Structural Engineering and Mechanics, *Vol. 73, No. 6 (2020) 631-640*
DOI: https://doi.org/10.12989/sem.2020.73.6.631

Critical thrust force and feed rate determination in drilling of GFRP laminate with backup plate

Hossein Heidary*[1], Mohammad A. Mehrpouya[2a], Hamed Saghafi[1,3a] and Giangiacomo Minak[4a]

[1]*Department of Mechanical Engineering, Tafresh University, First of Tehran road, Tafresh 3951879611, Iran*
[2]*Department of Mathematics, Tafresh University, First of Tehran road, Tafresh 3951879611, Iran*
[3]*New Technologies Research Center (NTRC), Amirkabir University of Technology, Tehran, 1591633311, Iran*
[4]*Department of Industrial Engineering (DIN), Alma Mater Studiorum, Università di Bologna, 24 Via Terracini, Bologna 40136, Italy*

(Received July 11, 2018, Revised October 21, 2019, Accepted November 12, 2019)

Abstract. Using backup plate is one of the most commonly used methods to decrease drilling-induced delamination of composite laminates. It has been shown that, the size of the delamination zone is related to the vertical element of cutting force named as thrust force. Also, direct control of thrust force is not a routine task, because, it depends on both drilling parameters and mechanical properties of the composite laminate. In this research, critical feed rate and thrust force are predicted analytically for delamination initiation in drilling of composite laminates with backup plate. Three common theories, linear elastic fracture mechanics, classical laminated plate and mechanics of oblique cutting, are used to model the problem. Based on the proposed analytical model, the effect of drill radius, chisel edge size, and backup plate size on the critical thrust force and feed rate are investigated. Experimental tests were carried out to prove analytical model.

Keywords: composite laminates; backup plate; analytical modelling; delamination; drilling

1. Introduction

Conventional drilling of composite materials using twist drills is by far the most frequently used methods in industries to produce accurate and high quality holes (Prabukarthi 2016). Although, various forms of damage can be produced in drilling of composite laminates, it has been shown that, delamination is the most serious one (Mohammadzadeh 2018). Delamination, reduces the strength and stiffness and thus limits the life of the structure (Davim *et al.* 2007, Marques *et al.* 2009, Liu *et al.* 2012, Zarif Karimi *et al.* 2012). Delamination, occurs during drilling of composite laminates by two distinct mechanisms: peeling up of the top layer and pushing out in the bottom layer(Do Kyun Kim 2018). Practically, it has been found that, the delamination related with push-out is more critical than that related with peel-up. There are several hypotheses regarding the formation of delamination at the exit side (Guenfoud 2018, Hwang 2018). However, most of them believe that delamination is the result of excess of stress induced by the cutting force applied to uncut laminate on the inter-ply bonding strength (Bhattacharyya and Horrigan 1998, Capello 2004, Heidary *et al.* 2014, Zarif Karimi *et al.* 2015).

There are several methods of decreasing delamination in drilling of composite materials. Use of a sacrificial plate, use of the support plate, use of the pre-drilled pilot hole,variable feed-rate strategy, and use of special drill bits are the main approaches to reduce delamination (Jain and Yang 1993, 1994, Persson *et al.* 1997, Mathew *et al.* 1999, Sardiñas *et al.* 2006). Some of these methods are very complicated and not feasible in practice. However, using the support plate is simple and practical. In contrary, using backup has some disadvantages such as increasing the machining time and needing to access to both sides of the plate. It should be mentioned that although preparing the backup setup consume time, by increasing the feed rate can compensate this wasting time. By applying backup plate can achieve to higher feed rate and lower delamination simultaneously. In order to reduce delamination, the thrust force must be controlled. Analytical analysis of composite drilling to determine the critical thrust force is therefore of great interest (Hocheng and Tsao 2003, 2005, 2006, Tsao 2006, 2007, Ojo *et al.* 2017).

Hocheng and Dharan proposed the first analytical model (Hocheng and Dharan 1990). They used linear elastic fracture mechanics (LEFM) and classical laminated plate theory (CLPT) to achieve an analytical model to investigate the critical thrust force at the delamination initiation in drilling of composite materials. This model determined a critical thrust force in terms of drilled hole depth and composite properties. This model was developed by Jain and Yang, assuming the material anisotropy and elliptical crack (Jain and Yang 1993, 1994). In their model, a concentrated central load is considered as the drilling thrust force. Hocheng and Tsao (Hocheng and Tsao 2003, 2006, Tsao 2012), extended this model, by taking a series of loading conditions into considerations. Thus, circular load, concentrated centered load associated with circular load, distributed circular load and stepwise distributed circular load were used for different drill types, such as saw drill,

*Corresponding author, Ph.D.
E-mail: heidary@tafreshu.ac.ir
[a]Ph.D.

http://www.techno-press.com/journals/sem&subpage=7
ISSN: 1225-4568 (Print), 1598-6217 (Online)

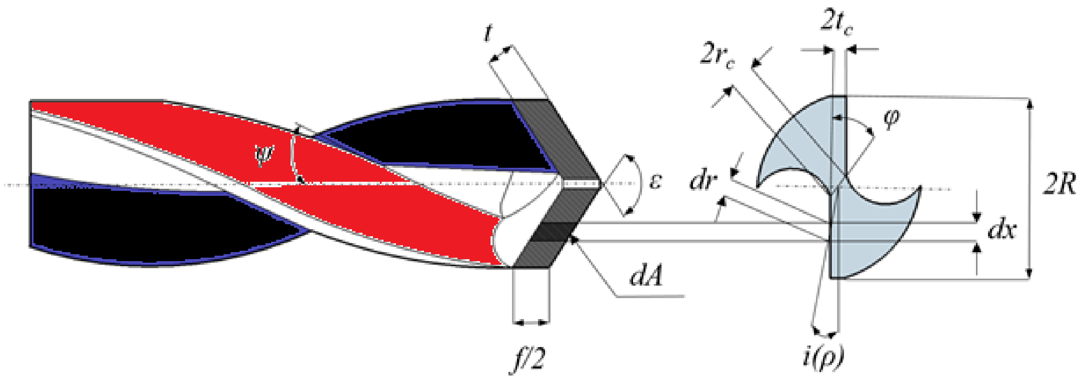

Fig. 1 Twist drill geometry parameters (Zarif Karimi *et al.* 2016)

candle stick drill, core drill and step drill, respectively.

In addition, there are few studies regarding determination of critical thrust force during drilling of composite laminate with backup plate (Hocheng and Tsao 2005, Tsao and Hocheng 2005, Tsao *et al.* 2012). In (Hocheng and Tsao 2005, Tsao and Hocheng 2005), Hocheng and Tsao used an analytical approach to determine critical thrust force in drilling of composite laminates by saw and core drill with backup plate. In a similar study, Tsao *et al.*, determined critical thrust force with an active backup plate (Tsao *et al.* 2012).

It should be noted that, controlling the thrust force directly is not possible, because, it greatly depends on the drilling parameters. Feed rate is the most important parameter which controls the thrust force directly. Therefore, some researchers have concentrated on the correlation of feed rate and thrust force by linear regression analysis (El-Sonbaty *et al.* 2004, Fernandes and Cook 2006, Tsao and Hocheng 2007, Singh *et al.* 2008, Tsao 2008, Khashaba *et al.* 2010, Khashaba *et al.* 2010, Campos Rubio *et al.* 2013). Unfortunately, this approach is not applicable, if the drilling condition changes. Various cutting force models for drilling composite materials are thus established analytically using orthogonal and oblique cutting models (Chandrasekharan *et al.* 1995, Langella *et al.* 2005).

The most important of them is presented by Langella *et al.* (2005). They applied the orthogonal cutting model proposed by Caprino *et al.* (Caprino 1996) as a basis, by observing that in a drilling process, the prerequisites for orthogonal cutting are met for an infinitesimal instant.

In this paper, critical thrust force is determined at the delamination initiation in drilling of composite laminates with backup plate based on the model developed by Hocheng and Dharan (Hocheng 1990). In this model, the anisotropy of the material and two simplified loading models are considered. In addition, the oblique cutting model proposed by Langella is used to determine critical feed rate, which is a controllable parameter (Langella *et al.* 2005).

2. Assumptions

1. Mode-I is assumed to be dominant failure mode, since other modes require higher energy for activating (DiPaolo 1996, Hocheng and Tsao 2006).

2. The considered plate is circular and single layer orthotropic with clamped edge.

3. The exerted forces by the cutting lips and chisel edge are simplified in two various types, i.e., concentrated central load and distributed uniformly in their corresponding regions.

4. It is considered the backup force is applied to the laminate in the form of peripheral distribution.

3. Drilling cutting model

In the previous study (Zarif Karimi *et al.* 2016), thrust force was determined based on the oblique cutting model. To start the analysis, twist drill geometry parameters are shown in Fig. 1.

Thrust force divided into two sections, i.e., chisel edge and cutting lips force. Cutting lips force is determined as:

$$T_L = 2B \times 10^{-1.089\gamma_m}(f/2)^{0.5}G \tag{1}$$

where, γ_m, f, and G, are average values of the rake angle, feed rate and geometrical parameter, respectively.

Furthermore, B is an unknown parameter which is considered as follows:

$$B \times 10^{-1.089\gamma_m} = K_n \tag{2}$$

where, K_n, is the specific energy for the vertical force, which can be determined by means of a single test as described in (Langella, Nele *et al.* 2005). In Eq. (1), γ_m, is defined as below:

$$\gamma_m = \frac{\displaystyle\int_\tau^1 \left(\tan^{-1}\left(\frac{\rho\tan\psi}{\sin(\varepsilon/2)}\right) + \tan^{-1}\left(\frac{f}{2\pi\rho R}\right)\right) d\rho}{\int_\tau^1 d\rho} \tag{3}$$

where, ε, ψ, ρ, ($\rho=r/R$) and R, are drill point angle, helix angle, normalized radius and drill radius, respectively. Moreover, τ is the limit of the integration that is defined as:

$$\tau = \frac{r_c}{R} = \frac{t_c/\sin\phi}{R} \tag{4}$$

where, r_c, t_c and ϕ are the chisel edge radius, the half thickness of the chisel edge and chisel edge angle, respectively. Also, the geometrical parameter, G, in Eq. (1)

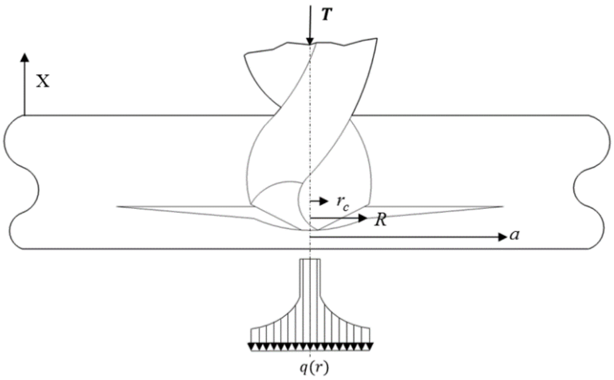

Fig. 2 Force and physical model of delamination in drilling of composite laminates

is defined by:

$$G = \int_{\tau}^{1} \left(1 - \frac{t_c^2 \sin^2(\varepsilon/2)}{2\rho^2 R}\right) R \sin(\varepsilon/2) d\rho = \frac{\sin(\varepsilon/2)\left(1 - \frac{r_c}{R}\right)(2r_c R - t_c^2 \sin(\varepsilon/2))}{2r_c}. \tag{5}$$

The resultant thrust force exerted on the chisel edge is shown as:

$$T_C = 2C \times 10^{-1.089\gamma_c} f^{0.5} t_c \tag{6}$$

where, γ_c, is the chisel edge rake angle considered to be constant and obtained as follows:

$$\gamma_c = -\tan^{-1}(\tan(\varepsilon/2)\cos\phi) \tag{7}$$

In order to determine an unknown constant, C, the specific energy at the chisel edge, $K_{n,chisel}$, is used as:

$$C \times 10^{-1.089\gamma_c} = K_{n,chisel} \tag{8}$$

The specific energies should be derived by a single drilling test. In this method, a drilling sample with a pilot hole is made. The diameter of the pilot hole is equal to the chisel edge diameter and its depth is equal to the half thickness of the specimen. This sample is drilled and the experimental thrust forces in each section are measured. The values of the specific energies are derived as follows:

$$K_n = \frac{T_{\exp}}{2(f/2)^{0.5} G}, \quad K_{n,chisel} = \frac{T_{\exp}^{chisel}}{2t_c f^{0.5}}. \tag{9}$$

The total thrust force will be the sum of the part values generated by cutting lips and the chisel edge. Fig. 2, shows the force model exerted by cutting lips and chisel edge on the composite laminate based on Eqs. (1) and (6).

4. Analytical model for delamination propagation with backup plate

4.1 Physical model

Fig. 2 illustrates the physical model of delamination in drilling of composite plates. The energy balance equation at the onset of delamination propagation is:

$$dU_d = dW - dU \tag{10}$$

where, U, W and U_d are the stored strain energy, the work done and the strain energy absorbed by crack growth respectively, which are represented:

$$dU_d = G_{IC}.dA \tag{11}$$

where, dA is the change in the delamination area and G_{IC} is the critical strain energy release rate in mode-I. For circular cracks, we have:

$$dA = 2\pi a da \tag{12}$$

For computing the work done by the drill, W, and the stored strain energy, U, determination of the plate deflection, w, is required. The bending deflection of a single layer orthotropic plate can be calculated by using the classic plate bending theory (Hou and Jeronimidis 2000). The plate deflection w of a thin plate with constant rigidity subjected to uniformly distributed load over a central circular area is governed by (Timoshenko and Woinowsky-Krieger 1959):

$$\nabla^4 w = \frac{q}{D} \tag{13}$$

where, q, is the distributed load and D is the bending rigidity of the plate. For composite materials, the bending rigidity is replaced with equivalent bending stiffness D', as follows:

$$D' = \frac{1}{8}(3D_{11} + 2D_{12} + 4D_{66} + 3D_{22}) \tag{14}$$

where, D_{ij}, are bending stiffness which are defined as follows:

$$D_{ij} = \frac{1}{3}\sum_{k=1}^{n}(Z_k^3 - Z_{k-1}^3)(\bar{Q}_{ij})_k \tag{15}$$

where n is the total number of layers, k is a free index indicating the layer sequence from a selected side of the laminate, $(\overline{Q_{ij}})_k$ is the transformed reduced stiffness of the k-th layer, referring to the global coordinate of the laminate, and Z_k stands for the distance of the lower surface of the k-th layer from the middle plane of the plate.

4.2 Load models

Due to variations of the rake angle, relief angle and inclination angle along the drill radius, load function is very complicated, as shown in Fig. 2. Hence, two simplified models are assumed for thrust force applied by the drill to the laminate. A central concentrated force is considered in the first model, which is the sum of forces applied on cutting lips and chisel edge regions. For the second case, this resultant concentrated force is considered to be distributed uniformly over the entire length of the drill bit. In both models, the backup force is assumed to be peripheral distribution force.

A predrilled backup plate underneath the specimen counteracts the downward bending deflection of the

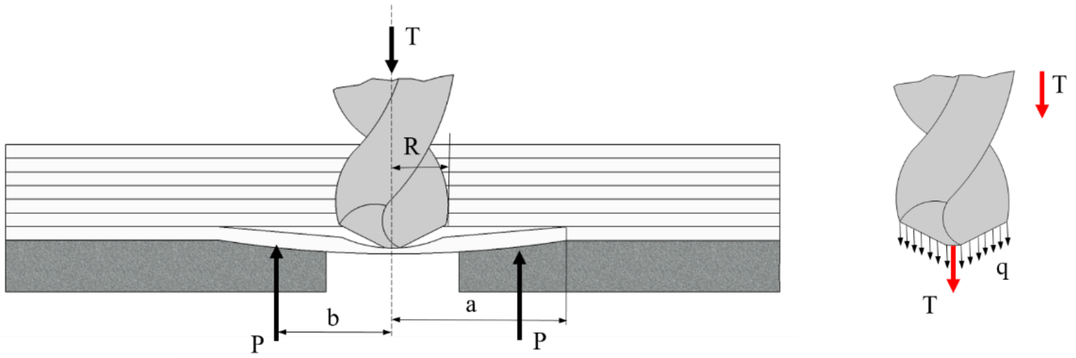

Fig. 3 Schematic depiction of delamination, when drilling composite laminates with backup

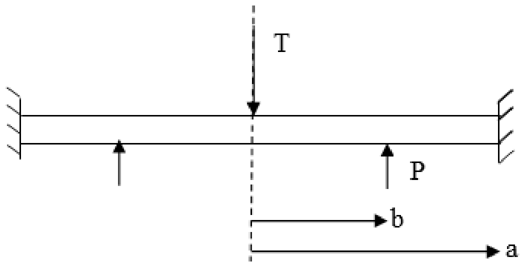

Fig. 4 Concentrated central drill load with circular backup load model

laminae that is caused by the drilling thrust force. A uniform upward force is initially applied to the back side of the work piece from the backup plate. As the drilling movements, the laminate starts to slightly deflect. The backup plate logically has greater stiffness than the laminate, hence, it does not fully conform to the laminate deflection. The internal reaction force with the downward bending of the uncut laminate lifts up the laminate and this changes the backup force from a uniform load to a peripherally distributed load. Therefore, the deflected specimen is subjected to both concentrated thrust force on the entry side and circular backup force from the bottom side, as shown in Fig. 3.

4.2.1 Concentrated central load

Fig. 4, shows the schematic of delamination in the last uncut laminae of the work piece, considering a concentrated central load model with peripheral distribution backup force, *P*. In this Figure, T_1 is the total thrust force exerted by a twist drill at the center of plate, *b* is the support plate radius and *a* is the radius of crack (delamination).

According to Eq. (13), for a circular plate with clamped edges subjected to a concentrated force at the center and peripheral distribution force at *b* as a backup force, the amount of deflection can be obtained as:

$$w(r) = \begin{cases} w_1(r) = -\dfrac{P}{8\pi D'}\left[(b^2+r^2)\ln\eta + \dfrac{(a^2+r^2)(a^2-b^2)}{2a^2}\right] + \\ \dfrac{T_1}{16\pi D'}\left[\left(2r^2\ln\left(\dfrac{r}{a}\right)\right) + a^2 - r^2\right] \qquad 0 < r < b \\ w_2(r) = -\dfrac{P}{8\pi D'}\left[(b^2+r^2)\ln\left(\dfrac{r}{a}\right) + \dfrac{(a^2-r^2)(a^2+b^2)}{2a^2}\right] + \\ \dfrac{T_1}{16\pi D'}\left[\left(2r^2\ln\left(\dfrac{r}{a}\right)\right) + a^2 - r^2\right] \qquad b < r < a \end{cases} \tag{16}$$

where, $\eta = b/a$ and the total thrust force *T* is the sum of the force applied on the cutting lips and chisel edge expressed as:

$$T = T_L + T_C = \frac{k_L}{\exp(\alpha_L\,\gamma_m)}\sqrt{f} + \frac{k_c}{\exp(\alpha_c\,\gamma_c)}\sqrt{f} \tag{17}$$

where, the constants K_L, K_c, α_L and α_c are calculated based on the following equations:

$$\begin{gathered} k_L = \sqrt{2}BG \\ k_c = 2Ct_c \\ \alpha_L = \alpha_c = 1.089\ln(10) = 2.51 \end{gathered} \tag{18}$$

According to the boundary condition *w*=0 at *r*=*b*, the ratio between *P* and T_1 can be achieved as:

$$2\pi q' b = P = \frac{T_1}{2}\left[\frac{(2b^2\ln\eta) + a^2 - b^2}{2b^2\ln\eta + \dfrac{(a^2+b^2)(a^2-b^2)}{2a^2}}\right] \tag{19}$$

The work done by backup force, *P*, is zero, because deflection is zero at *r*=*b*. Therefore, the stored strain energy, the work done and the strain energy absorbed by crack growth are expressed as the following equations, respectively

$$\begin{gathered} U = \pi D' \int_0^a \left[\left(\frac{d^2w}{dr^2} + \frac{1}{r}\frac{dw}{dr}\right)^2\right] r\,dr \\ U = -\frac{1}{16\pi D'}\frac{T_1^2 a^2 b^2[2b^2(\ln\eta)^2 - 2b^2\ln\eta - a^2 + b^2]}{[4b^2a^2\ln\eta + a^4 - b^4]} \\ \frac{\partial U}{\partial a}da = \frac{1}{4\pi D'}\frac{b^4 a T_1^2[b^4(\ln\eta)^2 - 2b^4\ln\eta - 2a^2b^2 + a^4 + b^4 + (\ln\eta)^2a^4 + 2b^2(\ln\eta)^2 + 2a^4\ln\eta]}{[4b^2a^2\ln\eta + a^4 - b^4]^2}da \end{gathered} \tag{20}$$

$$\begin{gathered} W = T_1\,w(0) = \frac{T_1}{8\pi D'}\left[\frac{T_1 a^2}{2} - P\left(b^2\ln\eta + \frac{a^2-b^2}{2}\right)\right] \\ \frac{\partial w}{\partial a}da = \frac{1}{2\pi D'}\frac{b^4 a T_1^2[b^4(\ln\eta)^2 - 2b^4\ln\eta - 2a^2b^2 + a^4 + b^4 + (\ln\eta)^2a^4 + 2b^2(\ln\eta)^2a^2 + 2a^4\ln\eta]}{(4b^2a^2\ln\eta + a^4 - b^4)^2}da \end{gathered} \tag{21}$$

$$U_d = G_{IC}.A = G_{IC}\pi a^2 \qquad \frac{\partial U_d}{\partial a}da = G_{IC}\,2\pi a\,da \tag{22}$$

The critical thrust force and the feed rate at the onset of crack propagation can be calculated as below:

$$T_{critical\,1} = \frac{2\sqrt{2}\pi\sqrt{D'G_{IC}}[4\eta^2\ln\eta + 1 - \eta^4]}{[\ln\eta + 1 + \eta^2\ln\eta - \eta^2]\eta^2} \tag{23}$$

$$f_{critical\,1} = \frac{8\pi^2 D' G_{IC}[4b^2a^2\ln\eta + a^4 - b^4]^2}{\chi^2[a^2\ln\eta + a^2 + b^2\ln\eta - b^2]^2 b^4} \tag{24}$$

where, the constant χ is calculated as below:

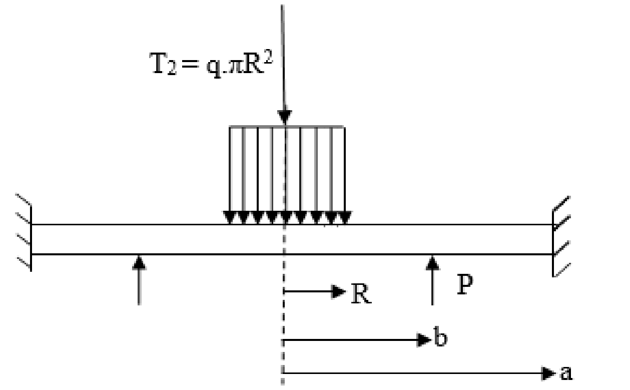

Fig. 5 Equivalent uniformly distributed drill load model with circular backup load model

$$\chi = \frac{k_L}{\exp\,(\alpha_L\,\gamma_m)} + \frac{k_c}{\exp\,(\alpha_c\,\gamma_c)} \tag{25}$$

4.2.2 Equivalent uniformly distributed load

Fig. 5 depicts the schematic of delamination in the last uncut laminate of the work piece, assuming an equivalent uniformly distributed load model with peripheral distribution backup force, P. In this figure, q is the thrust load exerted uniformly on the plate.

For a circular laminate with clamped edges subjected to a uniformly distributed load over the central circular area of radius R and peripheral distribution force at b as a backup force, the amount of deflection can be calculated as:

$$\begin{cases} w_1 = -\dfrac{P\left[\left(b^2+r^2\right)\ln\eta + \dfrac{\left(a^2+r^2\right)\left(a^2-b^2\right)}{2a^2}\right]}{8\pi D'} + \dfrac{T_2\left[4a^2-3R^2+4R^2\ln\left(\dfrac{R}{a}\right)-2r^2\left(-4\ln\left(\dfrac{R}{a}\right)+\dfrac{R^2}{a^2}\right)+\dfrac{r^4}{R^2}\right]}{64\pi D'}, & 0 \le r \le R, \\ w_2 = -\dfrac{P\left[\left(b^2+r^2\right)\ln\eta + \dfrac{\left(a^2+r^2\right)\left(a^2-b^2\right)}{2a^2}\right]}{8\pi D'} + \dfrac{T_2\left[2a^2+R^2-r^2\left(2+\dfrac{R^2}{a^2}\right)+2R^2\ln\left(\dfrac{r}{a}\right)+4r^2\ln\left(\dfrac{r}{a}\right)\right]}{32\pi D'}, & R \le r \le b, \\ w_3 = -\dfrac{P\left[\left(b^2+r^2\right)\ln\eta + \dfrac{\left(a^2-r^2\right)\left(a^2+b^2\right)}{2a^2}\right]}{8\pi D'} + \dfrac{T_2\left[2a^2+R^2-r^2\left(2+\dfrac{R^2}{a^2}\right)+2R^2\ln\left(\dfrac{r}{a}\right)+4r^2\ln\left(\dfrac{r}{a}\right)\right]}{32\pi D'}, & b \le r \le a. \end{cases} \tag{26}$$

According to the boundary condition w=0 at r=b, the ratio between P and T_2 can be achieved as:

$$2\pi q b = P = \frac{T_2}{4}\,\frac{2a^2+R^2-b^2\left(2+\dfrac{R^2}{a^2}\right)+2R^2\ln\eta+4b^2\ln\eta}{2b^2\ln\eta+\dfrac{(a^2-b^2)(a^2+b^2)}{2a^2}} \tag{27}$$

Therefore, the work done is:

$$W = \int dW = \int_0^R\int_0^{2\pi} q w_1(r)\; r\,dr\,d\theta = \frac{T_2}{\pi R^2}\int_0^R\int_0^{2\pi} w_1(r)\; r\,dr\,d\theta \tag{28}$$

$$W = \frac{1}{96\pi D'\left[4b^2a^2\ln\eta+a^4-b^4\right]}\begin{bmatrix} T_2^2(-12a^4b^2+10R^2a^4+12a^2b^4+2b^4R^2 \\ +16b^2R^2a^2\ln\eta+24R^2a^2b^2(\ln\eta)^2 \\ +12R^2a^4\ln\eta-12R^2a^2b^2-24b^4a^2\ln\eta \\ -12b^4R^2\ln\eta+24b^4a^2(\ln\eta)^2-12R^2\ln\left(\dfrac{R}{a}\right)a^4 \\ +12R^2\ln\left(\dfrac{R}{a}\right)b^4+6R^4a^2\ln\eta+6R^4a^2(\ln\eta)^2 \\ +3R^4a^2-3R^4b^2-48R^2\ln\left(\dfrac{R}{a}\right)b^2a^2\ln\eta) \end{bmatrix}, \tag{29}$$

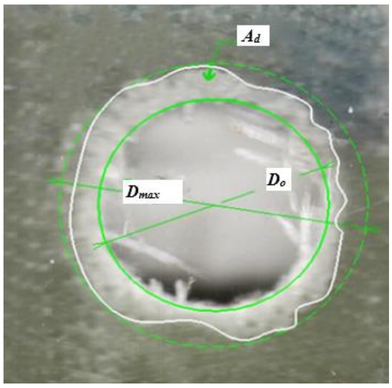

Fig. 6 Delamination area and its related parameters

$$\frac{\partial W}{\partial a}da = \frac{1}{8\pi D'\left[4b^2a^2\ln\eta+a^4-b^4\right]^2}\begin{bmatrix} T_2^2a(-4R^2a^4b^2(\ln\eta)^2-8R^2a^4b^2\ln\eta-8b^4R^2a^2(\ln\eta)^2 \\ +2R^4a^2b^2(\ln\eta)^2-8b^8\ln\eta+4b^8(\ln\eta)^2-4b^6R^2 \\ -8a^2b^6+4b^4a^4+R^4a^4+R^4b^4+8b^6a^2(\ln\eta)^2 \\ +8b^4a^4\ln\eta+4b^4a^4(\ln\eta)^2+R^4a^4(\ln\eta)^2+ \\ R^4b^4(\ln\eta)^2-4b^2R^2a^4+8R^2a^2b^4+8b^6R^2\ln\eta \\ -4R^2b^6(\ln\eta)^2+2R^4a^4\ln\eta-2R^4a^2b^2-2R^4b^4\ln\eta+4b^8) \end{bmatrix}da, \tag{30}$$

and the stored strain energy is:

$$U = -\frac{1}{192\pi D'\left[4b^2a^2\ln\eta+a^4-b^4\right]}\begin{bmatrix} T_2^2(-12a^4b^2+10R^2a^4+12a^2b^4+2b^4R^2+16b^2R^2a^2\ln\eta+24R^2a^2b^2(\ln\eta)^2 \\ +12R^2a^4\ln\eta-12R^2a^2b^2-24b^4a^2\ln\eta-12b^4R^2\ln\eta+24b^4(\ln\eta)^2a^2 \\ -12R^2\ln\left(\dfrac{R}{a}\right)a^4+12R^2\ln\left(\dfrac{R}{a}\right)b^4+6R^4a^2\ln\eta+6R^4a^2(\ln\eta)^2+3R^4a^2 \\ -3R^4b^2-48R^2\ln\left(\dfrac{R}{a}\right)b^2a^2\ln\eta) \end{bmatrix}. \tag{31}$$

Also, in view of Eq. (10), we have:

$$\frac{\partial U}{\partial a}da = \frac{1}{16\pi D'\left[4b^2a^2\ln\eta+a^4-b^4\right]^2}\begin{bmatrix} T_2^2a(-4R^2a^4b^2(\ln\eta)^2-8R^2a^4b^2\ln\eta-8b^4R^2a^2(\ln\eta)^2 \\ +2R^4a^2b^2(\ln\eta)^2-8b^8\ln\eta+4b^8(\ln\eta)^2-4b^6R^2-8a^2b^6 \\ +4b^4a^4+R^4a^4+R^4b^4+8b^6a^2(\ln\eta)^2+8b^4a^4\ln\eta+4b^4a^4(\ln\eta)^2 \\ +R^4a^4(\ln\eta)^2+R^4b^4(\ln\eta)^2-4b^2R^2a^4+8R^2a^2b^4+8b^6R^2\ln\eta \\ -4R^2b^6(\ln\eta)^2+2R^4a^4\ln\eta-2R^4a^2b^2-2R^4b^4\ln\eta+4b^8) \end{bmatrix}da. \tag{32}$$

Finally, the critical thrust force and feed rate at the onset of crack propagation with backup plate can be calculated as below:

$$T_{critical\,2} = \frac{4\sqrt{2}\pi\sqrt{D'G_{IC}}\,[4\eta^2\ln\eta+1-\eta^4]}{[\ln\eta+1+\eta^2\ln\eta-\eta^2](\beta^2-2\eta^2)} \tag{33}$$

$$f_{critical\,2} = \frac{32\pi^2D'G_{IC}[4\eta^2\ln\eta+1-\eta^4]^2}{\chi^2[\ln\eta+1+\eta^2\ln\eta-\eta^2]^2(\beta^2-2\eta^2)^2} \tag{34}$$

The comparison of $f_{critical\,1}$ and $f_{critical\,2}$ in Eqs. (24) and (34) gives:

$$\frac{f_{critical\,2}}{f_{critical\,1}} = \frac{1}{(\beta^2-2\eta^2)^2} \tag{35}$$

where, β=R/a. In the proposed model the critical thrust force and the feed rate are related to the crack size, a while in the previous models presented by Zhang *et al.* (2001), Gururaja *et al.* (Gururaja and Ramulu 2009), Jain *et al.* (Jain and Yang 1993) and Ojo *et al.* (2017), the critical thrust force is independent. They achieved this result based on an improper assumption, i.e., the load is distributed on the whole crack area, and in practice, delamination-free in drilling of composite materials is impossible task. However, it is possible to control the delamination condition.

Chen (1997) presented a parameter named “delamination factor” which is expressed by the following equation:

$$F_d = \frac{D_{\max}}{D_0} \tag{36}$$

where, D_0, is the nominal diameter of the hole (or drill bit) and D_{max} is the maximum diameter of the delaminated area (Fig. 6). It is worth mentioning that D_{max} and D_0 are crack length (2*a*) and drill radius (2R), respectively, in the proposed model.

Except conventional delamination factor, other methods are presented by (Davim, Rubio *et al.* 2007) and (Tsao *et al.* 2012). (Davim, Rubio *et al.* 2007) proposed the idea of an adjusted delamination factor (F_{da}) to evaluate the delamination size by digital image processing. The equation of the adjusted delamination factor can be expressed as follows:

$$F_{da} = F_d + \frac{A_d}{A_{\max} - A_o}(F_d^2 - F_d) \tag{37}$$

where A_{max} is the delamination area related to the D_{max}, A_0 is the drilled area of the D_o, and A_d is the delamination area in the vicinity of the drilled hole.

(Tsao *et al.* 2012) proposed the idea of equivalent delamination factor which can be calculated through Eq. (38):

$$F_{ed} = \frac{D_e}{D} \tag{38}$$

where is D_e the equivalent delamination diameter and can be expressed as follows:

$$D_e = \sqrt{\left[\frac{4(A_d + A_o)}{\pi}\right]} \tag{39}$$

Drilling process rate of composite laminates is directly related to the feed rate. Our aim is increasing the feed rate as much as possible, but it is restricted by allowable crack size which is determined by designer. In section 5, the allowable delamination factor is considered 1.5 to find critical thrust force.

5. Experimental program

In the first step, G_{IC} should be obtained by conducting double cantilever beam (DCB) specimen. The dimensions of manufactured sample are: width B = 20 mm, length L = 170 mm, nominal thickness t = 3.5 mm, and crack length a = 60 mm, which is produce by inserting a 20 m-Teflon film between mid-layers. On the other hand, some other samples were also provided for conducting drilling tests. In this case, the dimensions of each samples are as follows: B = 36 mm, L = 200 mm, and t = 5.5 mm. Four (stacking sequence: $[0]_4$) and seven layers (stacking sequence: [0/90/0/90/0/90/0]) of unidirectional glass/epoxy prepreg were used for manufacturing samples in DCB and drilling tests, respectively. The mechanical properties of composite laminate are mentioned in Ref.(Heidary and Mehrpouya 2019).

Based on the mechanical properties, bending stiffness D_{ij}, are determined as follows: D_{11}= 1.305 N.m, D_{12}=0.061 N.m., D_{22}=0.244 N.m., and D_{66}=0.141 N.m. Therefore, the equivalent bending stiffness, D', can be calculated by Eq. (14): D' =0.66 N.m.

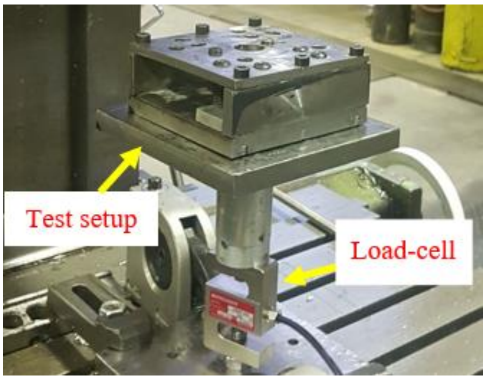

Fig. 7 The setup provided for drilling test

Table 1 Experimental condition for drilling tests

Test No.	Feed rate (mm/rev)	Backup condition
1	0.25	Without backup
2	0.25	With backup
3	0.508	Without backup
4	0.508	With backup
5	0.8	Without backup
6	0.8	With backup
7	1.16	Without backup
8	1.16	With backup

5.1 Conducting fracture and drilling tests

G_{IC} can be calculated according to ASTM standard [38] and using DCB test:

$$G_{IC} = \frac{3p\delta}{2Sa_0} \tag{40}$$

where, P, δ, S, and a_0 are the load, the displacement, the sample width, and finally the crack length, respectively. The tests were conducted using a computer-controlled servo-hydraulic universal testing machine which its load-cell capacity was 5 kN. The loading was displacement control with speed of 3 mm/min.

Drilling tests were done using an FP4M vertical machining center (Fig. 7) with maximum rpm and feed rate of 2500 and 200 mm/min, respectively. According to this figure, suitable fixtures were applied to fix the samples. The diameter of backup hole was 12 mm and the cutting velocity were 315 rpm. The specification of the drill bit used in experiments is as follows: 2Flutes HSS, 2R=10 mm, ε=118, ψ=30.

The fixture was placed on the load cell with 250 Kg capacity for measuring the thrust force (Fig. 7). The number of repetition for each test was three in both of fracture and drilling tests. For comparing the experimental and numerical outcomes deeply, four experimental tests with various backup conditions were considered as shown in Table 1(Heidary and Mehrpouya 2019).

6. Results and discussion

Fig. 8 illustrates the theoretical critical thrust force ratio as a function of the backup to crack size ratio ($\eta=b/a$) for concentrated load model. Hocheng's model with concentrated load model without backup is also shown (Hocheng and Tsao 2003). It is obvious that the backup plate has a significant effect on the critical thrust force and increases the critical thrust force. On the contrary, when the backup to the crack size ratio increases, the critical thrust force decreases rapidly. This is due to the fact that, by increasing the backup size, the supporting condition against the central concentrated load is decreased and, consequently, the crack propagates at a lower thrust force.

Fig. 9 illustrates the theoretical critical thrust force ratio as a function of the backup to the crack size ratio ($\eta=b/a$) for uniformly distributed load model with different drill radius to the crack size ratio ($\beta=R/a$). Hocheng's model with uniformly distributed load model without backup is also shown (Hocheng and Tsao 2003). Similar to the previous model, using the backup plate increases the critical thrust force significantly and the critical thrust force decreases by increasing the backup size to the crack size ratio ($\eta=b/a$). In this case, by increasing the drill radius to the crack ratio ($\beta=R/a$) the critical thrust force is decreased. This is due to the fact that, by increasing the drill radius to the crack size ratio, load is exerted on the greater part of the crack region and since the supporting backup size should be greater than the drill diameter (as shown in Fig. 3), the backup plate should be extended beyond the crack region, and thus, worsening the supporting condition.

Fig. 10 illustrates the theoretical critical feed rate ratio as a function of the backup to the crack size ratio ($\eta=b/a$) for two load hypotheses, i.e., concentrated central and uniformly distributed load model with different drill radius to the crack size ratio ($\beta=R/a$). It can be seen that the critical feed rate has a similar trend to the critical thrust force. In addition, the concentrated central model has a lower limit band for the critical feed rate. On the contrary, the uniformly distributed model allows designers to use a higher feed rate for free-delamination drilling, while in the concentrated central model a higher safety factor is considered owing to the assumed simplifications.

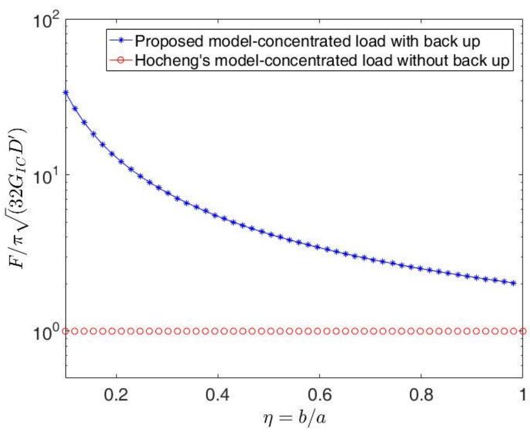

Fig. 8 Comparison of the critical thrust force predicted by present models with backup and Hocheng's model without backup

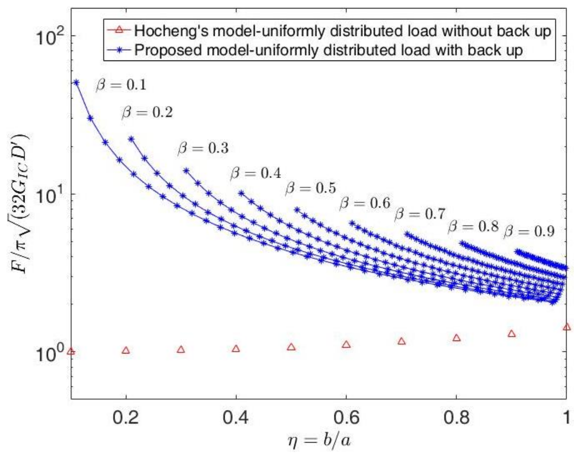

Fig. 9 Critical thrust force as a function of the backup to crack size with different drill radius to the crack size ratio

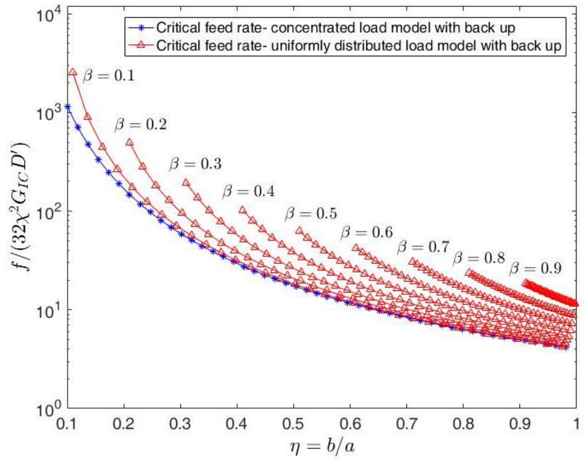

Fig. 10 Critical feed rate for concentrated central and uniformly distributed load with backup plate

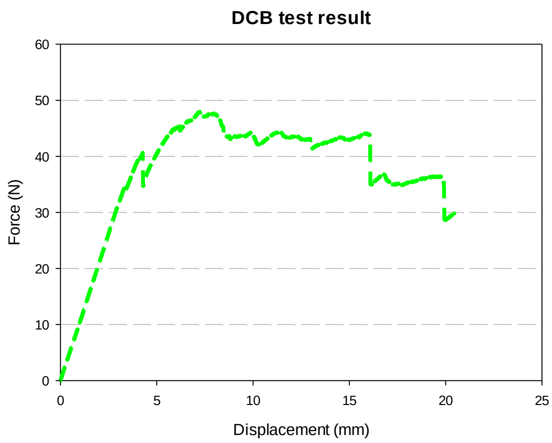

Fig. 11 Force-displacement curves obtained by DCB test

In order to calculate the critical thrust force, G_{IC} should be determined. Fig. 11 illustrates force-displacement diagram of DCB test. The average G_{IC} for tested glass/epoxy laminate is 475 N/m.

As an example, Fig. 12, shows force-displacement diagram during drilling of composite laminates with three repetitions. The test conditions are: F=0.508 mm/rev,

Table 2 Analytical values of the critical thrust force for different drilling condition

Model condition	Model equation	Analytical critical thrust force (N)
Drilling without backup-concentrated load (Zarif Karimi, Heidary *et al.* 2016)	$F_{cr} = \pi\sqrt{32G_{IC}D'}$	314.7
Drilling without backup-distributed load (Zarif Karimi, Heidary *et al.* 2016Zarif Karimi, Heidary *et al.* 2016)	$F_{cr} = \dfrac{\pi\sqrt{32G_{IC}D'}}{1-(1/2\beta)^2}$	402.8
Drilling with backup-concentrated load. Eq.(23)	$F_{cr} = \dfrac{2\sqrt{2}\pi\sqrt{D'G_{IC}}[4\eta^2\ln\eta + 1 - \eta^4]}{[\ln\eta + 1 + \eta^2\ln\eta - \eta^2]\eta^2}$	790.5
Drilling with backup-distributed load. Eq.(33)	$F_{cr} = \dfrac{4\sqrt{2}\pi\sqrt{D'G_{IC}}[4\eta^2\ln\eta + 1 - \eta^4]}{[\ln\eta + 1 + \eta^2\ln\eta - \eta^2](\beta^2 - 2\eta^2)}$	1208.4

Table 3 Comparison of the analytical and experimental results

Test No.	Feed rate (mm/rev)	Backup condition	Measured delamination factor	Analytical thrust force on the last layer (N)		Experimental thrust force on the last layer (N)	Error percentage (%)	
				Concentrated	Distributed		Concentrated	Distributed
1	0.25	Without backup	1.21	314.7	494.0	273.4	13.1	44.6
2	0.25	With backup	1.10	575.9	881.1	431.7	25.0	51.0
3	0.508	Without backup	1.32	314.7	557.0	295.1	6.2	47.0
4	0.508	With backup	1.24	650.4	994.4	545.5	16.1	45.1
5	0.8	Without backup	1.51	314.7	730.1	361.8	14.9	50.1
6	0.8	With backup	1.29	676.9	1036.9	545.6	19.3	47.2
7	1.16	Without backup	1.63	314.7	934.6	406.3	29.0	56.5
8	1.16	With backup	1.35	708.9	1085.7	646.1	8.8	40.4

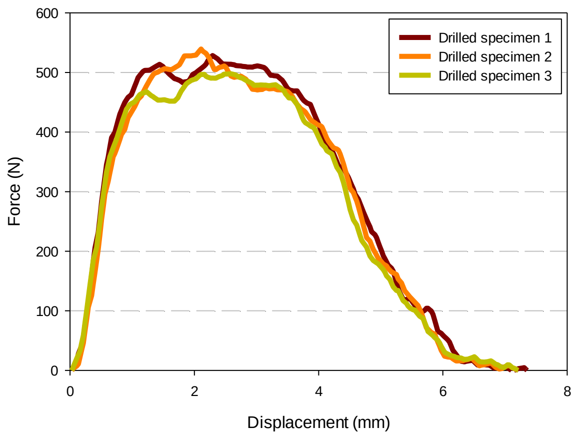

Fig. 12 Force-Displacement curves obtained by drilling test

N=315 rpm, 2R=10 mm, and without backup. It can be seen that the maximum thrust force is more than 500 N. The exerted thrust force on the last layer can be also determined using feed rate and thickness of each layer.

Table 2 shows the analytical critical thrust force values for drilling of glass/epoxy laminates with different load models and backup conditions. In order to determine the critical thrust force, the mechanical properties and the drilling parameters are: G_{IC}=475 N/m, D'=0.66 N.m., 2R=10 mm, 2b=12 mm, 2a=15 mm (F_d=1.5). It can be seen that, the analytical critical thrust force for distributed load is higher than concentrated load model in both backup conditions. It can be concluded that, the concentrated load model is more conservative.

Table 3 illustrates the measured delamination factor and the analytical and experimental thrust force on the last layer of glass/epoxy composite laminates. The analytical thrust force with backup plate can be determined by substitution of measured delamination factor on Eqs. (23) and (33). It can be seen that, error percentages for concentrated load model are less than 30% in these feed rate ranges. The error can be attributed to simplify assumptions mentioned in the section 2.

The results of the proposed analytical models can be investigated from different viewpoints. For example, the effects of each drill's geometrical parameters and backup condition, such as point angle, helix angle and rake angle on the critical feed rate can be studied. However, it is not possible to discuss all these findings and investigations in this article. These investigations will be discussed in detail in the future research.

7. Conclusions

This paper presents analytical models to predict the critical thrust force and the feed rate at the onset of delamination with backup plate. To achieve this goal, at first the oblique cutting model proposed by Langella was recalled to determine an analytical relation between the feed rate and the thrust force. Two various loading models were considered for the thrust force applied by the rotating drill bit to the laminate with backup plate, namely concentrated central and equivalent uniformly distributed load. Then, the critical thrust force for each loading model with backup plate was determined based on the elastic fracture mechanics and the classical plate bending theory. Finally, the critical feed rate for the onset of delamination was modeled by combining the resulting equations for the oblique cutting model and the critical thrust force.

The results revealed that the backup plate had a significant effect on the critical thrust force and increased the critical thrust force compared with the absence of the backup plate proposed by Hocheng. When backup to crack size ($\eta=b/a$) increased, the critical thrust force decreased rapidly. In the uniformly distributed model, by increasing the drill radius to crack ratio ($\beta=R/a$), the critical thrust force was decreased. According to the results, the critical feed rate had a similar trend to the critical thrust force and the concentrated central model had a lower limit band for the critical feed rate.

Experimental tests were conducted to verify the analytical model. Based on the results experimental and analytical models were in a good agreement and the error percentages for concentrated load model are less than 30%.

References

Prabukarthi, A., Senthilkumar, M. and Krishnaraj, V. (2016), “Study on drilling of CFRP/Ti6Al4V stack with modified twist drills using acoustic emission technique”, *Steel Compos. Struct.*, **21**(3), 573-588. https://doi.org/10.12989/scs.2016.21.3.573.

Mohammadzadeh, B., Choi, E. and Kim, W.J. (2018), “Comprehensive investigation of buckling behavior of plates considering effects of holes”, *Struct. Eng. Mech.*, **68**(2), 261-275. https://doi.org/10.12989/sem.2018.68.2.261.

Bhattacharyya, D. and Horrigan, D.P.W. (1998), “A study of hole drilling in Kevlar composites”, *Compos. Sci. Technol.*, **58**(2), 267-283. https://doi.org/10.1016/S0266-3538(97)00127-9.

Campos Rubio, J.C., Silva, L.J.D., Leite, W.D.O., Panzera, T.H., Filho, S.L.M.R. and Davim, J.P. (2013), “Investigations on the drilling process of unreinforced and reinforced polyamides using Taguchi method”, *Compos. Part B Eng.*, **55**, 338-344. https://doi.org/10.1016/j.compositesb.2013.06.042.

Capello, E. (2004), “Workpiece damping and its effect on delamination damage in drilling thin composite laminates”, *J. Mater. Process. Technol.*, **148**(2), 186-195. https://doi.org/10.1016/S0924-0136(03)00812-4.

Chandrasekharan, V., Kapoor, S.G. and DeVor, R.E. (1995), “A mechanistic approach to predicting the cutting forces in drilling: With application to fiber-reinforced composite materials”, *J. Eng. Industry*, **117**(4), 559-570. https://doi.org/10.1115/1.2803534.

Chen, W.C. (1997), “Some experimental investigations in the drilling of carbon fiber-reinforced plastic (CFRP) composite laminates”, *Int. J. Machine Tools Manufact.*, **37**(8), 1097-1108. https://doi.org/10.1016/S0890-6955(96)00095-8.

Davim, J.P., Rubio, J.C. and Abrao, A.M. (2007), “A novel approach based on digital image analysis to evaluate the delamination factor after drilling composite laminates”, *Compos. Sci. Technol.*, **67**(9), 1939-1945. https://doi.org/10.1016/j.compscitech.2006.10.009.

Kim, D.K., Ng, W.C.K. and Hwang, O. (2018), “An empirical formulation to predict maximum deformation of blast wall under explosion”, *Struct. Eng. Mech.*, **68**(2), 237-245. https://doi.org/10.12989/sem.2018.68.2.237.

El-Sonbaty, I., Khashaba, U.A. and Machaly, T. (2004), “Factors affecting the machinability of GFR/epoxy composites”, *Compos. Structures*, **63**(3-4), 329-338. https://doi.org/10.1016/S0263-8223(03)00181-8.

Fernandes, M. and Cook, C. (2006), “Drilling of carbon composites using a one shot drill bit. Part I: Five stage representation of drilling and factors affecting maximum force and torque”, *Int. J. Machine Tools Manufact.*, **46**(1), 70-75. https://doi.org/10.1016/j.ijmachtools.2005.03.015.

Fernandes, M. and Cook, C. (2006), “Drilling of carbon composites using a one shot drill bit. Part II: Empirical modeling of maximum thrust force”, *Int. J. Machine Tools Manufact.*, **46**(1), 76-79. https://doi.org/10.1016/j.ijmachtools.2005.03.016.

Caprino, G. and Nele, L. (1996), “Cutting forces in orthogonal cutting of unidirectional GFRP composites”, *J. Eng. Mater. Technol.*, **118**(3), 419-425. https://doi.org/10.1115/1.2806829.

DiPaolo, G., Kapoor, S.G. and DeVor, R.E. (1996), “An experimental investigation of the crack growth phenomenon for drilling of fiber-reinforced composite materials”, *J. Eng. Ind.*, **118**, 104-110. https://doi.org/10.1115/1.2803629.

Gururaja, S. and Ramulu, M. (2009), “Modified exit-ply delamination model for drilling FRPs”, *J. Compos. Mater.*, **43**(5), 483-500. https://doi.org/10.1177%2F0021998308097677.

Hocheng, H. and Dharan, C.K.H. (1990), “Delamination during drilling in composite laminates”, *J. Eng. Ind.*, **112**, 236-239.

Guenfoud, H., Himeur, M., Ziou, H. and Guenfoud, M. (2018), “The use of the strain approach to develop a new consistent triangular thin flat shell finite element with drilling rotation”, *Struct. Eng. Mech.*, **68**(4), 385-398. https://doi.org/10.12989/sem.2018.68.4.385.

Heidary, H. and Mehrpouya, M.A. (2019), “Effect of backup plate in drilling of composite laminates, analytical and experimental approaches”, *Thin-Walled Struct.*, **136**, 323-332. https://doi.org/10.1016/j.tws.2018.12.035.

Heidary, H., Zarif Karimi, N., Ahmadi, M., Rahimi, A. and Zucchelli, A. (2014), “Clustering of acoustic emission signals collected during drilling process of composite materials using unsupervised classifiers”, *J. Compos. Mater.*, **49**(5), 559-571. https://doi.org/10.1177%2F0021998314521258.

Hocheng, H. and Tsao, C.C. (2003), “Comprehensive analysis of delamination in drilling of composite materials with various drill bits”, *J. Mater. Process. Technol.*, **140**(1-3), 335-339. https://doi.org/10.1016/S0924-0136(03)00749-0.

Hocheng, H. and Tsao, C.C. (2005), “The path towards delamination-free drilling of composite materials”, *J. Mater. Process. Technol.*, **167**(2-3), 251-264. https://doi.org/10.1016/j.jmatprotec.2005.06.039.

Hocheng, H. and Tsao, C.C. (2006), “Effects of special drill bits on drilling-induced delamination of composite materials”, *Int. J. Machine Tools Manufact.*, **46**(12-13), 1403-1416. https://doi.org/10.1016/j.ijmachtools.2005.10.004.

Hou, J.P. and Jeronimidis, G. (2000), “Bending stiffness of composite plates with delamination”, *Compos. Part A Appl. Sci. Manufact.*, **31**(2), 121-132. https://doi.org/10.1016/S1359-835X(99)00064-0.

Hwang, H.J., Ma, G. and Kim, C.S. (2018), “Minimum thickness of flat plates considering construction load effect”, *Struct. Eng. Mech.*, **69**(1), 1-10. https://doi.org/10.12989/sem.2019.69.1.001.

Jain, S. and Yang, D.C.H. (1993), “Effects of feedrate and chisel edge on delamination in composites drilling”, *J. Eng. Ind.*, **115**(4), 398-405. https://doi.org/10.1115/1.2901782.

Jain, S. and Yang, D.C.H. (1994), "Delamination-free drilling of composite laminates", *J. Eng. Ind.*, **116**(4), 475-481. https://doi.org/10.1115/1.2902131.

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", *Compos. Part A Appl. Sci. Manufact.*, **41**(3), 391-400. https://doi.org/10.1016/j.compositesa.2009.11.006.

Khashaba, U.A., El-Sonbaty, I.A., Selmy, A.I. and Megahed, A.A. (2010), "Machinability analysis in drilling woven GFR/epoxy composites: Part II – Effect of drill wear", *Compos. Part A Appl. Sci. Manufact.*, **41**(9), 1130-1137. https://doi.org/10.1016/j.compositesa.2010.04.011.

Langella, A., Nele, L. and Maio, A. (2005), "A torque and thrust prediction model for drilling of composite materials", *Compos. Part A Appl. Sci. Manufact.*, **36**(1), 83-93. https://doi.org/10.1016/j.compositesa.2004.06.024.

Liu, D., Tang, Y. and Cong, W.L. (2012), "A review of mechanical drilling for composite laminates", *Compos. Struct.*, **94**(4), 1265-1279. https://doi.org/10.1016/j.compstruct.2011.11.024.

Marques, A.T., Durão, L.M., Magalhães, A.G., Silva, J.F. and Tavares, J.M.R.S. (2009), "Delamination analysis of carbon fibre reinforced laminates: Evaluation of a special step drill", *Compos. Sci. Technol.*, **69**(14), 2376-2382. https://doi.org/10.1016/j.compscitech.2009.01.025.

Mathew, J., Ramakrishnan, N. and Naik, N.K. (1999), "Investigations into the effect of geometry of a trepanning tool on thrust and torque during drilling of GFRP composites", *J. Mater. Process. Technol.*, **91**(1-3), 1-11. https://doi.org/10.1016/S0924-0136(98)00416-6.

Ojo, S.O., Ismail, S.O., Paggi, M. and Dhakal, H.N. (2017), "A new analytical critical thrust force model for delamination analysis of laminated composites during drilling operation", *Compos. Part B Eng.*, **124**, 207-217. https://doi.org/10.1016/j.compositesb.2017.05.039.

Persson, E., Eriksson, I. and Zackrisson, L. (1997), "Effects of hole machining defects on strength and fatigue life of composite laminates", *Compos. Part A Appl. Sci. Manufact.*, **28**(2), 141-151. https://doi.org/10.1016/S1359-835X(96)00106-6.

Jain, S. and Yang, D.C. (1993), "Effects of feedrate and chisel edge on delamination in composite drilling", *J. Eng. Ind.*, **115**(4), 398-405. https://doi.org/10.1115/1.2901782.

Jain, S. and Yang, D.C. (1994), "Delamination-free drilling of composite laminates", *J. Eng. Ind.*, **116**(4), 475-481. https://doi.org/10.1115/1.2902131.

Sardiñas, R.Q., Reis, P. and Davim, J.P. (2006), "Multi-objective optimization of cutting parameters for drilling laminate composite materials by using genetic algorithms", *Compos. Sci. Technol.*, **66**(15), 3083-3088. https://doi.org/10.1016/j.compscitech.2006.05.003.

Singh, I., Bhatnagar, N. and Viswanath, P. (2008), "Drilling of uni-directional glass fiber reinforced plastics: Experimental and finite element study", *Mater. Des.*, **29**(2), 546-553. https://doi.org/10.1016/j.matdes.2007.01.029.

Timoshenko, S. and Woinowsky-Krieger, S. (1959), *Theory of Plates and Shells*, McGraw-Hill

Tsao, C.C. (2006), "The effect of pilot hole on delamination when core drill drilling composite materials", *Int. J. Machine Tools Manufact.*, **46**(12-13), 1653-1661. https://doi.org/10.1016/j.ijmachtools.2005.08.015.

Tsao, C.C. (2007), "Effect of deviation on delamination by saw drill", *Int. J. Machine Tools Manufact.*, **47**(7-8), 1132-1138. https://doi.org/10.1016/j.ijmachtools.2006.09.016.

Tsao, C.C. (2007), "Effect of pilot hole on thrust force by saw drill", *Int. J. Machine Tools Manufact.*, **47**(14), 2172-2176. https://doi.org/10.1016/j.ijmachtools.2007.05.008.

Tsao, C.C. (2008), "Prediction of thrust force of step drill in drilling composite material by Taguchi method and radial basis function network", *Int. J. Adv. Manufact. Technol.*, **36**(1-2), 11-18. https://doi.org/10.1007/s00170-006-0808-8.

Tsao, C.C. (2012), "Effect of induced bending moment (IBM) on critical thrust force for delamination in step drilling of composites", *Int. J. Machine Tools Manufact.*, **59**, 1-5. https://doi.org/10.1016/j.ijmachtools.2012.03.001.

Tsao, C.C. and Hocheng, H. (2005), "Effects of exit back-up on delamination in drilling composite materials using a saw drill and a core drill", *Int. J. Machine Tools Manufact.*, **45**(11), 1261-1270. https://doi.org/10.1016/j.ijmachtools.2005.01.015.

Tsao, C.C. and Hocheng, H. (2007), "Parametric study on thrust force of core drill", *J. Mater. Process. Technol.*, **192**, 37-40. https://doi.org/10.1016/j.jmatprotec.2007.04.062.

Tsao, C.C., Hocheng, H. and Chen, Y.C. (2012), "Delamination reduction in drilling composite materials by active backup force", *CIRP Annals Manufact. Technol.*, **61**(1), 91-94. https://doi.org/10.1016/j.cirp.2012.03.036.

Tsao, C.C., Kuo, K.L. and Hsu, I.C. (2012), "Evaluation of a novel approach to a delamination factor after drilling composite laminates using a core-saw drill", *Int. J. Adv. Manufact. Technol.*, **59**(5), 617-622. https://doi.org/10.1007/s00170-011-3532-y.

Zarif Karimi, N., Heidary, H. and Ahmadi, M. (2012), "Residual tensile strength monitoring of drilled composite materials by acoustic emission", *Mater. Des.*, **40**, 229-236. https://doi.org/10.1016/j.matdes.2012.03.040.

Zarif Karimi, N., Heidary, H. and Minak, G. (2016), "Critical thrust and feed prediction models in drilling of composite laminates", *Compos. Struct.*, **148**, 19-26. https://doi.org/10.1016/j.compstruct.2016.03.059.

Zarif Karimi, N., Minak, G. and Kianfar, P. (2015), "Analysis of damage mechanisms in drilling of composite materials by acoustic emission", *Compos. Struct.*, **131**, 107-114. https://doi.org/10.1016/j.compstruct.2015.04.025.

Zhang, L.B., Wang, L.J. and Liu, X.Y. (2001), "A mechanical model for predicting critical thrust forces in drilling composite laminates", *Proc. Inst. Mech. Eng. Part B J. Eng. Manufact.*, **215**(2), 135-146. https://doi.org/10.1243%2F0954405011515235.

CC