DRILLING INDUCED EXIT-PLY DELAMINATION MODEL CONSIDERING TORQUE

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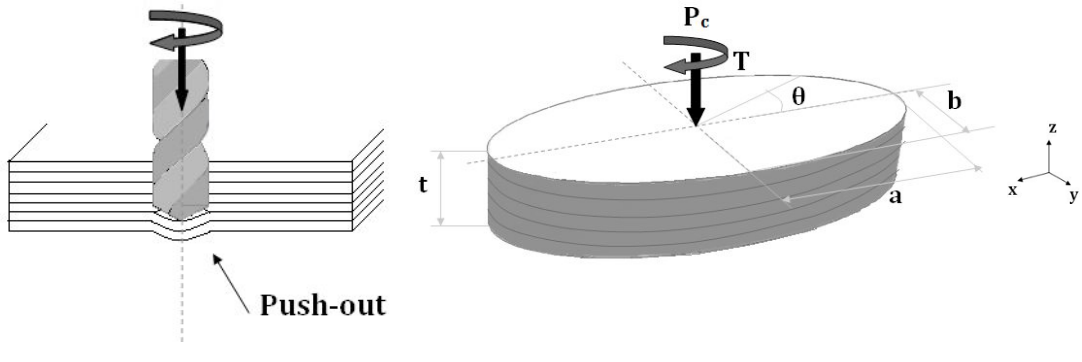
Keywords: MD-FRP laminates, exit ply delamination, drilling torque, LEFM

Abstract
Amongst all the drilling induced damage in laminated multi-directional fiber reinforced plastics (MD FRPs), exit-ply delamination is the most serious one. Exit-ply delamination is mainly caused due to the axial thrust force exerted by the chisel edge of the drill. Several attempts have been made in the past to provide analytical models relating material properties, layups, machining parameters (feed) with the delamination on the exit-side of the drilled hole. In the current work, a modified exit-ply delamination model has been presented using first order shear deformation theory (FSDT) in conjunction with classical lamination plate theory (CLPT) to account for the out-of-plane shear stresses τ_{xz} and τ_{yz} that are generated due to the rotation of the drill bit. The delamination zone is assumed to be an elliptical plate that is clamped on all edges and subjected to thrust force and torque along the axis of the drill. Suitable displacements fields have been assumed and a mixed-mode fracture criterion has been used to estimate the critical thrust force. These results have been verified experimentally. These forces can further be related to the process variables, viz., feed rate and cutting speed.

1. Introduction

With increased usage of FRPs in various industries, cost-effective and efficient methods of industrial production and manufacturing are needed. In the aircraft industry, FRPs are used due to their excellent strength and stiffness properties. Although FRP parts manufactured from molds are almost always in near net shape, various forms of machining including drilling and milling are required to meet the specified dimensions and fastener requirements [1]. In aircraft structures, where precision is of vital importance, an optimal manufacturing procedure that produces little or no damage is necessary. Damage due to drilling such as delamination, microcracking, fiber fracture, fiber pullout, matrix cracking and impact damage need to be quantified. This is done using various Non-Destructive Testing (NDT) techniques. Damage in FRPs has been measured using techniques such as liquid penetration, optical microscopy, ultrasonic C-scan, Scanning Electron Microscope (SEM), X-ray computed microtomography, digital photography, enhanced radiography, Digital Image Correlation (DIC) and Acoustic Emission (AE). Conventional approaches to minimizing defects include the use of fixtures to clamp the component and backing plate. However, these methods do not produce satisfactory results in cases such as, components with blind holes, where one cannot easily accommodate neither a fixture nor a backing plate due to the complexity and inaccessibility of the workpiece. Thus, numerical and analytical models can be used to analyze the complex material behaviour when the workpiece is being machined.



(a) (b)

Figure 1. Exit ply push out delamination due to drilling in FRPs. (a) push-out delamination; and (b) elliptical plate delamination model assumption.

Koenig et al. [1] did an elaborate study on the machining of FRPs and he stated the presence of a critical value of thrust force in the case of drilling, which could be related to the damage area at the exit, below which damage would not occur. With Hocheng and Dharan's seminal contribution to developing a critical thrust force model in 1990 [2] using Linear Elastic Fracture Mechanics (LEFM) approach, two modes of delamination have been identified (a) push out and (b) peel up. As the drill is fed through the laminate the uncut thickness decreases continuously and at a critical point when the thrust force exerted by the drill bit exceeds the interlaminar bond strength delamination occurs. This is referred to as Push out delamination and it occurs at the drill exit. The mechanism of peel-up is similar to that of push out with the difference that it occurs at the drill entrance where the cutting action of the drill bit introduces a peeling force that instigates delamination of the layers close to the top surface of the plate (Figure 1). Exit-ply delamination or push out delamination is more severe than peel up as it causes a reduction in stiffness of the component leading to a drop in the load carrying capacity and thereby a loss of structural integrity.

The Hocheng model [2] assumes the delamination zone under the drill bit to be a homogeneous isotropic circular plate clamped along its edges and the force from the drill's cutting edge as a concentrated point load to predict the force corresponding to delamination onset, i.e., the critical thrust force. However, since FRPs are inhomogeneous and anisotropic, the assumption of a circular delamination zone is not correct. The critical force for delamination from the Hocheng-Dharan model is given by,

$$F_c = \frac{8G_{Ic}Et^3}{3(1-\nu^2)} \tag{1}$$

where G_{Ic} is the critical strain energy release rate, E is the fiber modulus, h is the thickness and ν is the Poisson's ratio of the delaminating lamina.

Jain and Yang [3] proposed an exit ply push-out model to predict critical thrust force and critical feed rate for unidirectional composites where they assumed the delamination area to be elliptical plate clamped on all edges subjected to a concentrated load in the center. It was also assumed that the crack propagated via Mode I in a self-similar fashion with respect to the delamination propagation which made the ellipticity ratio always a constant. From the predicted and experimental force and feed rate values for the last few plies from the bottom they put forth the idea of using a variable feed rate strategy and modified tool geometry in order to avoid delamination. The drawback of this model is that it is applicable only to UD laminates. DiPaolo et al. [4] investigated crack growth phenomena in FRPs during drilling and observed that the delamination zone is rather elliptical and there are two modes of fracture Mode I (due to the distributed load from the chisel edge) and Mode III (due to torque exerted by the drill cutting lips, flutes and spall twisting). Lachaud et al. [5] assumed the force exerted by the drill on a circular delamination zone to be a point load and distributed load and concluded that the distributed load model results were closer to those obtained by experiments. He assumed the plate to be circular, as the delamination would propagate in a circular fashion for a multidirectional stacking sequence, and the portion of the plate in contact with the drill to be symmetric thereby neglecting the bending extension coupling terms.

Hocheng [2], Jain [3] and Lachaud [5] have proposed models that predict the critical thrust force responsible for delamination based on LEFM but these models fail to predict the length of the delamination zone because LEFM predicts that, once the critical strain energy release rate is reached the crack grows indefinitely, but that is not the case as observed from experiments. Zhang et al. [6] has experimentally determined the relation between thrust force and delamination zone size. He has developed a mechanical model for a multidirectional laminate by assuming the fractured zone to be an elliptical plate subjected to a point load at the center and has also employed Classical Laminate Plate theory (CLPT) to solve for the displacements [7] that are further used along with the Linear Elastic Fracture Mechanics criterion to determine the critical thrust force. He optimises the force using the ellipticity ratio parameter. Gururaja et al. [8] has modified this model by replacing the point load with a distributed load that was proven to be a more realistic representation of the drill force and the results obtained had a closer correlation with the experimental results. However, for a MD laminate, it would be more realistic to do a ply-by-ply analysis with the effect of torque included. The effect of torque on the exit-ply drilling induced delamination has hitherto not been accounted for in literature. The current work aims to modify the existing models representing the drilling mechanism and provide a better prediction for the critical thrust force by employing the first order shear deformation theory (FSDT) in conjunction with CLPT. FSDT is used in order to account for the out-of-plane shear stresses τ_{xz} and τ_{yz} that are omitted in CLPT.

2. Exit ply delamination considering torque

In the current work, a modified exit-ply delamination model has been presented using FSDT in conjunction with CLPT to account for the out-of-plane shear stresses τ_{xz} and τ_{yz} that are generated due to the rotation of the drill bit (c.f. Figure 1). The exit-ply delamination model assumes the delamination zone to be an elliptical plate that is clamped on all edges and subjected to a concentrated thrust force and torque along the axis of the drill. The delamination crack is assumed to propagate in a self-similar fashion based on a LEFM based mixed mode criterion that can be applied to relatively brittle composite laminates assuming: (1) propagation of crack is coplanar, (2) crack is oriented along plane of material symmetry, and (3) small plastic zone ahead of the crack. For the current problem, the 2D power law for mixed mode fracture in Mode I and II can be used given by:

$$\left(\frac{G_I}{G_{Ic}}\right)^{\alpha} + \left(\frac{G_{II}}{G_{IIc}}\right)^{\beta} = 1$$

$$\left(\frac{\left(P_c\frac{dw_{0b}}{dA} - \frac{dU_{CLPT}}{dA}\right)}{G_{Ic}}\right)^{\alpha} + \left(\frac{\left(T\frac{d\Theta}{dA} - \frac{dU_{CLPT}}{dA}\right)}{G_{IIc}}\right)^{\beta} = 1$$

$$\left[\frac{\xi}{2\pi a}\frac{1}{G_{Ic}}\left(P_c\frac{dw_{0b}}{da} - \frac{dU_{CLPT}}{da}\right)\right]^{\alpha} + \left[\frac{\xi}{2\pi a}\frac{1}{G_{IIc}}\left(T\frac{d\Theta}{da} - \frac{dU_{CLPT}}{da}\right)\right]^{\beta} = 1 \tag{2}$$

Here, a displacement formulation has been used to get the strain energies under bending and torsion separately. A mixed mode fracture criterion has been used to account for these two mechanisms, bending results in predominantly mode I fracture, while explicit accounting for torsion results in mode II fracture. Suitable displacements fields have been assumed based on [7] as follows:

$$u = \left(1 - \frac{x^2}{a^2} - \frac{\xi^2 y^2}{a^2}\right)\left(u_1\,\frac{x}{a} + u_2\,\frac{y\,\xi}{a} - u_3\left(\theta\,\frac{y\,\xi}{a}\,z\right)\right)$$

$$v = \left(1 - \frac{x^2}{a^2} - \frac{\xi^2 y^2}{a^2}\right)\left(v_2\,\frac{x}{a} + v_1\,\frac{y\,\xi}{a} + v_3\left(\theta\,\frac{x}{a}\,z\right)\right)$$

$$w = w_{0b}\left(1 - \frac{x^2}{a^2} - \frac{\xi^2 y^2}{a^2}\right)^2 + w_{0s}\,\theta\,xy\left(\frac{\xi}{a}\right)\left(1 - \frac{x^2}{a^2} - \frac{\xi^2 y^2}{a^2}\right) \tag{3}$$

Using these displacements, the mixed-mode fracture criterion is used to estimate the critical thrust force (Equation 1). These results have been verified experimentally. These forces can further be related to the process variables, viz., feed rate and cutting speed. Figure 2 depicts a comparison of critical thrust force predictions from torque inclusive model. The model is found to underestimate the critical thrust forces.

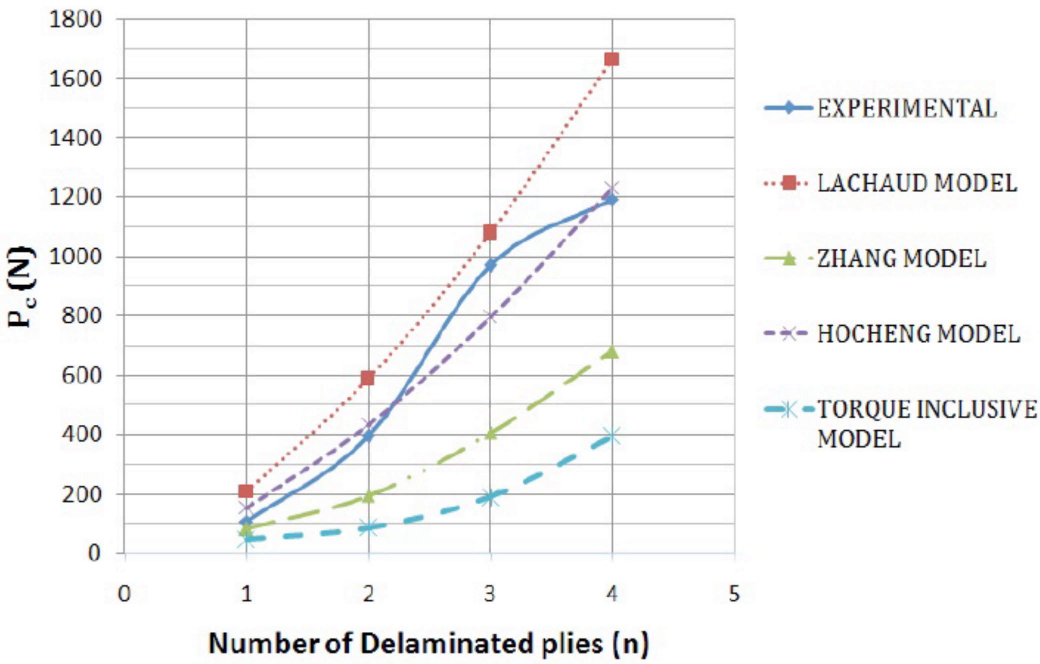


Figure 2. A comparison of the critical thrust force predictions considering torque and other models.

3. Conclusions

In the analytical model presented the force exerted by the drill has been simplified as a point load as 80% of the drill force is contributed by the chisel edge and torque has been included to replicate the rotational force exerted by the cutting lips. The lower value of predicted thrust forces as compared to the experimental results could be attributed to many factors such as:

- the drill force approximation;
- the fracture criterion;
- omission of inertia terms
- omission of effects of temperature and friction.

A distributed load or a combination of a distributed load and a centred point load would represent the drill force better as seen in existing literature. Also, drilling being a very dynamic process would imply that inertia terms would contribute to the thrust force, which has been neglected in the present model.

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