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Thermo-mechanical modelling of FRP cross-ply composite laminates drilling: Delamination damage analysis

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ABSTRACT

Among other factors, thrust force, feed rate, twist drill bit chisel edge and point angle are the principal factors responsible for delamination drilling-induced damage during thermo-mechanical deformation. Hence, in this paper, an analytical thermo-mechanical model is proposed to predict critical feed rate and critical thrust force at the onset of delamination crack on CFRP composite cross-ply laminates, using the principle of linear elastic fracture mechanics (LEFM), classical plate theory, cutting mechanics and energy conservation theory. The delamination zone (crack opening Mode I) is modelled as an elliptical plate. The advantages of this proposed model over the existing models in literature are that the influence of drill geometry (chisel edge and point angle) on push-out delamination are incorporated, and mix loads condition are considered. The forces on chisel edges and cutting lips are modelled as a concentrated (point) and uniformly distributed loads, resulting into a better prediction. The model is validated with models in the literature and the results obtained show the flexibility of the proposed model to imitate the results of existing models.

1. Introduction

Fibre reinforced polymer (FRP) composite laminates possess attractive characteristics like chemical resistance, low weight, design flexibility, high strength and high stiffness-to-weight ratio [1–4]. These properties account for manufacturing of structural parts with FRP composite in the aircraft and spacecraft industries, where drilling of the structural parts is frequently encountered for manufacturing either riveted assemblies or structural repairs [1,5,6]. Due to inherent anisotropy and structural inhomogeneity in the FRP composite laminates [3], drilling operation may cause delamination in the structural parts which in turns lowers the bearing strength and stiffness of the structure [7,8]. This consequently impairs the load bearing capacity of the structure. In this context, exit-ply delamination has been identified as the most critical damage phenomenon for structural components [7,9].

Drilling takes an indispensable role among the principal machining operations which include, but are not limited to, milling, turning and boring [10]. It attracts an average of 50% of the total material removal operations [11,12]. The drilling operation is performed by a cutting tool, commonly known as a drill bit. Drill bit, such as twist drill has a multi-cutting parts with different designed complex geometry [10]. The geometric design of drills determines their efficiency and durability (tool life). Consequently, the total quality of the drilled holes depends on the geometry of the drill used. The geometric parts of drill include the point angle, chisel edge/angle, cutting lip [13–16], helix angle, diameter, and web [10]. The resultant effects of these parts are directly on the drilling variables or parameters. These parameters include, but are not limited to, drilling forces such as thrust force and torque [17], cutting force [18], cutting speed, feed rate [10], material removal rate (MRR) and depth of cut [19–21]. Among these variables, feed rate plays a crucial role in determining the quality of drilled holes of FRP composite laminates. It determines the magnitude of a thrust force during drilling operation; thrust force mainly depends on feed rate and chisel edge [22].

To eliminate the problem of delamination in drilling, calculation of the critical thrust force below which no damage occurs is important. To achieve this, classical plate theory approach is employed and assumption of linear elastic fracture mechanics (LEFM) mode I is invoked to determine the amount of work required to initiate and cause propagation of delamination drilling-induced damage in the composite laminates [5–7,9,23–27]. In an

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attempt to simplify calculation of the critical thrust force, many analytical models in the literature focus more on the mechanics of the FRP composite laminates while ignoring the role of drill characteristics such as drill point geometry (drill diameter, rake angle, chisel edge angle), cutting mechanism, chip formation and cutting parameters such as feed rate, among others. In addition, the effect of machining temperature which may influence drilling damage is usually not accounted for. Properties of laminate composites are usually affected by high temperature [28,45] and since drilling operation is associated with thermo-mechanical deformation, a theoretical model which accounts for critical thrust force with thermal effect is desirable.

Several studies on the effect of machining parameters on force and torque prediction have been presented [29–33] and investigation based on numerical modelling has been also detailed [34–36]. Specifically, theoretical analysis based on hypothesis of orthogonal cut described by Langella et al. [36] reveals that the total force responsible for drilling is composed of contributions from the cutting lips and chisel edge, as illustrated in Fig. 1. This important observation assists in reconciling the disparity between concentrated and distributed load critical thrust force models in the literature [5–7] as the total thrust force can now be adequately represented by the sum of the applied force on the cutting lips and chisel edge respectively as reported by Karimi et al. [23]. Investigation shows in the work of Langella et al. [36] and Won and Dharan [37] that the thrust force due to chisel edge contribution constitutes about 60–80% at high feed rate and 40% at low feed rate, an observation which underscores the significance of the choice of feed rate in determining the critical thrust force to avoid delamination. Furthermore, from recent works in the literature, it is concluded that numerical studies on the influence of the geometric parts of drills on FRP composites drilling as the key determinants of occurrence of delamination during thermo-mechanical deformation of FRP composite laminates when subjected to drilling operation have received less attention [10,38–42].

To improve the understanding of the influence of machining parameters on delamination drilling-induced damage and in line with the realities mentioned above, based on the work of Gururaja and Ramulu [7] and Jain and Yang [22], a new thermo-mechanical formulation for the prediction of minimum critical thrust force and feed rate for analysis of delamination in composite laminates is proposed. The current formulation accounts for the total thrust force by part contributions from the cutting lips and chisel edge of the drill using the principle of superposition.

The proposed model allows to analyse the effect of drill point angle on the critical values of the thrust force and feed rate. To determine the relationship between the feed rate and the thrust force, the general form of the model in Langella et al. [36] is employed.

2. Model formulation

According to classical laminate theory, stress in the laminate k, as depicted in Fig. 2 may be calculated using the relation:

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} \underline{Q}_{11} & \underline{Q}_{12} & \underline{Q}_{16} \\ \underline{Q}_{12} & \underline{Q}_{22} & \underline{Q}_{26} \\ \underline{Q}_{16} & \underline{Q}_{26} & \underline{Q}_{66} \end{bmatrix} \left\{ \begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} + z \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} - \begin{Bmatrix} \alpha_x \\ \alpha_y \\ 2\alpha_{xy} \end{Bmatrix} \theta(z) \right\}, \tag{1}$$

where $\underline{Q}_{ij}$ $(i, j = 1,\ 2,\ 6)$ are the elements of the transformed stiffness matrix and $\theta(z)$ is the temperature variation along the thickness. $\varepsilon_i^0 (i = x, y)$, γ_{xy}^0 and $k_i\,(i{=}x, y, xy)$ are the mid-plane strains and the curvatures of the ply which can be expressed as:

$$\begin{Bmatrix} \varepsilon_x^0 \\ \varepsilon_y^0 \\ \gamma_{xy}^0 \end{Bmatrix} = \begin{Bmatrix} \dfrac{\partial u^0(x,y)}{\partial x} \\ \dfrac{\partial v^0(x,y)}{\partial x} \\ \dfrac{\partial u^0(x,y)}{\partial y} + \dfrac{\partial v^0(x,y)}{\partial x} \end{Bmatrix}, \quad \begin{Bmatrix} k_x \\ k_y \\ k_{xy} \end{Bmatrix} = \begin{Bmatrix} -\dfrac{\partial^2 w}{\partial x^2} \\ -\dfrac{\partial^2 w}{\partial y^2} \\ -2\dfrac{\partial^2 w}{\partial x \partial y} \end{Bmatrix}. \tag{2}$$

Here, u^0, v^0 and w are, respectively, the mid-plane displacements in the x and y directions and the deflection of the laminate ply. The resultant moments, according to classical Kirchhoff's assumption neglecting the mid-plane strains ε_x^0 , ε_y^0 and γ_{xy}^0 are expressed as:

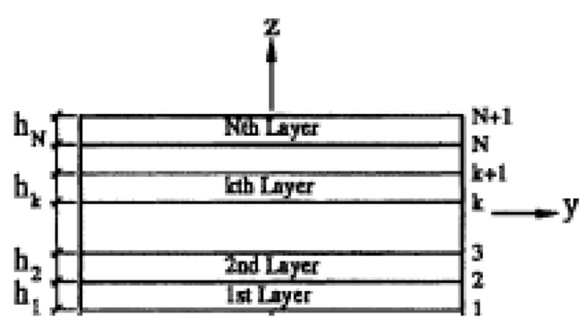

Fig. 2. Laminate geometry.

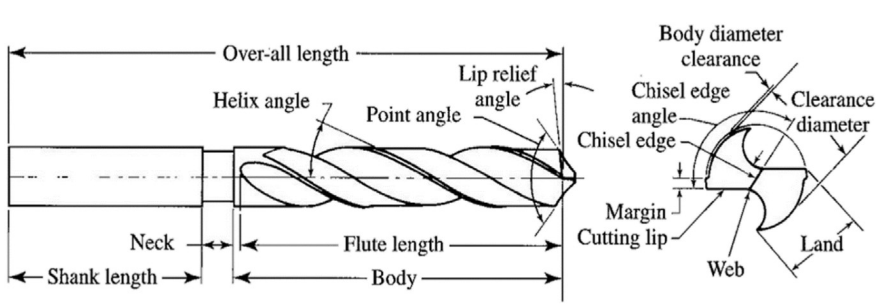

Fig. 1. A typical geometry of a double-fluted twist drill bit [10].