiency instigated the development of mode-dependent criteria for a more correct assessment of the various intralaminar damage modes in FRPs, distinguishing tensile and compressive matrix and fibre failure [4,5,1]. Hashin and Rotem were the first to make this distinction to pose a set of criteria based on logical reasoning [16], followed upon by the more physically based Hashin criteria [17].

This led to the development of state-of-the-art failure theories. A key contribution and leading theory was posed by Puck and Schürmann [18,19]. A strong physical foundation, extending from the Mohr-Coulomb fracture theory for brittle materials, lends strength to its predictions. Past implementations have found good agreement with experimental results [2,3]. In its wake, LaRC criteria were formulated on a similar basis, but extending in particular the treatment of fibre kinking [20–22]. The latest installment, the LaRC05 criteria, is at the forefront in terms of physically based intralaminar damage initiation criteria. A different, more empirical approach was taken by Cuntze and Freund, describing damage on the basis of the Failure Mode Concept [23,24], yielding predictive accuracy on par with Puck and LaRC05 criteria [2,3].

2.2. Material degradation models

Stiffness reduction in the constitutive relationship by means of a MDM reflects the effect of damage in CDMs [6,25]. Reduction can be either instantaneously or gradually. Traditionally, sudden MDMs have been used, showing little physical basis, but offering a simple and effective approach for PDA [26–29].

Gradual MDMs are arguably better able to capture the physical nature of the damage process. A prominent form of gradual degradation is the bilinear softening law, guiding the degradation by means of fracture energies [30,31,7,8]. In conjunction with the Matzenmiller et al. damage matrix [32], these bilinear softening models have yielded good accuracy [33,34,30,31,7,8]. These softening laws offer the additional benefit of alleviating mesh dependence through the crack band model of Bažant and Oh [35] and alleviating convergence issues in implicit schemes through gradual stiffness reduction.

3. Fracture mechanics

Fracture mechanics models typically employ either VCCT or CZMs. VCCT has a relatively strong physical basic in the framework of LEFM and has found extensive use for cases in which the crack path is known in advance [36,37]. Their use in composites is most widespread for the modelling of delaminations in which interface nodes are released to model the progression of cracks. Some authors, however, consider the sharp crack tips assumed in LEFM unphysical for damage in composites, such as delaminations, and rather argue that failure occurs over a process zone [38,39]. CZMs employ this principle using traction-separation laws which define a gradual softening behaviour over the interface [38]. For the model presented in this paper a CZM is used for modelling both the delaminations and matrix cracks (in conjunction with XFEM), in light of the following advantages of CZMs:

1. No precrack is required as opposed to VCCT, making CZM very suitable for a general framework;
2. Progression of damage is embedded in their formulation and requires no mesh updating;
3. Multiple cracks are allowed to join without any special formulation.

A number of disadvantages apply to CZMs:

1. No distinction between shear modes (mode II & III) as no crack front is explicitly modelled [40];
2. Very fine meshes are required [41,42];
3. A lacking strong physical foundation [37]. Recent experimental evidence suggests that interfacial damage is not confined to the interface and the interfaces follow a trapezoidal traction-separation law [43], contrary to what CZMs assume [44,45,42,46].

4. Blending and numerical implementation

Numerical implementation is performed in ABAQUS [47], extended with user subroutines for material constitutive behaviour and CDM implementation (UMAT) and damage initiation for XFEM (UDMGINI). These components are individually discussed hereafter, followed upon by a discussion on blending and model integration.

4.1. UMAT

Material constitutive behaviour and damage initiation and propagation for the CDM are defined in a UMAT, called at each integration point. At each increment, the local variables are passed onto the UMAT. In the UMAT, the following actions take place subsequently:

1. The local stresses and strains are retrieved and subsequently used to evaluate failure criteria. Material properties required are read in from an external input file, containing a library of materials.
2. When damage is detected, damage variables are updated and – if viscous regularization is adopted – gradually increased.
3. The damage variables act as flags to indicate whether property degradation is to take place. Property degradation follows as a direct reduction in material stiffness parameters, passed into the Jacobian.
4. The updated (damaged) stiffness matrix or Jacobian is used to update the stress tensor after incrementing the strain. The updated stress and strain tensor form the basis for the following iteration, passed into the main routine along with the defined Jacobian.

Damage initiation is designated by LaRC05 criteria for tensile and compressive fibre and matrix damage [21]. Stiffness degradation is performed through the three-dimensional bilinear softening model as implemented by Zhang et al. [7,8].

4.2. Cohesive zones

Cohesive zones for delaminations are implemented using ABAQUS integrated COH3D8 elements. An intrinsic formulation is used in which these elements are inserted between all plies except for those at the symmetry interface. An initial stiffness is provided using 50 times the out of plane ply stiffness. Damage is defined using quadratic failure criterion and the softening behaviour is given by a linear softening law. Mixed-mode behaviour is incorporated by using the Benzeggagh-Kenane interaction law [48]. Artificial viscosity is adopted for cohesive zones to improve the rate of convergence [7,33]. The viscosity parameter was based on a convergence study, yielding a value of $1\cdot10^{-5}$. This parameter is ideally kept small to minimize the artificial increase in energy associated with the introduction of this parameter.

To alleviate mesh dependence and reduce computational efforts typically associated with cohesive zones, interface strengths were reduced following the methodology by Turon et al. [42] based on the local element size. Reduction factors were similar for mode I and mode II, and of the order 2.0–2.5. Reported strengths are uncorrected.

4.3. Matrix cracking

Matrix cracks in the plies are modelled using XFEM and cohesive