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Finite element analysis of drilled holes in uni-directional composite laminates using failure theories

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Abstract

The use of fiber reinforced plastics has increased manifold over the last few years. Generally developed for aerospace and other high end applications, composites are now making inroads into the automotive and general engineering market. Thus good quality and cost effective manufacturing of FRP composites becomes imperative. Drilling holes is an important machining operation to ascertain the assembly in intricate composite sections. The research endeavors in the field of composite materials have focused on to check the laminate fail or not during drilling operation by using various composite failure theories. The theoretical results of failure theory results are found in good agreement with the FEA results

1. Introduction

Manufacturing of fiber reinforced plastic composite materials can broadly be classified as primary and secondary manufacturing. Through most of the composite products are made to a near net shape using any of the primary manufacturing process, such as hand layup, compression molding, pultrusion, and filament winding, secondary manufacturing in terms of machining and drilling becomes unavoidable. Holes making thus becomes an integral part of the product development cycle. a number of technique have been used to make holes in composite laminates, but conventional drilling by far is the most widely accepted hole generation method. Drilling of FRP composite materials presents a plethora of questions to the engineers and scientists.

The machining (drilling) of these composite materials are significantly affected by the tendency of these materials to delaminate under the action of machining forces, thrust force and torque respectively. With the regard to get the better quality characteristics of drilled composites, some problems were encountered such as surface delamination, fiber/resin pullout and hole surface roughness. Among the defects caused by drilling, delamination appears to be the most critical during the process. The works of various authors [1–6], when reporting on drilling composite materials, have shown that the hole surface quality (surface roughness) is strongly dependent on cutting parameters, tool geometry (Point Angle) and cutting forces (thrust force).

Caprino and Tagliaferri [1] compared the interaction mechanisms between drilling tool and material. The results obtained are useful describing the damage history and help design drill geometries specifically conceived for composite machining. They also report that the type of damage induced in a composite material during drilling is strongly dependent on the feed.

The tool material and tool design have also been found to influence the drilling process in the context of fibrous composites. Chen [3] studied the effect of tool geometry on cutting forces. Various tool geometry parameters such as point angle, helix angle, and rake angle were analyzed. The tangential force that is torque was found to decrease with increasing point angle whereas the thrust force increased. The common objective of the efforts worldwide has been to improve the drilling operation in context of the FRP composite materials to minimize the drilling induced damage.

In this paper common objective is to predict the failure of uni-directional laminate plate during drilling with various speed, feed, and point angle by using finite element method. The FEA results of failure theory results are found in good agreement with the theoretical results.

2. Literature Review

The Literature review was done before identifying the field and nature of the present work. The knowledge gained from the literature review can be summarized as below.

Singh.I, Bhatnagar.N, and Viswanath.P [7] ‘Drilling of uni- directional glass fiber reinforced plastics: experimental and finite element study’ Materials design, Vol.29 (2008), pp. 546-553. This paper described the effect of thrust fore, torque of drill bit on composite plate during drilling - compare experiment result with FEA.

Abra˜o.A.M, Rubio.J.C, and Faria.P.E, Davim.D.V [8] ‘Drilling of uni- directional glass fiber reinforced plastics’. Experimental, Materials and Design, Vol. 29 (2008) 508–513.This paper described cutting tool geometry on thrust force and delamination when drilling UDGRP.

Mohan.N.S, Ramachandra, Kulkarni.S.M [9] ‘Influence of process parameters on cutting force and torque during drilling of glass–fiber polyester reinforced composites’ Composite Structure,Vol.71(2005) 407–41This paper evaluate effect of various cutting parameter during drilling the composite.

Babur Ozcelik, Eyup Bagci [10] ‘Experimental and numerical studies on the determination of twist drill temperature in dry drilling: A new approach’ Materials and Design, Vol27 (2006) 920–927. This paper described effect of temperature during drilling composite plate with various cutting parameter without cutting fluid.

V. Krishnaraj, S. Vijayarangan and A. Ramesh Kumar [11] studied the damage generated during the drilling of Glass Fibre Reinforced Plastics (GFRP) which was detrimental for the mechanical behaviour of the composite structure. This work was focused on analysing the influence of drilling parameters (spindle speed and feed) on the strength of the GFR woven fabric laminates and further to study the residual stress distribution around the hole after drilling. Holes were drilled at the centre of the specimens in a CNC machining centre using 6 mm diameter micro grain carbide drill for various spindle speeds (1000 4000 rpm) and feed rates (0.02, 0.06, 0.10 and 0.20 rev/min). Degree of damage depends on the feed rate and spindle speed. Experimental results indicate that failure strength and stress concentration are related to the drilling parameters and a drilling parameter (3000 rpm and 0.02 mm/rev), which gives better mechanical strength.

3. Calculation of Thrust Force & Pressure

Thrust force during drilling can be defined as “the force acting along the axis of the drill during the cutting process.” Cutting forces help monitor tool wear, since forces increase with tool wear. Thrust force is also used to monitor tool wear and, in turn, monitor tool life. Tool failure can occur if tool wear is not monitored. Other than being an important factor in the monitoring of tool wear, thrust force is considered to be the major contributor of de lamination during drilling. Considerable research has been done to prove that there is a “critical thrust force” that causes de lamination, and thrust force below that will constrain or eliminate de lamination during drilling. Vibratory drilling has been known as one of the methods to reduce thrust force during drilling of steel and during drilling of composites. Machining of de lamination free composites using conventional methods would lower the cutting quantities. If the “critical thrust force” is known, then the machining efficiency can be increased and higher quantities can be machined. This thesis deals with the prediction of thrust force at which de lamination will occur during drilling of composites.

Thrust Force for uni-directional composite plate [7]

$$F = 1.4365\rho + 402.8315f - 98.0319 \qquad (1)$$

Where

ρ=point angle of drill bit.

f= feed of drill pit (mm/rev).

Thrust pressure for uni-directional composite plate (q) = F/A

$$A = 3.14 * d^2 \qquad (2)$$

Where,

F= Thrust Force

A= Area of drilled hole

D = drilled hole.

Because the thrust force applied is very difficult. Reason is to apply thrust force is each node of the drilled hole. It's complicated one. So the thrust pressure is used to apply input into finite element software.

4. Failure Criteria

To determine whether a laminate will fail due to applied loading, the program first calculates stresses across the different plies. It next applies a failure criterion based on these stress levels using a failure theory. A laminate is considered to fail when a first ply or a first group of plies fails.

Failure of composites occurs in multiple steps. When stress in the first ply or a first group of plies is high enough, it fails. This point of failure is the first ply failure (FPF) beyond which a laminate can still carry the load. For a safe design, laminates should not experience stress high enough to cause FPF. The point where the total failure occurs is termed the ultimate laminate failure (ULF). Failure of composites occurs on a micromechanical scale due to fiber damage, matrix cracking, or interface or inters phase failure.

These local failure modes cannot predict global laminate failure satisfactorily.

4.1. Maximum Stress Failure Theory

In this theory failure predicted in lamina if any of the normal or shear stress in the local axes of a lamina is equal to or exceeds the corresponding ultimate strengths of uni-directional lamina.

$$\left.\begin{array}{l} -(F_{1C}) < S_{XX} < (F_{1T}) \\ -(F_{2C}) < S_{YY} < (F_{2T}) \\ -(F_{12}) < S_{ZZ} < (F_{12}) \end{array}\right\} \quad (3)$$

4.2. Maximum Strain Failure Theory

In this theory failure predicted in lamina if any of the normal or shear strain in the local axes of a lamina is equal to or exceeds the corresponding ultimate strengths of uni-directional lamina.

$$\left.\begin{array}{l} -(\varepsilon_{1C}) < \varepsilon < (\varepsilon_{1T}) \\ -(\varepsilon_{2C}) < \varepsilon < (\varepsilon_{2T}) \\ -(\gamma_{12}) < \gamma < (\gamma_{12}) \end{array}\right\} \quad (4)$$

4.3. Tsai-Wu Failure Criterion

The Tsai-Wu criterion is applied to composite shells. The Tsai-Wu failure criterion is a phenomenological failure theory which is widely used for anisotropic composite materials which have different strengths in tension and compression. This failure criterion is a specialization of the general quadratic failure criterion proposed by Gol'denblat and Kopnov and can be expressed in the form

$$F=f_1*s_{xx} + f_2 * s_{yy} + f_{11} * s_{xx}^2 + f_{22} * s_{yy}^2 + f_{33} * s_{zz}^2 + 2 * f_{12} * s_{xx} * s_{yy} < 1 \quad (5)$$

Where,

$f_1 = (1/F_{1T}) - (1/F_{1C})$

$f_2 = (1/F_{2T}) - (1/F_{2C})$

$f_{11} = (1/F_{1T}F_{1C})$

$f_{22} = (1/F_{2T}F_{2C})$

$f_{66} = (1/F_6^2)$

$f_{12} = -0.5 * (f_{11} * f_{22})^{1/2}$

F should be less than 1 for lamina to be safe. The maximum stress and the maximum strain failure criterion represent the material failure in the principal direction only. The Tsai Wu Failure criteria take into account the interaction of the stress components in all directions. In this work, this criterion has been applied for finding the damage around the hole drilled with different drills. Therefore, it is a more realistic approach to predict failure than the maximum stress and strain theories.

4.4. Tsai-Hill Failure Criterion

In this theory assumed the failure in the material takes places only when the distortion energy is greater than the failure distortion energy yield criterion to anisotropic materials

(SXX/f1T)2-(SXX*SYY/f1T)2+(SYY/f2T)2+ (SXX/f12)2 < 1 (6)

5. Finite Element Prediction of Failure Index

Finite element analysis model was developed using a standard FEA software package to evaluate the behavior of UD-GFRP. Various stages of operation involved is as detailed below:

- Create 2D composite plate with dimensions of 25 x 25 x 3 mm and constrained all degree of freedom on surrounding edge of the plate.
- Choose the element for plate is PLANE42.
- Specify the Material properties for the composite UD-GFRP lamina
- Specify the Ultimate strength for UD-GFRP
- Create center hole with 6mm on plate because 6 mm drill bit diameter used for drilled plate.
- Depending upon the feed rate and point angle of the drill, apply the calculated pressure from equation (1) along the circumference of the hole.
- Using fine mesh option the generated model has been meshed as shown in figure 1.
- The model is solved for the determination of various induced stresses in the laminate viz. σx, σy, σxy.
- The Tsai-Wu failure index can be obtained for the applied loading condition from the post processed result as shown in figure 2.

Table 1. *Material property of Laminate.*

Parameter	Value
Modulus of elasticity, E_X (GPa)	48
Modulus of elasticity, E_Y (GPa)	12
Poisson’s ratio	0.25
Bulk modulus, G_{XY} (GPa)	6

Table 2. *Strength property of Laminate.*

Parameter	Value
Longitudinal tensile strength, X_L (GPa)	1000
Longitudinal compressive strength, X_C (GPa)	- 6000
Transverse tensile strength, Y_L (GPa)	30
Transverse compressive strength, Y_C (GPa)	- 150
Shear Strength S_{LT} (GPa)	40

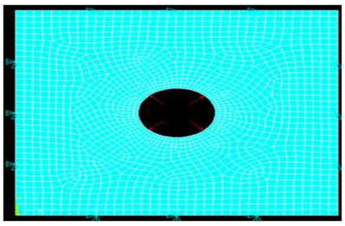

Figure 1. *Load and Boundary conditions of the UD-GFRP.*

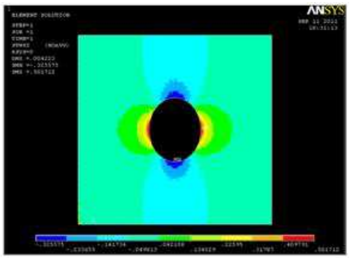

Figure 2. *Tsai-wu failure index for UD-GFRP.*

6. Theoretical Calculation of Failure Index

The global stress vector obtained from FEA results should be converted into local stress vector using the following transformation matrix.

$$\begin{Bmatrix} \sigma_{11} \\ \sigma_{22} \\ \tau_{12} \end{Bmatrix} = \begin{bmatrix} C^2 & S^2 & 2SC \\ S^2 & C^2 & -2SC \\ -SC & SC & C^2 - S^2 \end{bmatrix} \begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \tau_{xy} \end{Bmatrix} \quad (7)$$

But, for this case, Fiber orientation angle of the UD-GFRP is zero. Hence the global stress of the laminate is equal to local stress values.

The Tsai-Wu failure index using equation (5) was calculated employing the local stress values and ultimate strength of the laminate. When the failure index value tends to become more than one then the lamina tends to become fail. Similarly, failure index was computed using Tsai - Hill failure theory employing equation (6). The obtained failure index using Tsai-Wu criteria is tabulated in table 3.

Table 3. *Failure index for various pressure.*

S.NO.	Applied Pressure (GPa)	Theoretical Tsai-Wu failure index	Numerical Tsai-Wu failure index	Error (%)	Thrust force (N)
1	10	0.324	0.310	4.2	282.7
2	15	0.45	0.428	4.77	424.05
3	20	0.68	0.637	6.2	565.7
4	25	0.88	0.806	8.33	706.75
5	30	1.2	1.028	14.3	848
5	27	1.16	1	13.7	765

7. Results & Discussion

Trial and error method is used to find critical thrust pressure with constant drill bit size. Gradually increased thrust pressure from zero when the Tsai-Wu failure index reached at one in ANSYS that pressure is called critical trust pressure. From the previous table, it can be observed that for 6 mm hole diameter, the critical thrust pressure is about 27 MPa.

The above conclusion arrived from Tsai-Wu failure criteria is further validated from other theoretical failure criteria viz. Maximum stress theory, Maximum strain theory and Tsai-Hill failure theory. Thus obtained value of failure index and mode of failure are tabulated as under.

Table 4. *Failure prediction by various failure criterion.*

Tsai Wu failure index	Maximum stress theory	Maximum stress theory	Tsai-Hill theory failure index
1	The matrix of the lamina failure (transverse direction failure)	The matrix of the lamina failure (transverse direction failure)	1.12

Critical feed obtained by using equation (1) for unidirectional laminate for 6 mm drill bit diameter can be calculated as tabulated in Table 5.

Table 5. *Critical feed rate for 6 mm drilled holes.*

Point angle of drill (degree)	Critical feed (mm/rev)
118	1.71
112	1.74
108	1.754
100	1.784
90	1.81

The effect of drill bit angle over critical feed rate is shown in graphical form in figure 3 as follows.

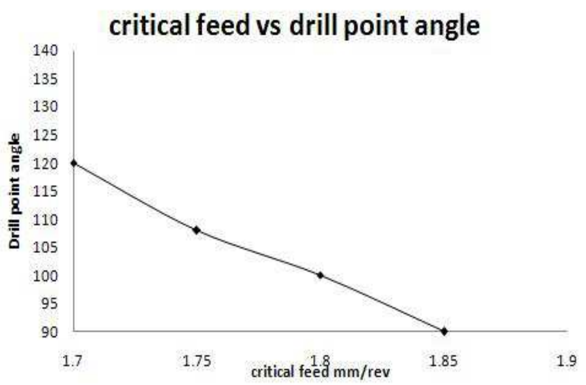

Figure 3. *Effect of drill bit angle over critical feed rate for UD-GFRP.*

8. Conclusions

The following conclusions can be drawn from the present research initiative:

- The unidirectional composite plate fails when the thrust force reaches above critical force value.
- The critical feed rate of the drilling increases with decrease the point angle of the drill.

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