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A simplified layered beam approach for predicting ply drop delamination in thick composite laminates

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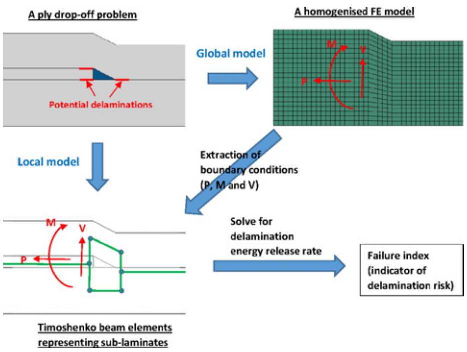
HIGHLIGHTS

- A novel global-local approach is proposed to predict ply-drop delamination in thick tapered composites.
- The ply-drop is represented locally by an assembly of Timoshenko beams with loading obtained from a global FE model.
- The relative accuracy given by the approach can be used to efficiently rank delamination hazards of multiple ply-drops.
- Its applicability to thick tapered composite specimens is demonstrated.

GRAPHICAL ABSTRACT



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ABSTRACT

The prediction of delamination onset is a challenging task in the design of thick tapered composite laminates, where multiple ply terminations ("drop-offs") are present. This paper addresses the development of a global-local finite element-based design approach for tapered laminates, whereby layered Timoshenko beam models are employed to predict delamination initiation from individual drop-offs. This modelling strategy provides a fast and conservative method for evaluating the strength of tapered composite laminates. Parametric test cases are presented in order to validate the methodology and understand its limitations. Finally, the application of the tool to a relatively thick tapered composite test specimen comprising multiple ply-drops is demonstrated.

1. Introduction

1.1. Strength prediction for tapered laminates

The reasons why through-thickness tapering is commonly adopted in lightweight structures are twofold: 1) achieving a predefined geometrical shape (e.g. a given aerofoil shape for a helicopter rotor blade); 2) minimizing structural weight while retaining sufficient stiffness and strength. In composite laminates, tapering always involves shedding thickness via "terminating" (i.e. dropping-off) plies at locations determined by the target geometry. Due to the ensuing geometrical and material discontinuity, ply drop-offs act as interlaminar stress risers, causing the onset and propagation of delamination [1,2]. This represents the primary failure mode of tapered laminates, usually causing a severe strength knockdown

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compared to the nominal load carrying capability of the constituent composite material.

The design of tapered composite laminates is usually based on rules of thumb [3–5], which have been deduced both from experimental testing, strength/buckling optimisation and/or elementary fracture mechanics. These design guidelines involve: 1) having a minimum number of plies (thickness) dropped at any given station; 2) keeping the stagger distance between ply terminations to at least three times the dropped thickness; 3) terminating plies in order, starting from the stiffest (0°) and ending with the most compliant (90°); 4) keeping the laminate symmetric and balanced while plies are dropped, in order to avoid membrane/bending and bending/twisting coupling. However, the rules of thumb summarised above are often conflicting; for example, it is difficult to maintain symmetry and balance while dropping plies in order according to their relative stiffness. Moreover, depending on the specifics of the problem considered (e.g. overall geometry and material employed), some rules of thumb may be more important than others in dictating the final strength. Finally, the design guidelines discussed above do not allow for a strength assessment, even in an approximated fashion.

Therefore, several analytical and numerical techniques for the predicting the strength of tapered laminates have been proposed in the literature. These approaches can be broadly classified in [1]: 1) strength-based [3,6–14]; 2) fracture mechanics-based [15–24]. Strength approaches rely upon calculating the stress distribution at a ply drop-off location and then apply interactive stress criteria (e.g. quadratic) for delamination onset [3,10]. Analytical strength models are primarily based on shear lag approximations [8,10,14], while numerical techniques rely either on displacement-based [6] or hybrid finite element analysis [9]. Owing to the singular nature of tractions at a ply termination, point stresses or average stresses should be considered [6]. Fracture mechanics methods involve estimating the energy release rate (ERR) associated with delamination emanating from a ply drop-off and then employ the Griffith criterion for propagation. This is done either in the context of analytical beam/plate modelling [18,21–23] or via finite element analysis (FEA). The latter can be coupled either with the virtual crack closure technique [15–17,19,24] or cohesive zone modelling [25]. Cohesive zone FEA applied to ply-drop analysis has the advantage of being able to predict both delamination onset and growth, unifying strength and energy-based integrity assessments [25].

1.2. Open challenges

Despite the vast literature devoted to predicting the effect of tapering on composite strength, significant challenges still arise when trying to estimate the load carrying capability of thick laminates comprising multiple ply drop-offs, particularly in the context of preliminary design. This is due to the fact that "high-fidelity" models of tapered components require meshes at sub-millimetric scale (typically one ply thickness as characteristic element dimension), in order to resolve the stress field and the associated ERR at individual ply terminations. An illustrative example of a "high-fidelity" model for a severely tapered composite component [25] is provided in Fig. 1. The model (Fig. 1b) comprises one solid element per ply through the thickness, with zero-thickness cohesive elements on each interface to model delamination onset. The mesh was constructed from scanned images of an actual coupon (Fig. 1a), representing in detail the curvature of individual plies as well as the geometry of the resin pockets associated with individual drop-offs. These features were found to strongly influence the actual strength of tapered laminates [3,6,10,14,15,20,23,25], hence they need to be included in the models for the sake of accuracy. A model as that presented in Fig. 1 requires 1 man-day to be set up and several hours to run on a multi-core high performance computer. Clearly modelling at such level of detail is unfeasible during preliminary design, when multiple design alternatives must be evaluated. This is the primary reason why "global-local" FEA approaches have been proposed in the literature for the analysis of delamination onset/growth at/from ply drop-offs [3,13,26]. A "global-local" FEA strategy may streamline the modelling procedure, but the computational cost of local ply-by-ply high-fidelity models is still prohibitive. Moreover, the actual features associated with individual ply drops (i.e. local ply curvature, resin pocket geometry) are heavily influenced by the manufacturing process and are not known a priori. Predicting the aforementioned features would require modelling of the manufacturing process before any virtual strength testing can be carried out, further aggravating the computational burden. Hence, any predictive method for delamination prediction from ply drop-offs must be robust enough to cope with manufacturing uncertainties and process variability.

1.3. Paper overview

This paper presents a novel global-local FEA framework for the strength assessment of thick composite laminates. The underlying approach is based on considering coarse meshes at the global scale, where the presence of ply drop-offs is not explicitly modelled, homogenised mechanical properties are considered and relatively few elements are employed through the thickness. The global models are linked with local FEA analyses, where individual ply drop-offs are represented as assemblies of shear-deformable Timoshenko beams. The main objective is to provide a computationally cheap method for estimating the strength of tapered laminates. The methodology proposed here is an extension of that presented in Refs. [23,24], which relied on shear-undeformable Euler-Bernoulli beam assemblies. Regarding robustness, the method is formulated considering worst-case scenarios for the geometrical arrangement of each individual ply drop-off, i.e. those that correspond to the largest strength knockdowns. This is done in order to yield a conservative strength prediction. The paper is organised as follows: the beam assembly representing individual ply drops is presented in Section 2, together with the methodology for the estimation of the ERR associated with the delaminations emanated from the ply termination. Section 3 addresses the validation of the simplified modelling methodology for single ply drop-offs, which is carried out via comparing the predicted strength with that obtained from high-fidelity cohesive zone models in Abaqus/Standard. Finally, Section 4 provides two

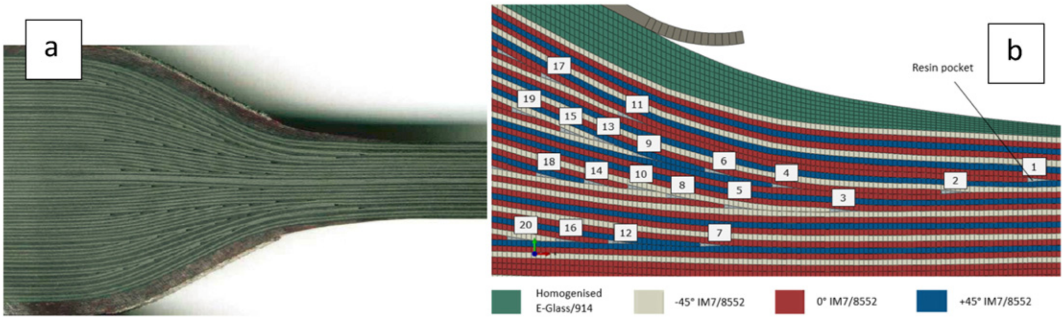

Fig. 1. (a) A severely tapered carbon/epoxy composite laminate, (b) the corresponding high-fidelity FE half-model generated from the scanned image of an actual specimen [25].