ON THE INTRA/INTERLAMINAR COUPLING OF LAMINATED COMPOSITES: MODELING, IDENTIFICATION AND VALIDATION

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Summary The prediction of the behavior of laminated composite structures up to final fracture is at the heart of today's virtual structural testing challenge. Indeed, failure may occur due to the interaction of small-scale degradations, such as transverse intraply cracks and interface delamination, which are difficult to account for in calculations on the structure's scale. Here, in order to model the interaction of intra- and interlaminar degradations, we present a new and relatively simple micromechanics-based interface mesomodel which is intended to become part of LMT-Cachan's development called the "enhanced damage mesomodel of laminated composites". The intra/interlaminar coupling depends on a small number of material constants which could be identified from standard tests. The predictive capabilities of this interface mesomodel are illustrated by several test cases: holed plates in tension and low-velocity impact problems.

The last quarter-century has witnessed considerable research efforts in the mechanics of composites in order to understand and predict the behavior of these materials, the ultimate goal being the design of the materials/structures/manufacturing processes. Even in the case of laminated composites (which are the most studied and, therefore, the best understood), the prediction of the evolution of damage up to and including final fracture remains a major challenge which is at the heart of today's "virtual structural testing" revolution engaged in by the aeronautical industry, which is facing a rapid and drastic increase in the use of laminated composites. Virtual structural testing consists, whenever possible, in replacing the numerous experimental tests used today by virtual tests.

An answer to the virtual structural testing challenge is what is called the "damage mesomodel for laminated composites", developed at LMT-Cachan since the 1980s [1]. The mesomodel is built in the framework of continuum mechanics. The main assumption is that the behavior of any laminate under any loading up to final fracture can be described using two elementary entities: the ply and the interface. The damage state of each mesoconstituent is quantified by mesodamage indicators which, in general, are associated with a loss of stiffness. These indicators are assumed to be constant throughout the thickness of the elementary ply, but not throughout the thickness of the laminated composite. The ply is described as a full three-dimensional orthotropic and damageable continuum. The interface, however, is a surface entity whose material directions depend on the relative orientations of the neighboring plies, *i.e.* a cohesive interface which enables the transfer of displacements and stresses from one ply to the next. Identification procedures for the ply and interface models have already been defined [2]. What is being proposed today for virtual testing is an enhanced version based on micromechanics.

The starting point for the development of this micromechanics-based enhanced mesomodel was the need to improve the predictions of the standard version in terms of delamination. Even though the standard version of the mesomodel led to realistic responses for complex engineering problems, it was shown to underpredict the delaminated areas in some industrially significant test cases, such as low-velocity impact. This means that a standard cohesive interface may not be capable of producing realistic responses in terms of delamination. A heuristic remedy was proposed in [3].

In this paper, we return to the main issue associated with mesoscale modeling, which is the correct description of the interaction between delamination and transverse microcracking. This is a rather ancient question in micromechanics [4-8], and numerous works, all using discrete models, have attempted to derive analytical and numerical solutions to problems involving this interaction. Both transverse intraply cracks and delamination cracks are described in detail; thus, the competition between the two mechanisms can be modeled directly. Indeed, the physics of the problem is very well-known (see the review papers [6,7]). The difficulty lies elsewhere, namely in the fact that the discrete modeling of every single discontinuity becomes unfeasible for complex engineering problems involving several thousands of cracks. For example, even with today's high-performance computational tools [9], the computational micromechanical model introduced in [2] leads to prohibitive computational efforts and, thus, is far from meeting the virtual structural testing requirements. Let us also mention intermediate approaches where splits are described *a priori* on the mesoscale as cohesive cracks [10,11].

This situation could be improved significantly if one could create a real synergy among the approaches on different scales. One could jokingly say that, on the one hand, there is the micromechanics of laminates where one counts cracks and, on the other, there is the meso- or macromechanics of laminates where one measures stiffness. Previous works have proved that a complete bridge between the two approaches exists and can be built [12,13]. As a result, the present version of the damage mesomodel could be viewed as a homogenized version of the computational micromechanics model [2], and a first model of the intra/interlaminar coupling has been given in [14]. In this paper, we go back to the basic interface problem which constitutes part of the micro-meso bridge. This problem, which is defined over a 3D-cell, is solved numerically for realistic situations. In [13], it was already proven that a good approximation is obtained by considering that the interface mesomodel depends only on the interface variables and the microcracking rates of the adjacent plies. Here, we go beyond [13] and derive a damage mesomodel from micromechanics for any ($+\alpha$,$-\alpha$) interface and for adjacent plies with different damage states. This interface mesomodel is both relatively sound physically and relatively simple. It depends only on material constants which can be calculated by solving the basic interface problem. The identification procedure, which relies on standard delamination tests, is not modified. In order to illustrate the predictive capabilities of the enhanced interface mesomodel, we present the example of a holed plate. A companion paper presents the validation for low-velocity impact tests.

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