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Compressive failure of composites: A computational homogenization approach

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ABSTRACT

This paper revisits the modeling of compressive failure of long fiber composite materials by considering a multiscale finite element approach. It is well known that this failure follows from a fiber microbuckling phenomenon. Fiber microbuckling is governed by both material and geometrical quantities: the elasto-plastic shear behavior of the matrix and the fiber misalignment. Although all these parameters are easily accounted by a finite element analysis at the local level, the failure is also influenced by macrostructural quantities. That is why a multilevel finite element model (FE^2) is relevant to describe the compressive failure of composite. Furthermore, fiber local buckling leads to a loss of ellipticity of the macroscopic model, which can be a criterion of failure.

1. Introduction

It was long believed that the strength of long fiber composite is lower in compression than in tension [1–3]. This was mainly observed in pure compression tests, but flexural or buckling tests highlighted higher strength level than in tension or pure compression [4–6]. In other words, compressive strength is not only a material property, but it depends on structural data like specimen size, stacking sequences of composite laminates or loading conditions. In the same spirit, it was experimentally established that a single carbon fiber embedded in an epoxy resin is able to bear higher compressive stress than in tension [7]. One can also mention that the reliability of some pure compression tests is questionable. For instance, the GARTEUR program pointed out that experimental strength depends strongly on the experimental set up [8], which was corroborated by finite element studies, see for instance [9]. In other words, the compressive strength cannot be defined without knowledge of structural data.

Besides, it is well known that compressive strength is governed by an instability called fiber microbuckling [10]. Fiber microbuckling is a local instability that depends mainly on fiber volume fraction, on nonlinearity of matrix behavior in shear and on fiber waviness [11,12], i.e. on microstructural data. Explicit critical stresses established from a kink band analysis are available [12,13], which can be corroborated by microstructural finite element computations, see for instance [14,15]. One can refer for instance to [6,14–20] for a full bibliography on the topics.

Hence, a consistent model should involve macroscopic data at the scale of the structure and microscopic data at the scale of the fiber and of the microbuckling wavelength. The model of Drapier et al. [21,16] is a partial answer because it accounts both for microscopic and macroscopic data, but it is limited to few wavelengths and cannot be applied directly to the whole structure. A common criticism can be done to these various local [13–15] or semi-local [16] modeling: they propose maximal values of the stress from microstructural instability analyzes, but it is implicitly assumed that this macroscopic stress is not influenced by the local instability. Concurrent models are nowadays available, for instance the multilevel finite element technique (FE^2) also called computational homogenization [22–24] that considers two nested continuum models needing constitutive assumptions only at the local level. Such a concurrent modeling will be applied in this paper.

Therefore, a consistent numerical modeling of compressive strength has to involve a double scale analysis, by coupling instabilities at microscopic level with a structural analysis. There are many papers about instability phenomena in heterogeneous materials. In the first one by Abeyaratne and Triantafyllidis (1984) [25] about porous materials, it was found that the homogenized material may loose ellipticity while the matrix remains elliptic. Other papers [26,27] established a strong connection between macroscopic loss of ellipticity and bifurcation buckling at the local level.

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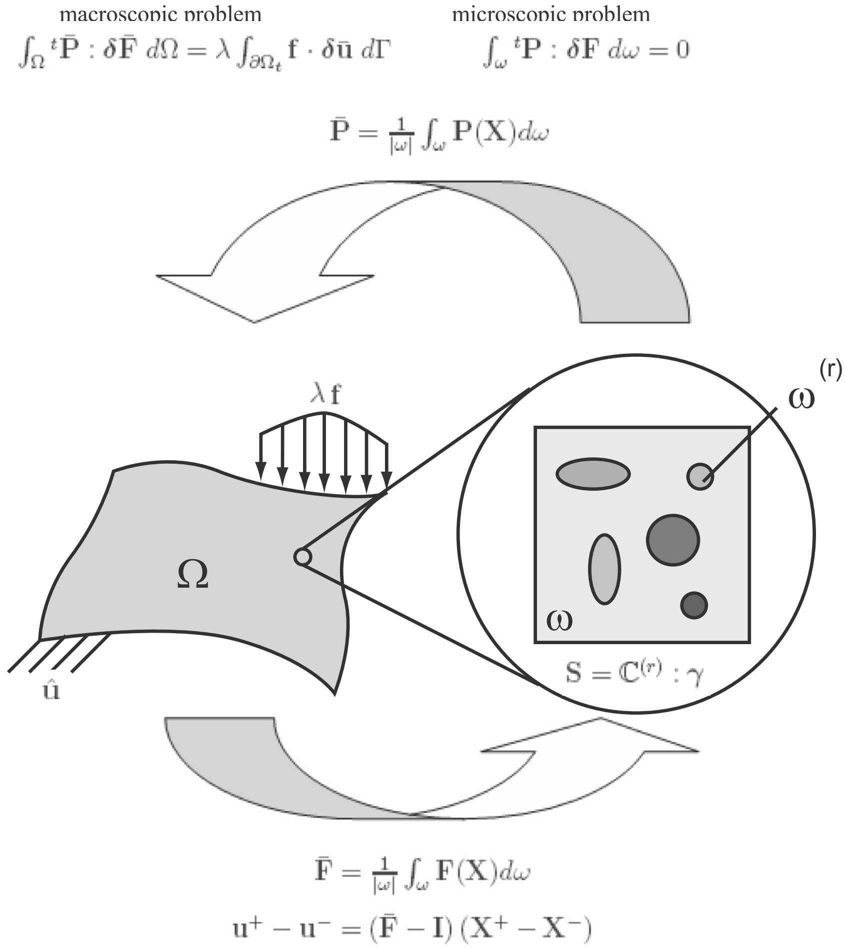

Fig. 1. Computational homogenization scheme.

Nezamabadi et al. [28,29] studied the compressive behavior of long fiber composite structures in a FE^2 framework and proved a similar connection between bifurcation at the local level and maximal macroscopic loading. Additional studies can be found in [27,30–37].

In the present paper, the same FE^2 approach as in [28,29] will be used to discuss the connection between local bifurcation, loss of ellipticity at the macroscopic scale and the kink band stress proposed by Budiansky and Fleck [13]. It is quite well known that the ellipticity condition is related to the stability of a continuous medium and is a necessary condition for the well-posedness of a boundary value problem [38]. Loss of ellipticity is considered as a failure criterion, see for instance [39,40] that has been used in multi-scale frameworks [30,33,35]. Only the classical first gradient continuum model will be considered at the macroscopic level. This is a bit restrictive because the account of fiber bending stiffness is necessary to predict the microbuckling wavelength [41], which should require a model with an internal length such as Cosserat theory [42,43] or second order homogenization [44].

The paper is organized as follows: in Section 2, our multiscale models [28,29] will be shortly described, the connection between local instability and macroscopic loss of ellipticity will be explained and two classical failure criteria will be presented. Section 3 is devoted to numerical applications. Several multilevel numerical applications will be discussed, especially beam bending tests that can be considered as reference cases [6]. This permits us to revisit the relation between microbuckling, macroscopic loss of ellipticity, mesh sensitivity and kink band predictions, in a multiscale framework with a single constitutive assumption at the microscopic level.

2. Failure model of long fiber composites

2.1. A generic computational homogenization

Let us describe the main features of a multilevel finite element scheme (FE^2) that is also often called computational homogenization. Such a model is described by two nested domains, each material point belonging together to the so-called macroscopic domain Ω and to a microscopic domain ω, also called Representative Volume Element (RVE) or basic cell. Here both domains are in their reference configuration. After the finite element discretization, each domain is associated to a mesh so that a microscopic domain (or a microscopic mesh) is associated with each integration point of Ω. According to [45], FE^2 models are characterized by the lack of constitutive law at the macroscopic level and by the localization/homogenization relations. In the case of heterogeneous hyperelastic materials, the multilevel model is represented in Fig. 1 and Table 1, where all macroscopic quantities are denoted by $\bar{(\cdot)}$. Classically $\bar{\mathbf{F}} = \nabla\bar{\mathbf{u}} + \mathbf{I}$, is the macroscopic deformation tensor, $\bar{\mathbf{u}}$ denotes the macroscopic displacement field and $\bar{\mathbf{P}}$ is the first macroscopic Piola–Kirchhoff stress tensor. The corresponding quantities at the microscopic level are denoted as $\mathbf{F}, \mathbf{u}$ and $\mathbf{P}$, while γ and $\mathbf{S}$ represent the Green–Lagrange strain and the second Piola–Kirchhoff stress tensor.