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Critical thrust force predictions during drilling: Analytical modeling and X-ray tomography quantification

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ABSTRACT

In the past, several experimental and analytical studies have been conducted aimed towards predicting the critical thrust force responsible for delamination at the hole exit during drilling. Among these analytical models, few take into account the coupling between bending and stretching often observed in multi-directional (MD) laminates with an un-symmetrical stacking sequence considering the presence of an elliptical crack. In addition, in these analytical models, the tool/composite contact region is modeled without taking into account the chisel edge effect. In the present study, a unique analytical model for critical thrust force prediction has been proposed that explicitly accounts for the effect of the chisel and cutting edges. The interaction zone (composite/chisel edge and composite/principal cutting edge) has been modeled using classical lamination plate theory (CLPT) and linear elastic fracture mechanics (LEFM) principles. In addition, a comparison between the proposed analytical model predictions and experimental results from quasi-static punch tests accompanied with different X-ray tomography observations led to choosing the accurate loading profile developed during drilling.

1. Introduction

The use of composite materials for structural applications is increasing in many industries such as aerospace, automotive and sports equipment due to their superior performance compared to traditional metallic materials. Fibre reinforced plastics (FRPs) are the most widely used composites with carbon or glass as reinforcements. After the setup of manufacturing and demoulding of the composite structures, machining operations (trimming and drilling) are required to obtain the necessary shape, dimensions and surface quality [1–4]. However, machining composites with conventional process remains a challenging task due to the inherent anisotropy and heterogeneity of composites resulting in a multitude of damage such as matrix cracking, fibre pull-outs, delamination, thermal degradation etc. [4–6]. Among conventional machining operations, drilling operation is most vital for assembly by bolts or rivets as well as for structural repairs [2–10]. The twist drill used for metallic materials is very commonly used to drill composite structures as well [6–12]. Drilling induced exit-ply delamination has been identified as the most deleterious damage phenomenon for structural components as it results in a significant loss of strength and stiffness of the laminate and, consequently its load carrying capacity [2,7]. For these reasons, several authors have focused on the understanding of the delamination phenomena at the hole exit.

Experimental studies conducted by several research groups concludes that the size of delamination at the hole exit is strongly dependent on the feed rate and the macroscopic geometry of the point angle of the drill of the tool [3,8–13]. Higher feed rates were found to result in higher delamination factors, i.e., the ratio of the maximum hole diameter and the original (intended) hole diameter. Krishnamoorthy et al. [12] characterized the delamination at the hole exit using an infra red camera and observed that the minimum delamination at the hole exit is observed for the twist drills with point angle varying from 100° to 120°. In addition, performance of two different tool materials (PCD tool and WC tool) was compared by measuring the resulting delamination extension by Durão et al. [2]. It was found that, delamination factors measured in specimens drilled with WC tool are smaller than those drilled using PCD tool. Recently, Zitoune et al. [13] studied the influence of double cone drill geometry on the machining quality when drilling carbon/epoxy laminate reinforced by a uniform layer of thermoplastic. It has been shown that the presence of the thermoplastic layer increases the critical energy release rate in

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Nomenclature

A_{ij}	coefficients of the extensional stiffness matrix (N/mm)	G_{lt}	shear modulus (N/mm^2)
a	half the delamination size along the L direction	h	ply thickness (mm)
B_{ij}	coefficients of the extension and bending coupling matrix (N)	K	parameter relating to F
b	half the delamination size along the T direction	q	lateral uniform load (N/mm)
C_i	parameter relating to F	U	strain energy (N mm)
D_{ij}	coefficients of bending stiffness matrix (N mm)	V_f	fibre content (%)
E_{ll}	Young's modulus in the L direction (N/mm^2)	W	external work (N mm)
E_{tt}	Young's modulus in the T direction (N/mm^2)	Z	displacement in the Z direction (mm)
F	global thrust force (N)	α	ratio defining the contribution of the load exerted by the chisel edge
F_1	part of the thrust force applied by the chisel edge (N)	θ	angle of fibre orientation
F_2	part of the thrust force applied by the cutting lips	ξ	ellipticity ratio
G_{Ic}	critical strain energy release rate in mode I (J/mm^2)		

mode I thereby reduces the delamination at the hole exit even at high feed rates (feed rate of 0.3 mm/rev for a diameter of 6.35 mm).

Phenomenologically, drilling induced exit ply delamination occurs when the thrust force pushing the last uncut lamina via the chisel edge causes interlaminar fracture. Onset of exit-ply delamination is said to occur when the thrust force exceeds a critical value also called critical thrust force (CTF). Most modeling efforts have been directed towards calculating this value of CTF. The earliest CTF model was developed by Hocheng and Dharan [14] based on linear elastic fracture mechanics (LEFM) approach by assuming an isotropic plate with a circular self-similar crack under the drill bit. This hypothesis led them to use the classic theory of bending of thin circular plates embedded at the ends and subjected to a concentrated point load to determine the critical force of delamination. Subsequently, they extended the approach for special drill bits such as candle stick drill, saw drill and core drill that are designed to reduce delamination by distributing the thrust force away from the chisel edge onto the periphery of the tool [15–17]. Upadhyay et al. [18] studied the effect of chosen load profile (point load versus distributed load) and deformation (small versus large deformations) of the uncut plies on CTF. More recently, Karimi et al. [19] presented an analytical model to predict critical thrust force and feed rate at the onset of delamination. This model is based on an oblique cutting model while using LEFM and classical plate theory for model derivations. The results of this model showed that a lower critical thrust force is predicted than those proposed by Hocheng et al. [14–17].

Jain and Yang [20] considered a more realistic elliptical plate as delamination zone under the cutting tool indicative of the orthotropic properties applicable for a unidirectional laminate. Zhang et al. [21] looked at exit-ply delamination of CFRPs rigorously by incorporating coupling between bending and stretching components while using classical lamination plate theory (CLPT) for stress analysis of an elliptical anisotropic composite plate subjected to a point load in conjunction with LEFM to predict delamination onset. The ellipticity ratio of the anisotropic thin plate was estimated using an optimization scheme. Gururaja and Ramulu [22] modified the Zhang model [21] to account for a more realistic representation of the contact forces experienced by the uncut composite laminate during drilling by considering uniformly distributed load acting on the elliptical anisotropic plate allowing for bending-extension coupling. More recently, other researchers like [9,15] showed that the use of special drill without the chisel edge like core drill decreases delamination at the hole exit. Therefore, the delamination at the exit of the hole is directly linked to the geometry of the tool and then to the effect of the chisel edge.

2. Exit-ply delamination model

Fig. 1 depicts the drilling induced exit-ply delamination mechanism in FRPs. Delamination onset criterion is defined using LEFM Mode I energy balance equation as follows:

$$dW = dU + G_{Ic}dA \tag{1}$$

where dW is the variation in external work done, dU is the infinitesimal strain energy, dA is the increase in the area of the delamination crack, and G_{Ic} is the Mode I critical strain energy release rate of the laminate. Variations in existing CTF prediction models arise due to varied assumptions in crack geometry, stress analysis procedure and applied loads on the exit ply.

2.1. Zhang model

Zhang et al. [21] assumed an elliptical delamination zone as revealed in drilling experiments (cf. Fig. 2). 'a' and 'b' represent the major (aligned with the fibre direction (L)) and minor (aligned with the transverse direction (T)) axes of the ellipse. A point load (q) acting at the center of the elliptical plate simulated the loading experienced by the uncut plies during drilling. Using the displacement function approach detailed in Bert [23], the CTF predictions were given by:

$$F_z = \sqrt{\frac{\pi G_{Ic}}{\xi(C_3 - K)}} \tag{2}$$

where K is given by:

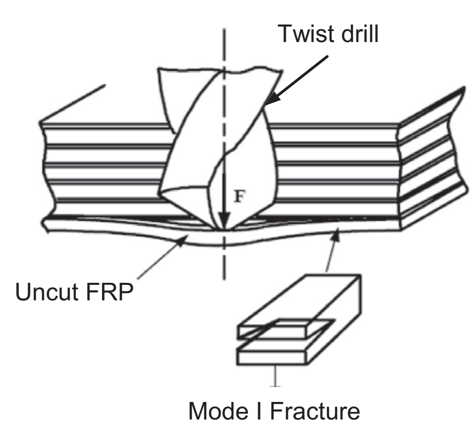

Fig. 1. Schematics of drilling in composite materials [19].