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Experimental and numerical investigations in conventional and ultrasonically assisted drilling of CFRP laminate

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Abstract

Carbon fiber-reinforced plastic (CFRP) composites are attractive for many industrial applications due to their superior properties. The parts made from CFRP are usually manufactured to a near-net shape; however, various machining processes, such as drilling, are often required to facilitate component assemblies. Conventional Drilling (CD) of CFRP induces high stresses in the vicinity of the drilled hole; along with high thrust forces on a drilling tool. An advanced drilling technique known as Ultrasonically Assisted Drilling (UAD) has been used to demonstrate its several advantages over CD including a reduced thrust force. A 3D finite element (FE) models simulating CD and UAD techniques for drilling in CFRP laminates were developed using the general-purpose FE software ABAQUS/Explicit. The numerical results obtained with the FE model were found to be in a good agreement with the experimental data.

Keywords: Conventional drilling; Ultrasonically assisted drilling; Carbon-fiber-reinforced plastic composite; Thrust force and torque ; Finite element modelling

1. Background

Advanced composite materials are being widely used in structural and load-bearing applications, due to their high strength and low density. In aerospace and aeronautical structures, often, conventional metal parts are being replaced with ones made of carbon fiber-reinforced plastics (CFRPs).

Generally, parts made of CFRPs are produced to near-net shape, though additional machining operations are often required for component assembly. One of the most common machining operations used in the aerospace industry is drilling – to generate holes for rivets and bolts to allow assembly of intricate parts. It is estimated that 250 million twist drills per annum are consumed in the US aerospace industry alone [1]. According to Faraz [2], in Airbus A350 aircraft, about 55,000 holes are drilled to assemble numerous parts made of composite material. Thus, machining of composites is an important aspect of manufacturing technology. It has been demonstrated that machining of CFRP materials differ significantly in many aspects from that of metallic materials. The primary reasons for this difference are the anisotropy and heterogeneity of CFRPs as well as the effect of highly abrasive carbon fibers; which accelerates tool wear [3, 5].

Conventional drilling (CD) in CFRP gives rise to various damage phenomena such as transverse matrix cracking, fiber-matrix debonding, fiber breakage/rupture and interply delamination [6, 8]. Delamination is a commonly observed interlaminar damage phenomenon in CFRP composites arising due to separation of the adjacent laminae; reducing overall stiffness and load-bearing capacity of the structure. Several researchers [3, 5, 7] explained the causes and mechanisms of composite damage. It was widely reported that manufacturing-induced delamination is related to machining parameters such as thrust force, feed rate and speed of cutting. The thrust force was regarded as the most critical factor in this respect, and its critical value, below which the delamination is considered to be negligible, was defined [6, 8]. Thus, a need for a less invasive drilling technique

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capable to mitigate damage in drilling CFRP components is recognized.

A novel drilling technique, known as ‘Ultrasonically Assisted Drilling’ (UAD) has gained a lot of interest in the last few years [16]. The working principle of UAD involves superposition of high-frequency vibration, typically in the range of 20 kHz, generated by exciting piezo-electric ceramic rings, on a twist drill bit along the feed direction during drilling [10, 11]. Fundamentally, UAD is a completely different process form CD. In UAD, the tool-workpiece interaction is intermittent with significantly higher deformation rates; whereas in CD, cutting is continuous. UAD was shown to be beneficial for drilling holes in brittle materials and has many documented advantages when compared to CD, e.g. reduction in thrust forces, improved surface finish, better hole quality, lower tool wear and elimination of burrs [12, 13].

This work compares CD and UAD techniques in drilling of CFRP composite laminate M21/T700. It employs a 3D finite element (FE) model of drilling in CFRP laminate developed in FE software ABAQUS 6.10.

2. Experiments

2.1. Material Specification

The studied CFRP laminate consisted of 34 plies through its thickness with a stacking order $[(0/45/90/-45)_{4s}/0]_{2s}$ as shown in Figure 1.

The overall dimensions of the CFRP laminate used in our drilling experiments were 100 mm × 25 mm × 15 mm. The experiments to determine the mechanical properties of M21/T700 CFRP laminate were conducted at the Materials Testing Laboratory, Loughborough University, UK.

The mechanical properties of a unidirectional 0° ply (i.e. all fibers are oriented in the primary loading direction) are listed in Table 1. These mechanical properties were found comparable with those reported by Hallett et al. [9]

Table 1. Mechanical properties of M21/T700 unidirectional CFRP laminate

E_{11} [GPa]	$E_{22} = E_{33}$ [GPa]	$\nu_{12} = \nu_{13}$	$G_{12} = G_{13}$ [GPa]	G_{23} [GPa]
115	14	0.29	4	3.2

2.2. Experimental Setup

A universal lathe machine was modified to accommodate an ultrasonic drilling fixture with the flexibility of switching between conventional and ultrasonic drilling regimes. The experimental setup mainly consisted of a piezoelectric transducer mounted in the lathe chuck and a drill bit attached to the transducer as shown in Figure 2.

A two-channel Kistler™ dynamometer was mounted on an angle plate fixed on the carriage of the lathe. The work-piece was clamped on the dynamometer. The thrust force data was recorded using Picoscope™ and later post-processed with Matlab. The average values of thrust forces were recorded for the period of complete engagement of the drill with the work-piece.

In UAD, ultrasonic waves with a constant resonant frequency of 32.2 kHz and vibration amplitude of 20 µm were superimposed on the drill tip. Both CD and UAD experiments were repeated three times for each set of drilling parameters to ensure consistency in results using the same drill bit. For all the experiments conducted, HSS DORMER ADX jobber carbide twist drill of Ø 6 mm was used.

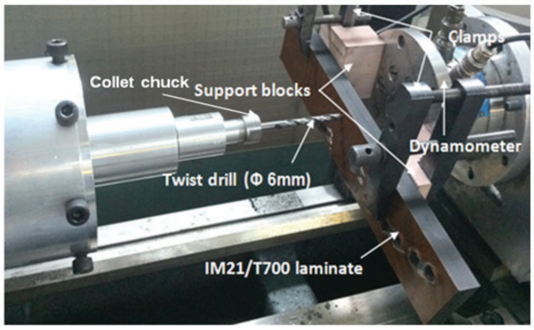

Figure 2. Experimental setup for drilling of CFRP laminate

Figure 1. Microstructure of M21/T700 composite laminate

The experimental process parameters used in CD and UAD trials are listed in Table 2.

Table 2.Experimental parameters for drilling CFRP laminate

Parameter	Magnitude
Rotational speed [rpm]	260, 540, 800, 1200, 1700
Feed rate [mm/min]	50
Vibration frequency [kHz]	30
Vibration amplitude [µm] *(peak to peak, without tool - material contact)*	20

2.3. Result

2.3.1. Thrust forces

The thrust forces were measured to investigate the effectiveness of UAD in relation to CD. Table 3 lists the thrust forces for process parameters of Table 2.

Table 3 Thrust forces in CD and UAD

Speed [rpm]	Force [N] CD	Force [N] UAD	Average force reduction [%]
260	272 ±11	229±9	15.8
540	138±12	117±11	15.2
800	125±10	96±8	23.2
1200	121±9	88±10	27.3
1700	119±8	82±13	31.1

For all the experimental trials, the feed rate was kept constant at 50 mm/min.

With increasing rotational speed, the thrust force in CD was observed to decrease, as expected. Interestingly, the relative force decrease in UAD was noticeably higher, which is demonstrated by the increasing force reduction as shown in Table 3.

Thus, higher rotational speeds are recommended in drilling CFRP when using the UAD technique.

3. Finite element analysis of drilling in CFRP

3.1. Finite Element Model

A solid, continuum FE model of drilling in CFRP laminate (Figure 3) based on the Lagrangian formulation [18], was developed.

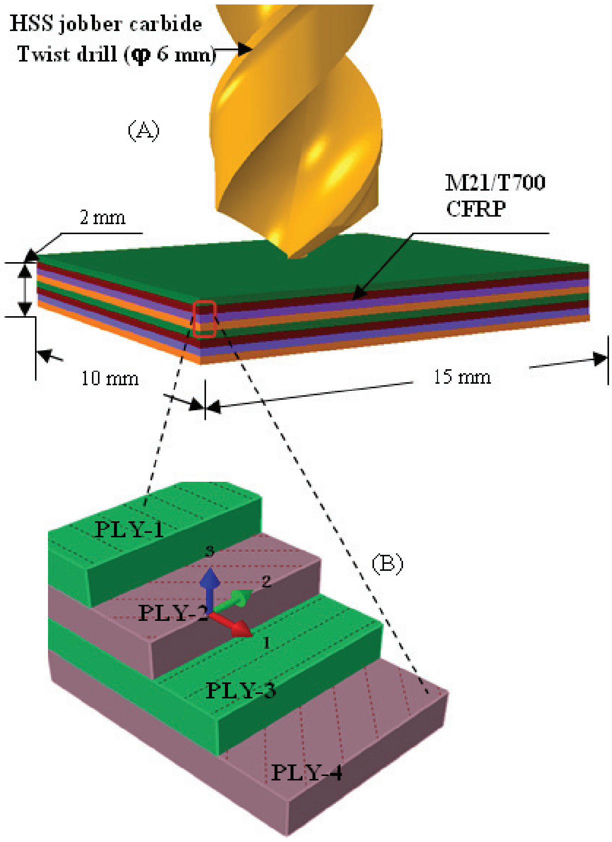

Figure 3. (A) Finite element model for simulating drilling process. (B) Details of stacking order in M21/T700 unidirectional CFRP laminate (first four layers)

The FE model consists of eight layers of the CFRP laminate. A commercial finite element software ABAQUS/Explicit is used for simulations. The inertia effect was accounted for due to the dynamic nature of the drilling process. The developed FE model aims to simulate both CD and UAD techniques qualitatively; comparing drilling-induced thrust forces and stress distribution in the work-piece during the process. Details of the FE model are discussed below.

3.1.1. Geometry, mesh and elements

In order to account for complexity of the problem and available computing resources, only 8 first plies of CFRP are modelled by adequately capturing the position, at which full drill engagement was obtained during experiments to calculate the thrust forces.

A 3D geometry of 6 mm twist drill with a point angle of 140° and helix angle of 31° was modelled in ABAQUS. The drill was modelled as a rigid body; the inertia effect was accounted for. Figure 3 shows the FE model of drilling process.

The mesh was optimized to reduce computational cost without compromising accuracy. The mesh size of the work piece was refined in the immediate vicinity of the drilled area to capture high stress gradients during the drilling process. An element deletion technique was used to model material removal during drilling. Elements in the refined cylindrical zone were removed when failure criterion was met in the simulation. The CFRP laminate was modelled using 8 noded, 3D brick elements of type C3D8R, while the drill was modelled with 4- noded, 3D discrete rigid elements of type C3D4. The CFRP model consists of 200,000 elements with the smallest element size of 10 μm. The drill was meshed with 15000 elements, with the smallest element size of 150 μm.

3.1.2. Drill-work piece contact

The contact and friction parameters used in the simulations were based on a number of experimental factors such as cutting speed, feed rate, geometry and surface properties. Kinematic contact conditions were assumed between the drill and composite laminate with a constant coefficient of friction of 0.3 [4]. The geometric boundary conditions, mesh sizes and element types for individual parts were kept constant while modelling both the CD and UAD techniques. Both models require on average 62 hours on a 24 Intel Quad-core processors with 48 GB RAM each to finish the analysis using High Performance Computing (HPC) facility available at Loughborough University.

3.1.3. Boundary condition and loading

Conventional drilling (CD)

The CFRP laminate was fixed at all four vertical edge faces, while the drill was constrained to rotate only about its own axis with a specified speed and fed vertically downwards into the work piece with a feed rate of 50 mm/min. In order to investigate the effect of rotational speed on drilling, the FE analysis was performed for combinations of five rotational speeds (refer Table 2) and a constant feed rate to model experimental process parameters.

Ultrasonically assisted drilling (UAD)

In UAD, ultrasonic vibrations are superimposed at the drill tip. In order to incorporate this boundary condition, a time-dependent sinusoidal movement representing an ultrasonic wave is imposed on the drill tool in the axial direction. Each wave consists of 30,000 periodic sampling points for one second of simulated period of drilling with peak-to-peak amplitude of 20 μm and ultrasonic frequency of 30 kHz (Table 2). The drill is thus vibrated along the vertical direction as well as rotated about its own axis independently.

3.1.4. Constitutive material model

The matrix and fibers are modelled as 3D homogenized orthotropic plies, where ply properties in principal fiber direction are obtained with in-house experiments. The plies are constructed with appropriate orientations in order to represent actual CFRP stacking order, as discussed in Section 2. The Hashin's failure criteria [14], used to model initiation and evolution of damage in long-fiber composites available in ABAQUS [18] for plain-stress elements, was appropriately modified for implementation in 3D solid elements [14]. This allows for a better representation of the through-thickness stress variation in the plies. In order to model matrix damage, the Puck's failure criterion [15] was implemented. The progressive-damage model for fiber and matrix was implemented in ABAQUS/Explicit using a user-defined subroutine (VUMAT).

In the FE model of drilling in CFRP laminate employing element deletion mechanism [17], a material point is assumed to fail during deformation when either of the damage variables associated with fiber failure modes (tensile or compressive) reaches maximum damage $d_{\max}$. This element is removed from the mesh when this condition is satisfied at all of the section points at any one integration location of an element. Further to that, when an element is removed, it offers no further resistance to subsequent deformation.

The corresponding damage variables at all section point of a CFRP laminate are calculated using the following equations.

$$If\left(\frac{\sigma_{11}}{S^{11}}\right)^2+\left(\frac{\sigma_{12}}{S^{12}}\right)^2+\left(\frac{\sigma_{13}}{S^{13}}\right)^2=1, d_{ft}=1 \ldots (1)$$

$$If\left(\frac{\sigma_{11}}{X_{1c}}\right)^2=1, d_{fc}=1 \ldots\ldots (2)$$

$$If\left[\left(\frac{\sigma_{11}}{2X_{1t}}\right)^2+\frac{\sigma_{22}^2}{|X_{2T}.X_{2C}|}+\left(\frac{\sigma_{12}}{S_{12}}\right)^2\right]+\sigma_{22}\left(\frac{1}{X_{2T}}+\frac{1}{X_{2C}}\right)=1, and$$

$$\sigma_{22}+\sigma_{33}>0, d_{mt}=1$$

$$\sigma_{22}+\sigma_{33}<0, d_{mc}=1 \ldots\ldots (3)$$

Here σ_{11}, σ_{12}, σ_{13}, σ_{22} are the components of stress tensor at an integration point of an element. d_{ft}, d_f, d_{mt} and d_{mc} are the damage variables associated with failure modes in fiber tension, fiber compression, matrix tension and matrix compression, respectively. $\boldsymbol{X}^{T}$, $\boldsymbol{Y}^{T}$, $\boldsymbol{Y}^{C}$ and $\boldsymbol{S}^{L}$ represent longitudinal tensile strength, transverse tensile strength, transverse compressive strength and longitudinal shear strength, respectively; while $\boldsymbol{G}_{ft,c}$, $\boldsymbol{G}_{fc,c}$, $\boldsymbol{G}_{mt,c}$ and $\boldsymbol{G}_{mc,c}$ are tensile fiber fracture energy , compressive fiber fracture energy, tensile matrix fracture energy and compressive matrix fracture energy, respectively. The corresponding Hashin's damage parameters used in FE modelling are listed in Table 4

Table 4. Hashin's damage parameters [9,16]

X^T [MPa]	Y^T [MPa]	Y^C [MPa]	S^L [MPa]
2000	1200	150	50
$G_{ft,c}$ [N/mm]	$G_{fc,c}$ [N/mm]	$G_{mt,c}$ [N/mm]	$G_{mc,c}$ [N/mm]
12.5	12.5	1	1

3.2. Numerical Results

Thrust forces

The results showing the calculated thrust forces for both CD and UAD techniques generated by drilling in CFRP obtained from the FE simulations are shown in Table 5.

Table 5.Simulation results for thrust force results for CD and UAD with FE analysis

Cutting speed [rpm]	Thrust Force [N]		Force reduction [%]
	CD	UAD	
260	301	265	11.96
540	187	161	13.90
800	165	131	20.60
1200	144	109	24.30
1400	137	98	28.46

The thrust force magnitude shows a qualitative match with the experiments, primarily due to the reduced number of CFRP layers modelled. The relative force reduction shows an excellent co-relation with the experimental results, demonstrating potential capabilities of our models to predict features of the studied drilling techniques.

4. Conclusions

A comparative study of drilling in a CFRP laminate was presented for both conventional and ultrasonically assisted drilling techniques. The effectiveness of UAD when compared to CD was demonstrated in terms of reduction in the average thrust force.

The average thrust force reduction was observed to be as high as 30% under certain drilling conditions.

The drilling process was simulated using a general-purpose finite element software ABAQUS/explicit. The model was shown to replicate the drilling process effectively.

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