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A new analytical critical thrust force model for delamination analysis of laminated composites during drilling operation

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A B S T R A C T

Fibre reinforced polymer (FRP) composite laminates are employed in many industrial applications due to their attractive mechanical and structural properties. Machining operation, such as drilling of FRP laminates, plays a significant role in the assembly of parts in aircraft and spacecraft production. Among other production bottlenecks, drilling-induced delamination remains a major defect which adversely affects the quality of assembly parts. An efficient strategy in preventing this problem is the calculation of the critical thrust force above which delamination is initiated. Therefore, in this study, a new analytical model is proposed to predict the critical thrust force for delamination. Unlike the general models in the literature which derived only mode I strain energy release rate based on the assumption of classical laminate plate theory (CLPT) combined with linear elastic fracture mechanics (LEFM) mode I considerations in the elliptic delamination zone, the proposed analytical model is derived based on first-order shear deformation theory (FSDT) and accounts for mode I and mode II strain energy release rates in the delamination zone. This strategy allows to activate mixed mode criteria for delamination initiation which is a valid assumption for laminates with layers of different orientations. The present model is partly derived for general laminates subject to distributed loading and further extended to cross-ply laminate sequence subject to a mixed load condition. The results show that the effect of shear deformation in the prediction of the critical thrust force is influential with increasing ply thickness and the effect of chisel edge on shear deformation is more profound in the distributed load regime.

1. Introduction

Fibre reinforced polymer (FRP) composite laminates possess attractive characteristics like low weight, high strength and high stiffness-to-weight ratio [1,2]. These properties account for manufacturing of structural parts with FRP composites in the aircraft and spacecraft industries, where drilling of the structural parts is frequently encountered for manufacturing either riveted assemblies or structural repairs [3,4]. Due to inherent anisotropy and structural inhomogeneity in the FRP composite laminates [1], drilling operation may cause delamination in the structural parts which in turn reduces the bearing strength and stiffness of the structure [5,6]. This consequently impairs the load bearing capacity of the structure.

Drilling is an indispensable production process among several material removal operations such as milling, turning and boring [7]. It attracts an average of 50% of the total material removal operations [8,9]. Drill bit, such as twist drill, has multi-cutting parts with different designed complex geometries [7]. 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 [10–13], helix angle, diameter, and web [7]. These parts significantly influence drilling parameters and responses (thrust force, torque, cutting speed, feed rate, cutting force, material removal rate (MRR) and depth of cut), and also the quality of the drilled parts [14–18]. The feed rate plays a crucial role in determining the quality of drilled holes of FRP composite laminates as it determines the magnitude of the thrust force during drilling operation; thrust force mainly depends on feed rate and chisel edge [19,62].

Calculation of the critical force during drilling of FRP composites is an important strategy to prevent delamination of the drilled parts and to improve the quality of drilled products [63]. Analysis of multi-layered structures are generally developed by using the

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plate/shell theories for composites and by making an appropriate choice of 2D representation of the structure, type of formulation (stress-based or displacement-based) and variable description (Equivalent Single Layer Models or Layer-Wise Models) [20,21].

The Classical Laminate Plate Theory (CLPT) approach which is a 3-parameter shell theory with classical displacement formulation and an equivalent single layer description combined with assumption of linear elastic fracture mechanics (LEFM) mode I has been employed to analyse the laminate structure during drilling operation to determine the amount of work required to initiate and cause propagation of delamination drilling-induced damage in the composite laminates [3–5,22–27]. Classical laminate plate theory provides reasonable results for thin laminates as it ignores the effect of out-of-plane shear deformation. Consequently, CLPT underestimates deflection and overestimates buckling load of moderately thin or thick laminates in which shear deformation is significant [28–30]. In addition, relative displacements between layers of the composite laminates which influences delamination process [31–33] are not taken into account in CLPT since the interfaces between the layers are considered as perfectly bonded. Delamination are typically analysed by considering the interfacial interactions between different layers of the laminate which is often accomplished by cohesive zone (CZM) description of the interface between the laminates [34,35]. The basic idea of the cohesive zone modelling of interfaces involves derivation of traction-separation law which describes the in-plane and out-of-plane tractions at the interface of the laminates together with appropriate shell theory to evaluate the onset and propagation of delamination [36–38].

To address the shortcomings of CLPT, Reissner and Mindlin [39,40] proposed the first-order shear deformation theory (FSDT) in which shear deformation is accounted for by linear variation of the in-plane displacement through the thickness and introduce a shear correction factor to provide a balance between the assumed constant stress state and the actual stress state [41,42]. FSDT is a 5-parameter theory which belongs to the category of axiomatic approaches with displacement formulation and equivalent single layer description [20,21]. To reduce the number of unknowns required to perform stress analysis of plates in the traditional FSDT, Thai and Choi [43,44] proposed a modified FSDT which uses four unknowns by partitioning the transverse displacement into bending and shear components and expressing the rotational degree of freedoms as functions of the partitioned transverse displacement. Thus, reducing the unknowns and governing equations for the plates. Similar partitioning strategy has been employed for higher-order shear theory in Ref. [63].

Many analytical models in the literature focus primarily 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 the feed rate, among others [64]. Several studies on the effect of machining parameters on force and torque prediction [16,45–49] and investigations based on numerical modelling detailed in Refs. [50–52] reveal that the total force responsible for drilling is composed of contributions from the cutting lips and the chisel edge, as illustrated in Fig. 1. Consequently, this important observation assists in reconciling the disparity between concentrated and distributed load critical thrust force models in the literature [3–5] 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 in Ref. [22]. In this regard, a new critical force model which accounts for the effects of the point angle was recently proposed in Ref. [53].

Exit-ply delamination is considered the most critical damage phenomenon affecting structural components under the influence of drilling [5,23]. However, peel-up delamination which is associated with the geometry of the drill may occur by sliding of the plies up the flute of the drill due to unfavourable cutting conditions resulting in insufficient cutting of the fibre (see Fig. 2) [54]. It was pointed out that this type of defect constitutes 6% of the total damage of the drilling process and 27% for oval holes resulting in poor quality of drilled holes and increased manufacturing cost [55]. This phenomenon leads to the distribution of the energy release rates into different failure modes arising from different orientation of the plies around the cracked region leading to oscillatory stress and displacement around the crack tip. In this regard, analysis of critical thrust force based on mixed mode delamination is essential [54]. In addition, Silversides et al. [60] reported that delamination damage involves combination of mode I, II and III (Fig. 2), and that the inter-laminar failure energies are functions of the ratio of mode I/mode II loading. The onset or initiation and growth of delamination caused by bending cracks are dominated by mode I fracture toughness, while mode II and III fractures principally determined the growth and propagation of the entrenched delamination caused by transverse loading. Hence, fundamentally, mode II loading from inter-laminar fracture characterisation is required to precisely predict the delamination damage on materials.

In this paper, a new analytical model for critical thrust force during drilling operation is proposed based on modified FSDT described in Ref. [44] accounting for shear deformation during the drilling process by partitioning of the transverse displacement into bending and shear parts. A solution satisfying the elliptic crack configuration is proposed here for the transverse shear displacement based on which mode II strain energy release rate is derived and computed. To the knowledge of the authors, this is the first analytical thrust force model derived based on FSDT. The new model is partly derived to update the modified exit-ply model proposed by Guraja et al. [5] for general laminates based on CLPT and distributed load assumptions and consequently, an extended derivation is provided for the model proposed by Ismail et al. [45] based on CLPT and mixed load assumptions for cross-ply laminates.

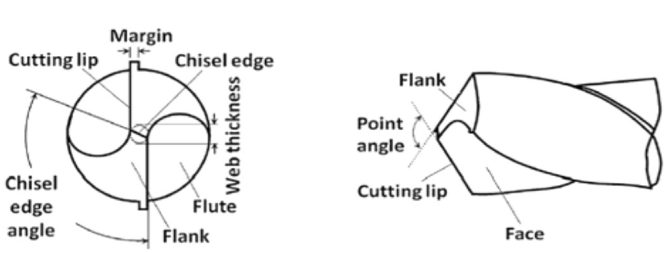

Fig. 1. A twist drill bit showing its tip and geometry [7].

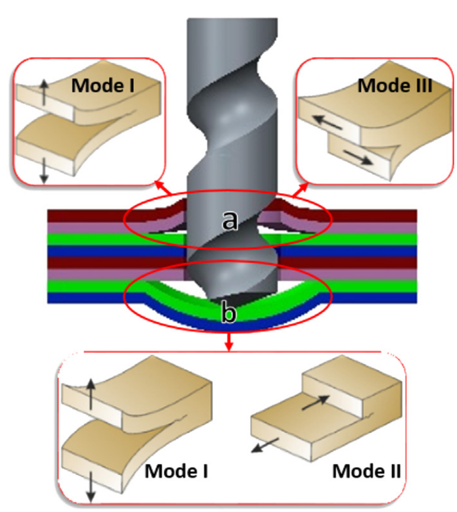

Fig. 2. Delamination phenomena depicting different modes during (a) peel-up and (b) push-out type.