International Journal of Fracture **77**: 111–140, 1996.

Modeling and simulation of crack propagation in mixed-modes interlaminar fracture specimens

O. ALLIX[1] and A. CORIGLIANO[2]
[1]*I.U.T. G.M.P Evry, Laboratoire de Mécanique et Technologie, E.N.S. de Cachan/ C.N.R.S./ Université P. et M. Curie. 61, avenue du President Wilson, 94235 Cachan, France*
[2]*Department of Structural Engineering, Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milano, Italy*

Received 23 January 1995; accepted in revised form 18 December 1995

Abstract. A study of mixed-mode crack propagation in bending-based interlaminar fracture specimens is here presented. A numerical scheme to simulate full crack propagation is proposed which makes use of interface laws relating interlaminar stresses to displacement discontinuities along the plane of crack propagation. The relation between interface laws and mixed-mode failure loci in terms of critical energies is discussed and clarified. Numerical simulations are presented and compared with analytical and experimental results.

1. Introduction

Delamination represents a major phenomenon of degradation in composite laminates. It consists of the separation of adjacent layers due to edge effects, impacts or other causes which originate important interfacial stresses (see e.g. [1]–[3]).

A great effort has been made in the literature in order to apply fracture mechanics concepts for the characterization of delamination, in particular in order to evaluate the resistance of a given laminate to delamination. Due to the complex stress states which develop in real laminated structures and which cause delamination, mixed-mode crack propagation is of primary importance in this respect. For the above reasons it is of interest to study the so-called interlaminar fracture specimens which are mainly conceived to obtain the fracture resistance of a given laminate in pure and mixed-mode conditions (see e.g. [4]–[17]).

In order to study and numerically simulate the process of delamination we have made use of a recently proposed meso-model approach ([18]–[20]). In this approach the laminate is conceived as a stacking sequence of homogeneous layers and interlaminar interfaces. Layer degradation is taken into account by means of a damage model which has given rise to many studies. A complete presentation of the single layer modeling and identification is given in [21]. The decohesion (i.e. delamination) of two adjacent plies is modeled using a damage interface model ([22], [23]). One of the advantages of this approach is that the mechanical behaviour of any laminated structure may be determined once the layer and the interface are completely identified. In the case of delamination this means, in turn, that the ability of laminates not to delaminate is characterized by some intrinsic characteristic of the interlaminar interface connection. Moreover, thanks to this type of approach, both initiation and propagation of delamination cracks may be numerically simulated. The above approach has already been applied to study or predict initiation and growth of delamination in the case of Edge Delamination Tension (EDT) ([24]) specimens, or in holed plates ([25]). Pure modes I and II interlaminar fracture specimens, in which the layers were assumed to be elastic, were analyzed in [26] in order to clarify the identification of interlaminar interfaces

using delamination specimens and to underline the interest of the proposed scheme for the simulation of delamination propagation.

It should be remarked that for the interlaminar connection a numerical approach similar to that discussed here was presented in [27], where use was made of *cohesive crack* models for the interface behaviour. More recent works concerning the same subject are [28] and [29].

The purpose of the present paper is mainly to complete the work presented in [26] and to deal with mixed-mode interlaminar fracture specimens. More precisely, the suitability of a certain class of interface models for the prediction of mixed-mode propagation is analyzed. In particular it is shown that, in the simple case of a steady state propagation of delamination, one can always associate with a specific interface model and in mixed-mode situations, a *failure locus*, described in terms of global fracture energies. The failure locus shows how the global fracture energy involved in the mixed-mode propagation process varies at varying coupling ratio between different modes. This connection allows for completion of a possible procedure of identification for the interface model and to better understand the link between typical fracture mechanics parameters such as the fracture energies and the formulation of an interface model. From a numerical point of view it is shown how to use such an interlaminar damage model in the case of specimens which can have unstable behaviours both under load and displacement control. Particular features of the numerical simulation adopted are the use of a local control algorithm and the way in which conditions of unilateral contact are directly taken into account through the interface model.

An outline of the paper is as follows. In Section 2, a discussion on bending-based interlaminar fracture specimens is presented. This is done in order to clarify some basic hypotheses which are introduced in the numerical model proposed and also to present analytical results, derived applying the beam theory, which are used in the paper for comparison with numerical computations. In Section 3, a class of mixed-mode interface laws is presented. Section 4 contains a discussion concerning the connection between a class of interface damage models and fracture mechanics in the general framework of the propagation of delamination in mixed-mode situations. This also leads to a proposal for a complete procedure for the interface identification. In Section 5, the numerical procedure used for simulation, already presented in [23] and [26], is briefly described. Finally, in Sections 6 and 7, numerical results and comparisons with experiments are presented.

2. Mixed-modes interlaminar fracture specimens

A number of delamination specimens have been proposed in the literature in order to evaluate, in the case of the propagation of delamination, the fracture energy of laminated composites in mixed-mode conditions. Many of these specimens are basically built starting from the same configuration of the classical Double Cantilever Beam (DCB) used for studying mode-I crack propagation, but loaded and constrained in different ways, so as to cause a fracture propagation in mixed I + II modes. Some representative examples are shown in Figure 1. All the specimens of Figure 1 can be dealt with by introducing some simplifying hypotheses, discussed in the following.

As usual for delamination specimens, the direction of fracture propagation is a priori known: the fracture propagates between two layers of the laminate composite. This is certainly true for $0°/0°$ specimens; when considering different layers lay up, the delamination crack can also propagate partly in one layer interface and partly in a different one. This phenomenon is not considered in the present study.