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Inverse method for estimation of composite kink-band toughness from open-hole compression strength data

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ABSTRACT

Fiber-reinforced polymer matrix composite materials can fail by kink-band propagation mechanism when subjected to in-plane compressive loading. This mode of failure is especially prevalent in compressive loading of laminates with holes, cut-outs, or impact damage. Most of the successful models for predicting compressive strength of such laminates require "fracture" toughness associated with kink-band propagation under in-plane compression. However, this property is difficult to measure experimentally, limiting the use of such models in design practice. In this paper an inverse method is proposed to estimate the kink-band toughness of the laminate from its open-hole compression strength data, which is an easier property to measure experimentally. Furthermore, a scaling relationship is proposed to estimate kink-band toughness for other laminate configurations of the same material. Through various investigations, it is shown that the developed inverse method and scaling relationships can serve as effective and accurate tools in the prediction of open-hole compression and compression after impact strengths for multiple layups of different material systems.

1. Introduction

Compression after impact (CAI) strength of composite laminates is one of the key properties required for initial sizing and design of composite structures for aerospace applications. This property is usually determined experimentally by subjecting laminates of interest to expected and/or required impact scenarios followed by in-plane compression testing. These experiments have been standardized by ASTM D7136 [1] and ASTM D7137 [2] so that the properties are measured in a consistent and repeatable manner. However, these tests are time consuming and expensive due to the wide range of parameters involved, especially for impact testing. For example, possible combinations of impactor mass, geometry, size, and velocity can create a large test matrix. Furthermore, as both the impact damage and the resulting CAI strength are a function of the laminate configuration (ply material and layup), testing is usually conducted on a narrow range of laminates based on past design experience. This limits the design space, especially during the preliminary design phase, to only those limited laminate configurations.

The limitations discussed in the foregoing paragraph have motivated the development of analytical and computational methods to predict impact damage [3–7] and CAI strength [8–18] of polymer-matrix composite materials. CAI failure is the compressive failure of a laminate that is weakened by impact damage. There are two predominant failure mechanisms that can occur in CAI failure. These include local sublaminate buckling of the delaminated plies and kink-band initiation and propagation from the vicinity of the impact damage, with the kink-band mechanism typically seen in higher modulus carbon fiber reinforced polymer matrix composites. The predominant mechanism can be different depending on the extent and the nature of the impact damage, material properties, and/or laminate configuration. It is also possible that the two mechanisms occur in a coupled manner where sublaminate buckling triggers the formation of the kink band that results in the final failure or vice versa. Based on these two mechanisms, there are two classes of analytical models proposed in the literature, namely, sublaminate buckling with or without delamination propagation [19–22] and kink-band propagation models [16,23]. The models that are based on the kink-band propagation mechanism are useful in predicting compressive failure of laminates with cut-outs such as open holes and notches as well as for CAI failure of sandwich panels [16,23,24]. However, kink-band propagation models require measurement of kink-band toughness which is also referred to as compressive fracture toughness in literature. In open-hole compression (OHC) and CAI failure of multi-directional laminates, kink bands form in 0° plies and propagate in the plane of the lamina. However, the kink band is accompanied by other damage mechanisms such as matrix and fiber damage in adjacent off-axis plies as well as delamination between plies [25]. Thus, in modeling OHC and CAI in laminates via kink-band

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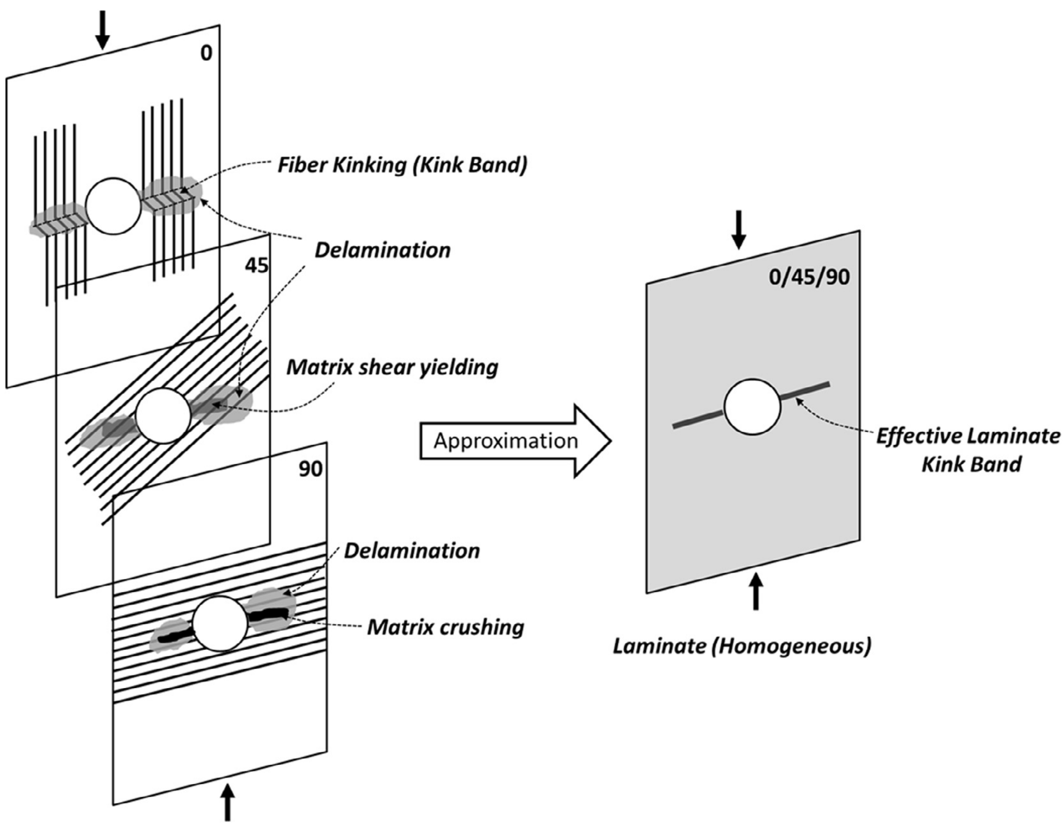

Fig. 1. Schematic showing OHC/CAI failure mechanisms in multidirectional laminate and their idealization as an effective kink band at the homogenized laminate scale.

propagation mechanism, it is implicitly assumed that the kink band and all accompanying mechanisms (delamination, matrix crushing in adjacent plies, etc.) can be modeled as an effective kink band at the homogenized laminate scale [25], as shown schematically in Fig. 1. Thus, the kink-band toughness of the laminate (represented by K_{Ic} throughout this paper) should be interpreted as the toughness associated with the propagation of the effective kink band. This toughness includes energy dissipation due to kinking in 0° plies, which itself includes dissipation due to the underlying micro-mechanisms such as fiber micro-buckling and inelastic shear deformation in the matrix, as well as dissipation associated with the damage in adjacent plies and delaminations.

The kink-band toughness is not an easy property to measure and hence it is not readily available. To obtain this parameter, Soutis and co-workers [24,26] employed a center-notched compression experiment while Ratcliffe et al. [23] and Jackson and Ratcliffe [27] used a compact compression test. A review and analysis of compressive fracture toughness testing methods in laminated composites is provided in Pinho et al. [28]. Despite the effort in developing experimental techniques to characterize the kink-band toughness and proving their effectiveness in doing so, currently there is no accepted standard procedure to measure this property. The difficulty in its measurement and lack of familiarity with the necessary testing methods limit the usefulness of kink-band-based CAI strength models, especially in an industrial design setting. While there have been attempts to determine the kink-band toughness from micromechanics-based models [29–32], these models still require certain parameters that are not easily measured (e.g., shear yield strength of the unidirectional laminate) or interpreted (e.g., fiber waviness angle). The present paper attempts to remedy this situation by estimating kink-band toughness from other readily available test data using an inverse methodology. The proposed methodology uses, as input, the unnotched and OHC strength properties, which can be measured using standardized test procedures (e.g., ASTM D6641 [33] and ASTM D6484 [34], respectively), to infer the kink-band toughness of the laminate. In addition, we demonstrate that the toughness scales with certain laminate elastic properties thus allowing prediction of kink-band toughness for other laminate configurations of the same material. The paper is organized as follows: in Section 2 we present the proposed inverse modeling approach. In Section 3 we demonstrate the procedure using OHC data available in literature and also develop the scaling relationships between the kink-band toughness and laminate attributes. Kink-band toughness predictions using micromechanics are also compared to those using the developed method in Section 3.

2. Approach

The inverse methodology proposed in this paper is based on the assumption that the open-hole compressive failure of PMC laminates occurs by kink-band initiation and propagation. This failure mechanism is likely to occur for most structural PMC layups and hole diameters of interest, as has been shown in various previous works (see, for example, Refs. [25,26,35]). As kink-band propagation has been found to be the predominant mechanism in OHC failure of PMC laminates, attempts have been made to predict the OHC strength by modeling the kink-band initiation and propagation from the stress concentration regions of the open hole [25,26]. These "forward" analytical approaches require two key laminate-level properties – the unnotched compressive strength (σ_{un}) and kink-band toughness (K_{Ic}). While the unnotched compressive strength can be obtained through standard experimental characterization or via calculations using, for example, laminate theory with an appropriate failure criterion, as demonstrated by Soutis et al. [25], greater difficulty exists in quantifying the kink-band toughness. Thus, these models typically use K_{Ic} estimated from micromechanics models [29–32] or, in some cases, measured from experiments [23,24,26–28].

As discussed in Section 1, CAI failure of composite structures also involves kink-band initiation and propagation and hence associated analytical models also require K_{Ic}. The commonality of this failure