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Numerical investigation of the effects of drill geometry on drilling induced delamination of carbon fiber reinforced composites

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ABSTRACT

Drilling is a major process in the manufacturing of holes required for the assemblies of composite laminates in aerospace industry. Simulation of drilling process is an effective method in optimizing the drill geometry and process parameters in order to improve hole quality and to reduce the drill wear. In this research we have developed three-dimensional (3D) FE model for drilling CFRP. A 3D progressive intra-laminar failure model based on the Hashin's theory is considered. Also an inter-laminar delamination model which includes the onset and growth of delamination by using cohesive contact zone is developed. The developed model with inclusion of the improved delamination model and real drill geometry is used to make comparison between the step drill of different stage ratio and twist drill. Thrust force, torque and work piece stress distributions are estimated to decrease by the use of step drill with high stage ratio. The model indicates that delamination and other workpiece defects could be controlled by selection of suitable step drill geometry. Hence the 3D model could be used as a design tool for drill geometry for minimization of delamination in CFRP drilling.

1. Introduction

The potential of composite materials was first realized by aerospace and defense industries. During the past decades, demand for the composite materials has increased in a variety of industries including aerospace, automobile, marine, civil, chemical and biological equipments, and sports. Owing to the versatile features and sophisticated characteristics of constituents, composites contribute to superior final properties in different applications. Particularly fiber reinforced composite laminates have become one of the most interesting groups of materials, due to their unique properties such as high specific strength, high specific stiffness, low thermal expansion, good corrosion resistance and low weight.

Typical examples of extensive application of composite laminates can be seen in the latest models of Boeing and Airbus airplanes [1]. Approximately 30% of external surface area of Boeing 767 consists of composite laminates [2] whereas the amounts of composite laminates used in both Boeing 787 Dream-liner and Airbus A350 are over 50% of the whole weight [3,4].

Although composite components are produced to near-net shape, machining is often needed to fulfill tolerance requirements for the assembly needs. Among machining processes, drilling is one of the most frequently used to make holes for assemblies of different parts with screws, rivets and bolts [5]. To ensure high strength and load capacity in the assemblies, damaged-free and precise holes must be obtained.

Some characteristics of composite laminates such as non-homogeneity, anisotropy, highly abrasive and hard reinforced fibers, and coexistence of hard abrasive fibers with soft matrix, make composites components difficult to machine [6,7]. The most frequent drilling induced defects are delamination, fiber pull-out, inter-laminar cracking or thermal damages in addition to other minor damages [8,9]. These damages can affect not only the load carrying capacity of laminated parts but also strength and stiffness, fatigue life and long term performance of the composite structure, thus reliability [10,11]. Rapid tool wear can be a significant factor on the extent of damage due to the very abrasive fibers [12]. Moreover, it increases the number of tool changes which affects the production cycle and the final cost.

Among the problems caused by drilling, delamination is considered the major damage in the drilling of fiber reinforced plastic composites. Delamination affects the structural integrity and long-term reliability of the composite components severely. It was reported that delamination induced hole quality problems causes approximately 60% of all part rejections in aircraft industry [13,14]. Therefore, delamination causes significant loss since drilling is often a final machining operation during assembly of laminated composite components.

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A few studies showed that delamination is closely related to the thrust force in drilling of composite materials [15–18]. The thrust force during drilling of composite laminates depend on input variables such as cutting speed or spindle speed, feed rate, drill bit geometry, number of drilled holes (tool wear), and the environment conditions.

The effect of tool geometry on drilling and delamination has been studied by several researchers. It was reported that the extent of delamination increased with increase of point angle of twist drill bit in drilling of woven CFRP [19,20] whereas a contrary tendency was reported in drilling of UD GFRP. Special drill bits, including straight flute drill bit [21–24], step drill bit [3,25–29], core drill bit [17,28,30,31], step-core drill bit [32], saw drill [17], candlestick drill [17], multifaceted drills [33] and split drill [34] have been also studied by a number of researchers. These studies are performed with the objective of reducing defects and damages by choosing the optimum drill geometry. The capabilities of the special drill bits compared to twist drill bit is to provide higher drilling feed rates without delamination by better distributed load and lower thrust force. The contributions of chisel edge to the thrust force for twist drill is reported to be in the range of 40–60% of the total thrust force [31]. The use of smaller chisel edge has been recommended for minimization of delamination due to lower thrust force [17,21,35,36].

Effects of pilot hole and back-up plates have been also analyzed [21,28,35–42]. Results showed that the use of a backup plate caused an increase in the critical thrust force whereas pilot hole eliminated the chisel edge effect, thus both allowed drilling at higher feed rates without delamination.

Few investigators have studied delamination numerically and analytically. The critical thrust force was first studied analytically by Hocheng and Dharan [43]. Linear elastic fracture mechanics (LEFM) method was employed and the critical thrust force which relates to the onset of delamination of composite laminates was calculated. Jain and Yang developed a realistic model for the onset of delamination by taking into account of the feed rate [31,44]. Drilling of composite materials has been simulated as 2D and 3D orthogonal cutting using finite element analysis. This is due to the complexity of machining process, stress and delamination analysis of laminated composites [45,46].

Several recent research have studied the delamination process induced during drilling CFRP and suggestions has been made in reduction of the damage level by optimization of drilling process parameters [47–50].

FE stress and failure analyses have been conducted using maximum stress and Tsai–Hill criteria owing to the limited capabilities of computer processors and FE tools. Latest advances in computational processors and improved FE formulations have allowed the development of complicated and more realistic 3D models to be solved with improved computational efficiency. In recent years, numerical predictions of delamination and critical thrust force have been performed in drilling of laminated composites [51–53]. The onset of delamination is modeled by virtual crack extension (VCE) method [46–51] and cohesive zone elements (CZEs) [52,53]. The latter approach of CZE overcomes some of the difficulties of the former methods of VCE. For example a pre-defined crack front is not required in CZE. These elements use a failure criterion that combines aspects of strength based analysis to predict the onset of the softening process, and a fracture mechanics based approach to predict the growth of delamination which is governed by the inter-laminar through-thickness stress components. However these studies suffer from some significant drawbacks such as lack of a progressive damage model for intra-laminar and inter-laminar properties. Moreover, the complex geometry of drill bit and machining process parameters such as feed rate and cutting speed have not been taken into account. In our more recent work, the influence of cutting parameters have been studied in a meso scale FE modeling by using a real 3D twist drill bit in the drilling of CFRP with continuum shell elements and CZE approach [54]. Whilst this model showed considerable improvement compared to the past simulation work in the area of drilling of CFC, still the use of shell elements imposed some unreal assumptions. Considering that the drilling process is a fully three dimensional process with the load being imposed in the third direction application of the shell elements and the associated inter-laminar and intra-laminar damage models could be far from the real process.

Optimization of the FE model, choice of element type and size and mesh refinement and also comparison of the results of the 2D and 3D models are discussed in another work which is currently under review. We have reported in detail significant improvement in the drilling of CFRP by using 3-D solid elements and 3-D integrated progressive damage models.

In the current research we use the optimized FE model to examine the effects of the geometry of drill bit in drilling CFRP. We investigate the performance of the step drill with different step ratio and make a comparison with twist drill. The effects of step drill on thrust force, torque, work piece stress, delamination onset and growth are considered and results are compared. It should be noted that despite rather large number of experimental study on drilling CFC, there is currently lack of any 3D simulation work of the drilling process with consideration of the real drill geometry and the prediction of induced delamination. Also in the experimental research area there is no indication of any study of the effect of stage ratio of step drill in drilling CFC. Therefore the current work presenting a full simulation tool to investigate these geometrical effects is novel and unique in its methodology and also results reported.

2. Numerical procedures

2.1. Stress model

Orthotropic material properties were assigned to each unidirectional composite lamina according to the fiber orientation by using a pre-defined local coordinate system. Linear elastic material behavior was assumed prior to any damage for each element and it can be calculated as below.

$$[\sigma_{11}] = [C][\varepsilon] \tag{1}$$

The mechanical properties of the UD plies are given in Table 1 [58,59].

2.2. Progressive failure model (intra-laminar failure)

The intra-laminar damage initiation criteria for fiber reinforced plastic composites in 3D case are based on Hashin's theory [55]. The initiation behavior was assumed to be orthotropic. The initiation criteria consider four different damage initiation mechanisms namely fiber tension, fiber compression, matrix tension, and matrix compression as expressed by Eqs. (2)–(5), respectively.

$$if\ \sigma_{11} > 0 \quad F_f^T = \left(\frac{\sigma_{11}}{\sigma_{11}^{f,T}}\right)^2 + \alpha\left(\frac{\tau_{12}}{\tau_{12}^f}\right)^2 + \beta\left(\frac{\tau_{13}}{\tau_{13}^f}\right)^2 \tag{2}$$

$$if\ \sigma_{11} \leqslant 0 \quad F_f^C = \left(\frac{\sigma_{11}}{\sigma_{11}^{f,C}}\right)^2 \tag{3}$$

$$if\ (\sigma_{22} + \sigma_{33}) > 0$$