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Isogeometric analysis of continuum damage in rotation-free composite shells

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Highlights

- A large-deformation, isogeometric rotation-free shell formulation is equipped with a damage model to simulate progressive failure in composites.
- Four intralaminar modes of failure are considered: Longitudinal and transverse tension, and longitudinal and transverse compression.
- The proposed methodology is valid in the regime of thin shell structures where damage occurs without significant evidence of delamination.
- The damage model is extensively validated against experimental data and its use is also illustrated in the context of multiscale composite damage analysis.

Abstract

A large-deformation, isogeometric rotation-free Kirchhoff–Love shell formulation is equipped with a damage model to efficiently and accurately simulate progressive failure in laminated composite structures. The damage model consists of Hashin's theory of damage initiation, a bilinear material model for damage evolution, and an appropriately chosen Gibbs free-energy density. Four intralaminar modes of failure are considered: Longitudinal and transverse tension, and longitudinal and transverse compression. The choice of shell formulation and modes of failure modeled make the proposed methodology valid in the regime of relatively thin shell structures where damage occurs without significant evidence of delamination. The damage model is extensively validated against experimental data and its use is also illustrated in the context of multiscale composite damage analysis.

Keywords: Isogeometric analysis; NURBS; Multiscale modeling; Continuum damage modeling; Laminated composites; Kirchhoff–Love shells

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1. Introduction

Damage in composite laminates exhibits complex behavior due to heterogeneous failure mechanisms occurring across different spatial scales. A damage model may be either discrete or continuous depending on the scales involved. The model is typically discrete for atomistic voids and lattice defects, and continuous for micro-, meso-, and

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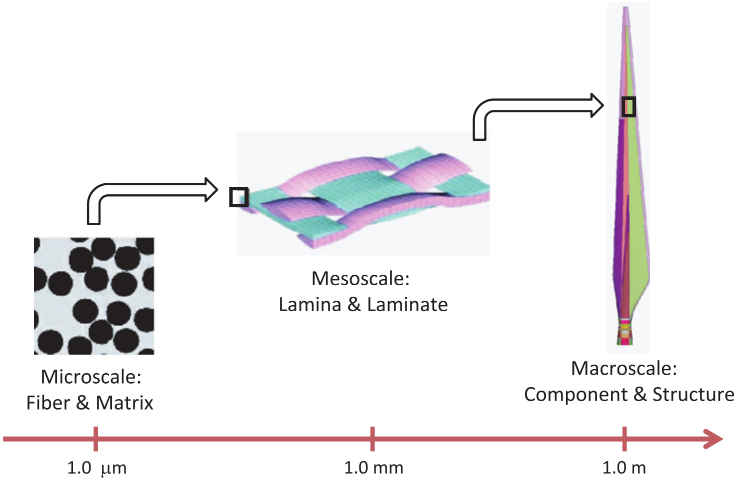

Fig. 1. Illustration of the multiple spatial scales involved in damage modeling of composite shell structures.

macroscales. At the microscale, a representative volume element (RVE) that is both small enough to distinguish the microscopic heterogeneities and large enough to represent the overall behavior of the heterogeneous medium is typically introduced to model phenomena such as separation (or debonding) at the fiber-matrix interface or the initiation, growth, and coalescence of microcracks [1]. At the mesoscale, various modes of damage, such as fiber fracture, matrix cracking, and delamination may be incorporated at the lamina or laminate level. At the macroscale, a composite laminate is typically modeled as a collection of plies, where each ply is an orthotropic medium with continuously distributed material properties and damage indices. (See Fig. 1 for an illustration of the multiscale concept.)

Most research on multiscale composite damage modeling is focused on a two-scale (micro–macro) concept [2,3,1,4]. In [5–7,4] the authors developed a computationally efficient anisotropic homogenization-based continuum model to simulate the fiber-matrix debonding in microstructural damage. The micromechanical model incorporates the path dependence effect by introducing a principal damage coordinate system. To overcome the limitation of the RVE periodicity, a hierarchical model consisting of multiple adaptive levels was conducted by the Voronoi-cell finite element method. In [3,1] the authors developed a homogenization method based on a two-scale asymptotic expansion of the damage tensor in a heterogeneous medium, which led to closed-form expressions relating local (microscopic) fields to overall (macroscopic) strains and damage. However, for certain composite systems, such as woven composites, the two-scale model is insufficient to describe the presence of strong heterogeneities. Refs. [3,1] further extended the two-scale damage theory to the three-scale theory by adding a larger-scale RVE on a mesoscopic scale. Similarly, the triple-scale asymptotic expansion of damage tensor has lead to a closed form expression relating the local (microscopic and mesoscopic) fields to the global (macroscopic) strains and damage.

Localization of deformation may occur during failure when high straining is developed in a small region of the material, while the rest of the structure experiences normal strain levels. A sharp decrease of loading capacity due to localization of deformation is termed strain softening [8,9]. Strain softening may lead to an ill-posed boundary value problem because the governing partial differential equations lose ellipticity for the static case and hyperbolicity for the dynamic case. Furthermore, high mesh sensitivity is sometimes observed in numerical simulations in the presence of strain localization. One successful remedy for this is a regularization technique that arises from nonlocal damage theory first introduced in [8,9]. Subsequently, in [10,11] the authors successfully used gradient-enhanced damage and plasticity models to control localization of deformation. In [12] the authors used Isogeometric Analysis (IGA) [13,14] based on Non-Uniform Rational B-Splines (NURBS) [15] to formulate and study higher-order gradient damage approximations that require higher-order smoothness of the underlying spatial discretization. In recent work [16], the authors incorporated gradient damage models into continuum shell elements.

In this paper, motivated by the multiscale modeling paradigm, we focus on the meso- and macroscale continuum damage mechanics (CDM) of composite lamina and laminates. Our main interests lie in the modeling of aerospace and civil engineering structures, which are often thin and curved laminated composite shells (see, e.g., [17] and Fig. 1). The recent successful application of IGA to thin shells in [18–23], including composite laminates in [24,25], and the recent work on CDM in composites [26] enable a formulation of an accurate and efficient damage modeling