Finite element analysis of drilling in carbon fiber reinforced polymer composites

V. A. Phadnis\textsuperscript{1}, A. Roy, V. V. Silberschmidt
Wolfson school of Mechanical and manufacturing Engineering
Loughborough University, Epinal way, LE11 3TU, UK

E-mail: V.A. Phadnis @lboro.ac.uk

Abstract. Carbon fiber reinforced polymer composite (CFRP) laminates are attractive for many applications in the aerospace industry especially as aircraft structural components due to their superior properties. Usually drilling is an important final machining process for components made of composite laminates. In drilling of CFRP, it is an imperative task to determine the maximum critical thrust forces that trigger inter-laminar and intra-laminar damage modes owing to highly anisotropic fibrous media; and negotiate integrity of composite structures. In this paper, a 3D finite element (FE) model of drilling in CFRP composite laminate is developed, which accurately takes into account the dynamic characteristics involved in the process along with the accurate geometrical considerations. A user defined material model is developed to account for accurate though thickness response of composite laminates. The average critical thrust forces and torques obtained using FE analysis, for a set of machining parameters are found to be in good agreement with the experimental results from literature.

1. Introduction

Driven by the advances in manufacturing technologies, carbon fiber reinforced plastic (CFRP) composites have gained widespread use as structural components in aerospace, naval, automotive and defence industries \[1\]. Drilling processes are extensively used to produce riveted and bolted joints for assembly operation of composite laminates with other components. For rivets and bolted joints, damage-free and precise holes must be drilled in the components to ensure high joint strength and precision. However, inherent characteristics of composite laminates such as non-homogeneous, anisotropic, and highly abrasive and hard reinforced fibres, result in difficulties during machining of composites\[1, 2\]. Several undesirable damages (such as delamination, and fiber pull-out) induced by drilling drastically reduce strength against fatigue, thus degrading the long-term performance of composite laminates \[3\].

To increase drilling efficiency of composite laminates with the least damage, it is essential to understand the effect of machining on CFRP. Several experimental studies have been carried out in the past \[4-7\]. Several analytical models \[8-10\] have also been developed to determine the critical thrust force and torque during drilling of composites, however these empirical formulae were solely based on
the geometric configuration of tool-workpiece system, and do not account for the thick composite laminates and general process conditions.

Finite element (FE) models of complex machining processes can provide insight into the underlying mechanics of material behaviour especially at high strain and strain-rate regimes. An accurate and reliable FE simulation of drilling enables good predictions of strain and stress distributions; cutting forces and torque; and discrete damage modes in composites by taking into account the complex drill geometry and process parameters. With the advent of high power computing facilities, simulation of the drilling process using FE analysis provides an excellent tool for this challenging problem in applied mechanics.

In this study, a 3D finite element (FE) model of drilling in carbon fibre reinforced plastic composite (CFRP) - Al 2024 stack is developed. A user defined material model has been incorporated in general purpose FE solver ABAQUS/Explicit to accurately capture the through-thickness response of composite stack. Material anisotropy in CFRP has been modelled by taking into account discrete ply orientations with the help of local material co-ordinate systems. The model is primarily used to investigate the effects of cutting speed and feed rate on thrust force and torque in drilling of CFRP.

2. Finite element analysis of drilling in CFRP laminate

2.1. Methodology

A 3D Lagrangian finite-element (FE) model of drilling of CFRP composite was developed in a commercially available FE software ABAQUS/Explicit. The model accurately characterises the dynamic characteristics of the drilling process accounting for the complex contact interaction between a drill bit and CFRP laminate surface. A stress based failure criteria [18-19] were incorporated in user-defined material model for CFRP composite, to facilitate element deletion of mesh elements which have undergone severe deformations.

The FE model was used to study the effect of a set of machining parameters involving drill spindle speed and feeds on the average critical thrust force and torque during drilling. The details of this FE model are discussed in the following sections.

2.1.1. Geometry and meshing

A CFRP composite laminate with stack sequence of [(90/-45/0/45)2s] was used in the FE analysis. A laminated CFRP plate with overall dimensions of 20 mm × 15 mm × 4.2 mm was modelled with an individual ply thickness of 0.26 mm. A plain carbide K-20 drill (118° point angle and 30° helix angle) of diameter Ø8 mm was modelled as a discrete rigid body in order to reduce the computational efforts required to discretise the complex drill geometry. A lumped mass and rotary inertia was applied at a reference point located at the chisel edge of the drill bit, in order to model the kinematics of the drill bit accurately. The corresponding FE setup is shown in figure 1.

The mesh used in this FE analysis was optimised through an extensive mesh convergence exercise. An optimum balance was achieved between mesh discretisation of highly complex drill geometry and stress distribution in CFRP laminate surface, for accurate prediction of thrust force and torque during drilling for the available computing resources. A refined mesh with a minimum size of 10 µm was used at and in the immediate vicinity of the workpiece volume to be drilled, while a coarse mesh was used to discretize the volume away from the process zone. The CFRP laminate was modelled using 8 node, 3D brick elements of type C3D8R with at least 3 elements in the z direction to accurately capture through-thickness stresses; while a twist drill was modelled with 4-node, 3D discrete rigid elements of type C3D4. The CFRP model consists of 1,021,000 elements while the drill was meshed with 15,000 elements, with the smallest element size of 150 µm. The reference point of drill was assigned with a single node mass and rotary inertia element, where axial velocity and rotations were applied.
2.1.2. **Boundary conditions and contact interactions**

The drilling feed and spindle rotations were applied at a reference point using velocity boundary conditions in order to account for dynamic characteristics of drilling process. A reference point at the drill tip was constrained in X and Y directions while axial velocity corresponding to the imposed feed rate was applied in the Z direction. The drill was also made to rotate about Z axis while rotational degrees of freedom about X and Y directions were constrained. The laminated work piece is fixed at all four vertical faces. The combination of cutting parameters used in FE analysis, to study drilling induced thrust force and torque, is listed in table 1.

![Diagram showing FE model of drilling CFRP composite laminate](image)

**Figure 1.** Setup showing FE model of drilling CFRP composite laminate

| Table 1. Process parameters used in FE modelling of drilling [11] |
|---------------------------------------------------------------|
| **Drill** | K20 carbide , Ø 8 mm, point angle 118° |
| **Spindle speed (rpm)** | 1050, 2020, 2750 |
| **Feed (mm/rev)** | 0.05, 0.1, 0.15 |

In order to account for frictional effects during the drilling process, a Coulomb friction model is deemed appropriate and a coefficient of friction of 0.3[12] was used in the model. A general contact algorithm in ABAQUS/Explicit [13] was employed to model penalty friction based interaction between drill and workpiece. The drill was modelled as an element based master surface while CFRP workpiece was modelled as an element based slave surface. The FE model required on an average, 54 hours on a 24 Intel Quad-core processors with 48 GB RAM to complete. All simulations were performed at the High Performance Computing (HPC) facility available at Loughborough University.

2.1.3. **Material modelling**

The composite laminate was modelled as an orthotropic homogeneous material. The composite used in experimental study was Hexcel UD epoxy/carbon fiber laminate T700/M21 with 58% fiber content. The elastic properties of T700/M21 (Table 2) were obtained from the literature [11]. The fracture properties of similar composite were also taken from literature[14] to model composite failure. The material removal was controlled by using two distinct criteria which accounts for failure in fibres and
matrix with the use of two distinct failure models. First, to account for fibre failure, Hashin’s damage model is implemented [15]. Element is removed from the mesh when damage parameter $d$ (which equals $d_{ft}$ or $d_{fc}$ in tension and compression respectively, here $d_{ft}$ and $d_{fc}$ refers to empirical parameter accounting for fibre damage in tension and compression respectively which varies from 0 to 1, where 0 - no damage, 1 - full damage) reaches 1 based on the corresponding failure strength in that direction, and it offers no subsequent resistance to the deformation. To account for failure in the brittle epoxy matrix, Puck’s fracture plane model [18] was implemented. Similar stress based technique was applied to delete damaged elements. In this case, elements were removed when $d_{mt}$ or $d_{mc} = 1$ (here $d_{mt}$ and $d_{mc}$ refers to empirical parameter accounting for matrix damage in tension and compression respectively which varies from 0 to 1, where 0 - no damage, 1 - full damage). K-20 Carbide twist drill was modelled as an elastic rigid material. Al- grade 2024 material was modelled using classical Johnson-cook model; the details of the material properties were taken from material data base available from [19].

3. Drilling experiments and results

Drilling experiments were conducted on a CFRP/Al stack with 16 layers of T700/M21 with a thickness of 4.2 mm and a 3mm thick aluminium sheet of Grade 2024. The layup sequence of the CFRP is described in Section 2.1.1. Details of the drilling experiments are available elsewhere [11]. The FE model was used to simulate drilling in CFRP/Al stack. The results obtained from numerical experiments and FE model of the drilling process at a feed rate of 0.1 mm/rev and a spindle speed of 1050 rpm are shown in Fig 4. Discrete drilling regimes can be observed for CFRP and Al-2024 with different peak thrust and torque magnitudes. The computational results correspond closely with the experimental results.

The primary focus of this paper is to study drilling induced thrust force and torque in CFRP. Hence effect of drilling process parameters on thrust force and torque in drilling Al-2024 has not been discussed. The validated FE model was used to predict the effect of drilling feed rate and spindle speed on the thrust force and torque (section 4.2) for a range of drilling parameters (Table 1). The results were compared against experimental results as shown in figure 5 and 6.

![Figure 4. Thrust force analysis using FE modelling (feed 0.1 mm/rev, spindle speed = 1050 rpm)](image-url)
The overall results indicate that, thrust force decreases with the increase in spindle speed (Fig 5(a)). The thrust force was observed to highest at the cutting speed of 26.4 m/min (1050 rpm spindle speed), while the minimum cutting speed was observed at 69.1 m/min cutting speed (2750 rpm spindle speed). The results obtained from FE simulation showed that average thrust force (Fig 5(b)) decreases from 20% to 25% when cutting speed was increased from 48% to 62%, while average thrust force increases from 29% to 40% when drill feed was increased form 50% to 67%. It was also noted that the percentage thrust force reduction was maximum for the combination of lowest feed and highest cutting speed, which was also observed in experimental results.

Figure 6(a) shows experimental analysis of drilling induced torque. The results indicate that drilling torque increases with an increase in feed rate. The results obtained from FE analysis (Fig 6(b)) revealed that torque was the highest at a feed rate of 0.15mm/rev and a spindle speed of 1050 rpm. The FE analysis also showed that, torque increases from 16% to 33% when feed was increased from 50% to 67%, while it decreases from 20% to 31% when cutting speed was increased form 48% to 62%.

Thus it is recommended to use low feed and high speed for drilling of CFRP composite material in order to reduce the thrust forces.
4. Conclusion

A finite element model of drilling in CFRP composite has been developed. The effects of cutting speed and feed rate on the thrust force and torque was studied using numerical simulations. The FE model was validated using experimental results for a combination of drill feed and cutting speed; which was later used to predict thrust force and torque for varying process parameters. Our studies demonstrate the importance of feed rate and spindle speed with respect to the average drilling forces. We conclude that both thrust force and torque may be reduced by using a combination of low drill feed rate and high cutting speeds/spindle speed, while drilling CFRP composite materials.

5. References

[1] Abrão A M, Faria P E, Rubio J C C, Reis P and Davim J P 2007 Drilling of fiber reinforced plastics: A review Journal of Materials Processing Technology 186 1-7
[2] Teti R 2002 Machining of Composite Materials CIRP Annals - Manufacturing Technology 51 611-34
[3] Mishra R, Malik J, Singh I and Davim J P 2010 Neural network approach for estimating the residual tensile strength after drilling in uni-directional glass fiber reinforced plastic laminates Materials &amp; Design 31 2790-5
[4] Khashaba U A, El-Sonbaty I A, Selmy A I and Megahed A A 2010 Machinability analysis in drilling woven GFR/epoxy composites: Part I – Effect of machining parameters Composites Part A: Applied Science and Manufacturing 41 391-400
[5] Tsao C C and Chiu Y C 2011 Evaluation of drilling parameters on thrust force in drilling carbon fiber reinforced plastic (CFRP) composite laminates using compound core-special drills International Journal of Machine Tools and Manufacture 51 740-4
[6] Karnik S R, Gaitonde V N, Rubio J C, Correia A E, Abrão A M and Davim J P 2008 Delamination analysis in high speed drilling of carbon fiber reinforced plastics (CFRP) using artificial neural network model Materials &amp; Design 29 1768-76
[7] Lazar M-B and Xirouchakis P 2011 Experimental analysis of drilling fiber reinforced composites International Journal of Machine Tools and Manufacture 51 937-46
[8] Tsao C C and Hocheng H 2008 Evaluation of thrust force and surface roughness in drilling composite material using Taguchi analysis and neural network Journal of Materials Processing Technology 203 342-8
[9] Durão L M P, de Moura M F S F and Marques A T 2008 Numerical prediction of delamination onset in carbon/epoxy composites drilling Engineering Fracture Mechanics 75 2767-78
[10] Strenkowski J S, Hsieh C C and Shih A J 2004 An analytical finite element technique for predicting thrust force and torque in drilling International Journal of Machine Tools and Manufacture 44 1413-21
[11] Zitoune R, Krishnaraj V and Collombet F 2010 Study of drilling of composite material and aluminium stack Composite Structures 92 1246-55
[12] Klinkova O, Rech J, Drapier S and Berghreau J-M 2011 Characterization of friction properties at the workmaterial/cutting tool interface during the machining of randomly structured carbon fibers reinforced polymer with carbide tools under dry conditions Tribology International 44 2050-8
[13] 2010 Abaqus User’s manual, version 6.11 RI: Hibbitt, Karlsson & Sorensen Inc.)
[14] Irisarri F-X, Bassir D H, Carrere N and Maire J-F 2009 Multiobjective stacking sequence optimization for laminated composite structures Composites Science and Technology 69 983-90
[15] Hashin Z 1980 Failure Criteria for Unidirectional Fiber Composites Journal of Applied Mechanics 47 329-34
[19] Johnson, G. R., and W. H. Cook 1985 Fracture Characteristics of Three Metals Subjected to Various Strains, Strain Rates Temperatures and Pressures *Engineering Fracture Mechanics* **21**, 31–48

[20] ASM Aerospace Specification Metals, Inc., Florida, US