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Advanced beam model for fiber-bridging in unidirectional composite double-cantilever beam specimens

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Abstract

This work investigates the interlaminar fracture and fiber-bridging in double-cantilever beam specimens from the theoretical and experimental points of view. Crack initiation and propagation tests were performed on unidirectional E-glass/polyester double-cantilever beam specimens. The well-known classical beam theory-based solution agrees excellently with the experimental results in the case of crack initiation tests. In contrast, the classical model seems to be inadequate for the evaluation of the propagation test data. The apparent contradiction was attributed to the fiber-bridging phenomenon. Thus, a novel beam model was developed, which accounts for the effect of fiber-bridging. Based on the solution of beam theory, the number of the bridging fibers and the bridging force can be approximated. The former reaches a peak value and decreases notably, while the force tends to a plateau value as the crack grows.

Keywords: Double-cantilever beam; Fracture toughness; Beam theory; Fiber-bridging; Winkler foundation

1. Introduction

The double-cantilever beam (DCB) test is a standard (ASTM D5528, ISO/DIS 15024) method to measure the mode-I interlaminar fracture toughness of composite materials. Within the scope of linear elastic fracture mechanics (LEFM) the DCB specimen is treated as a slender beam. The researchers provided a large amount of theoretical analyses on the DCB specimen. An advanced solution for the DCB specimen was developed by Kanninen, applying a Timoshenko beam on Winkler-type elastic foundation [1]. Later, Williams [2] extended the elastic foundation model for orthotropic materials, the elegant solution was

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referred to by numerous authors [3–5]. In fact, the elastic foundation model does not account for the effect of fiber-bridging, which is an essential feature not only in unidirectional, but even in angle-ply laminate DCB specimens [4]. Furthermore it is observable also under mixed-mode I/II conditions [6].

The bridging fibers increase the resistance to delamination. In this case the energy release rate increases with the crack length, this feature is known as the *R*-curve effect. Numerous authors have investigated the fiber-bridging in composite materials. The phenomenon was studied by Suo et al. [7] in certain composite specimens. It was highlighted that the *R*-curve cannot be considered as a material property, since it depends on the specimen size and geometry. The concept of the bridging law is widely applied in the literature to characterize the *R*-curve for DCB specimens. Kaute et al. [8] introduced a semi-empirical model for fiber-bridging modeling. The bridging law was composed by the product of two terms: the fiber force and the number of bridging fibers per unit area of crack face. The functions of these two terms were determined based on experiments. Unfortunately this model required too much parameters to be determined. Later Yan et al. [9] introduced a numerical model based on an elastic-plastic damage interface between the adjacent plies of the composite laminate. The experiments by Hashemi et al. [10] were utilized to validate their model. Tamuzs et al. applied also the finite element technique for fiber-bridging modeling in carbon/epoxy DCB specimens [11]. The bridgings were represented by nonlinear spring elements along the bridged zone of the specimen. The behavior of the springs was controlled based on the determined bridging law. Sohn et al. investigated the fiber-bridging using the bridging stress function in the case of polycrystalline alumina composites [12]. The bridging tractions were estimated based on the measured crack opening displacement. The phenomenon was studied also in short fiber-reinforced composites. An extensive study was carried out by Lindhagen and Berglund [13], the fiber-bridging in several type of composite materials was investigated and the bridging laws were determined using the DCB coupon loaded by pure bending moments. Also, Fernberg and Berglund [14] determined the bridging law for certain short-fiber-reinforced composites. A remarkable feature is that the bridging law was found to be a material parameter in these studies.

In the present work we developed a model for fiber-bridging analysis based on classical beam theory. Traditional DCB test (see Fig. 1) including crack initiation and propagation on unidirectional E-glass/polyester specimens was performed providing input data for the analysis. The main goal of our work is to provide information on the number of bridgings and the bridging force. The approximate character of these quantities would be useful in order to understand the phenomenon more deeply. The presented method is relatively easy to apply by using a Maple worksheet.

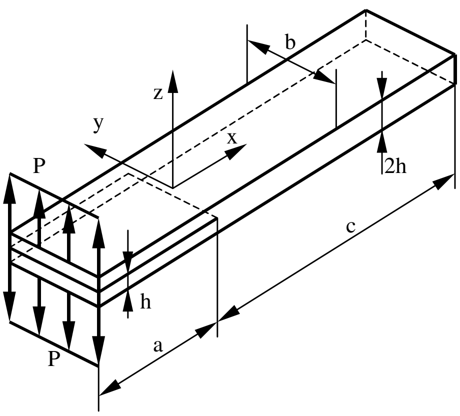

Fig. 1. DCB specimen for mode-I delamination testing.