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Analytical Study of Thrust Force for Drilled Composite

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Abstract: Composites are laminated materials and can be manufactured to achieve required mechanical properties. The delamination is major issue in machining of composites. Due to delamination there is change in mechanical properties of composites. So, the model based on linear elastic facture mechanics, laminated plate theory and mechanics of cutting is used and modified for the case of ellipticity ratio 1.

Key words: composite, drilling, thrust force.

INTRODUCTION

The Composite materials have got wide importance now a days because these materials have replaced conventional solid metals in many application areas. For example, in automobile field the cars are being manufactured from key to chassis by glass/carbon fibre composites. In composites, the combination of two constituent materials leads the final product to have properties that are not identical to any of the constituent. The advantage of composite materials lies in their high strength which yields high stiffness. Low density of composite materials allows for low weight of components. Non-isotropic nature of composites creates opportunity to tailor their properties according to design requirements. This flexibility in design allows fiber orientation in the direction of major stresses. Length to diameter ratio of fibers is called aspect ratio. Continuous fibers have longer aspect ratios. While using composites in various fields such as aircraft, space, automotive, sporting goods, marine etc. They undergo manufacturing processes. For assembly, drilling of composite parts is necessary. Carbon fiber reinforced plastic (CFRP) materials have wide application areas. The drilling operation causes defects to the CFRP components in the form of delamination, micro-cracks, matrix burning, Fiber pull out etc. The analytical study for drilling induced thrust have been done by S. Jain et al. [1]. The optimum machining parameters are required for minimum defects to the components in drilling operation. Due to the damage generated during such machining operations there is change in mechanical behavior of the composite product. R. A. Kishore et al. [2] Studied drilling parameters to get maximum after drilling tensile strength using the Taguchi method. The optimum levels of the drill point geometry, the cutting speed and the feed rate have been determined. Drilling is the method which accompanies 40% of all material removal processes. The drilling induced damage could be reduced with the use of special drill bits. C. C. Tsao [3] conducted the drilling experiments with step-core drill to investigate the thrust force. The delamination is related to the thrust force. The parameters taken were diameter ratio, feed rate and spindle speed. Results shows that diameter ratio and feed rate have most significant influence on thrust force. The geometrical parameters of drill have influence on the behavior of drilled composites. The effect of all the forces acting on drill is represented by resisting torque and thrust force. The action at the chisel edge is not truly a cutting action, but it is pushing action into material like a wedge. The optimization of drilling parameters like cutting speed, feed, point angle and chisel edge width in drilling of glass fiber reinforced polymer (GFRP) composites is done by Vinod Kumar Vankanti et al. [4]. The aspects of the mathematical analysis and use of nontraditional methods in machining of composites is reviewed by H. Hocheng et al. [5]. Among the various drill types twist drill causes larger thrust force, but still it is most economic to use twist drills. As drilling induced thrust force increases beyond critical thrust force the delamination occurs. The evaluation of delamination factor in drilling of CFRP composites is done by C. C. Tsao et al. with the use of ultrasonic C-scan technique [6]. The technique of acoustic emission for measurement of residual tensile strength of drilled composite was used by Navid Zarif Karimi et al. [7]. Acoustic emission means the generation of transient elastic waves by the rapid release of energy from localized sources within a material which is under deformation. This is most accurate method for determining mechanical properties of composite materials. The study of residual tensile strength after drilling in flax natural fiber epoxy composite was done by Abdul Nasir, A.A. et. al. [8]. In this study, they found that feed rate is the most significant parameter to affect the residual tensile strength. The experimental work for the stated material for hole quality is done and given by Girish Pandit et al. [9].

ANALYTICAL STUDY

Expression for critical thrust force

The value of thrust force causing delamination is called critical thrust force. Analytical model to calculate critical thrust force is given by S. Jain et. al. [1] for unidirectional laminate. This model is referred and modified to calculate critical thrust force for woven laminate of carbon fiber phenol composite specimen.

The thrust force which is assumed to act along the axis of drill and acts as point load, depends on process and geometric parameters. The vertical movement of drill dw_0 causes deflection of lamina, and it causes delamination. The energy balance equation obtained from Linear Elastic Fracture Mechanics [1] is given as,

$$Pdw_o = GdA + dU \quad (1)$$

Where, G is crack propagation energy, dU is infinitesimal strain energy, and dA is increase in crack area. The crack

propagation area is assumed as of elliptical shape for UD laminates, but for woven laminate it is assumed to be circular. From Timoshanko's theory [1] the deflection of an elliptical plate of dimensions a and b, which is assumed to be clamped, and subjected to a central point load P is,

$$w = wo\left(1 - \frac{x^2}{a^2} - \frac{y^2}{b^2}\right)^2$$

Where,

$$wo = \frac{P}{\pi ab\left[\frac{6D11}{a^4} + \frac{4(D_{12}+2D_{66})}{(a^2b^2)} + \frac{6D_{22}}{b^4}\right]}$$

For circular delamination zone of woven lamina i.e. for a=b,

$$wo = \frac{Pa^2}{\pi[6D_{11}+4(D_{12}+2D_{66})+6D_{22}]} = \frac{Pa^2}{\pi}Y^* \quad (2)$$

Where,

$$Y^* = \frac{1}{[6D_{11}+4(D_{12}+2D_{66})+6D_{22}]}$$

And

$$D_{11} = \frac{E_{11}h^3}{12(1-v_{12}v_{21})},\ D_{22} = \frac{E_{22}h^3}{12(1-v_{12}v_{21})},$$

$$D_{12} = \frac{v_{12}E_{22}h^3}{12(1-v_{12}v_{21})},\ D_{66} = \frac{Gh^3}{12}$$

Also, the expression for strain energy in unidirectional laminate given by [1] as,

$$U = 4\pi abw_0^2\left[\frac{D_{11}}{a^4} + \frac{D_{22}}{b^4} + \frac{2}{3}\frac{(D_{12}+D_{66})}{a^2b^2}\right]$$

For a=b,

$$U = \frac{4\pi w_0^2}{a^2}\left[D_{11} + D_{22} + \frac{2}{3}(D_{12}+D_{66})\right] \quad (3)$$

Putting value of w_0 from equation (2) in eq. (3),

$$U = \frac{4P^2a^2}{\pi}X^* \quad (4)$$

Where $X^* = \frac{[D_{11}+D_{22}+\frac{2}{3}(D_{12}+D_{66})]}{[6D_{11}+4(D_{12}+2D_{66})+6D_{22}]}$

Taking infinitesimal increase in area of delamination as,

$$dA = \pi(a+da)(b+db) - \pi ab = \pi(adb + bda) = 2\pi adb = 2\pi bda$$

For a=b,

$$dA = 2\pi ada \quad (5)$$

Differentiating Eq. (2) and Eq. (4) w.r.t. a,

$$dw_o = \frac{2Pa}{\pi}Y^*da \quad (6)$$

$$dU = \frac{8P^2a}{\pi}X^*da \quad (7)$$

Hence, using above equations (1), (5), (6) and (7) the relation for critical thrust force is given by,

$$P^* = \pi\sqrt{\frac{G_{IC}}{(Y^* - 4X^*)}}$$

Thus, modifications have been made in above relations to get thrust force at which delamination will start in bidirectional laminate.

Analysis of model for CFRP specimen

The modified model is used to calculate the critical thrust force for CFRP specimen explained in [8]. The modified model considers the term neglected by [1], which has effect on value of critical thrust force at increased specimen thickness. The properties of material are used here as shown in table 1. As phenol and epoxy matrix materials have closer values of crack propagation energy, same value of 250 J/m^2 is used.

Table 1: Material properties of CFRP woven specimen

E_{11} (Pa)	E_{22} (Pa)	G_{12} (Pa)	v_{12}	G_{IC} (J/m^2)
7E+10	7E+10	5E +09	0.1	250

The bending stiffness values are calculated for the thickness of 0.39 mm, and shown in table 2.

Table 2: Bending stiffness values (N-m) for woven CFRP specimen

D_{11}	D_{22}	D_{12}	D_{66}	X^*	Y^*
0.38025	0.38025	0.03802	0.02471	0.20354	0.20354

The critical thrust force value obtained for CFRP specimen from the model is 187 N. this value is compared with the values for other materials.

RESULTS AND DISCUSSION

The critical thrust force is calculated and compared with the other materials like glass/epoxy, kevlar/epoxy and boron/epoxy composites [1]. The plot of critical thrust force vs type of material is shown in fig. 1.

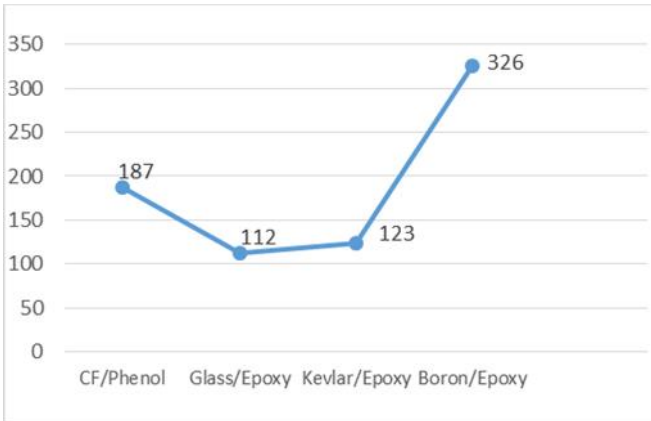

Fig.1: Critical thrust force (N) vs type of material

The value of critical thrust force decreases as we reach to the bottom lamina. Hence the graph showing the variation of critical thrust with increase of specimen thickness is shown in fig.2. The specimen consisting of 8-plies is considered here.

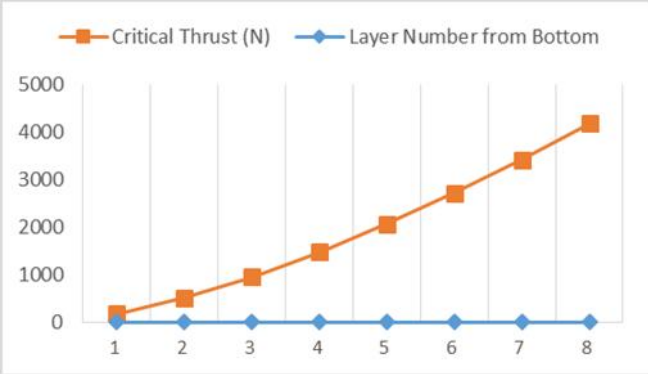

Fig.2: Critical thrust vs Layer number from bottom

The variation of critical thrust for all the four composites is compared as shown in fig.3.

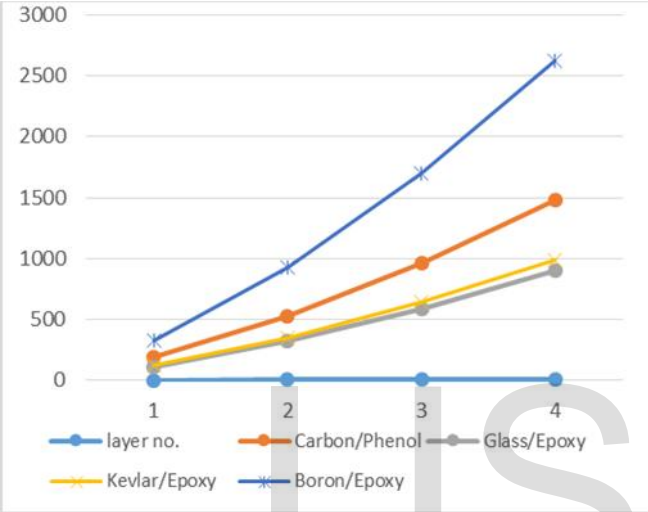

Fig.3: Variation of critical thrust for fiber composites

There is difference in values obtained by the model given by [1] and modified model, because one of the term in previous model was neglected. That difference is shown in graph in fig. 4. The percent difference remains constant of value 2 percent.

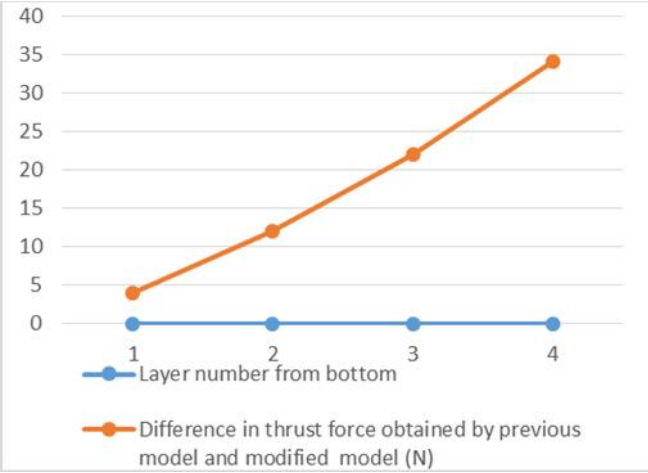

Fig. 4: Difference in critical thrust force (N) for two models

The percentage difference in critical thrust force by the two models above is constant for each material though layer thickness goes on increasing, but value is different for different materials. The percent difference values for four different composites are shown in fig. 5.

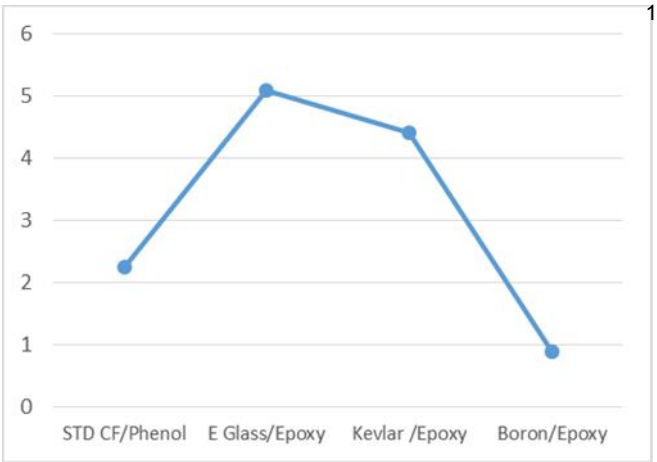

Fig. 5: Percent difference in critical thrust force obtained by two analytical models

CONCLUSION

The thrust force coming on composites in drilling process mainly depends on feed rate and chisel edge width. As can be seen from graph, the critical thrust force for carbon fiber phenol composite is 187 N at last lamina. Compared to boron/epoxy (326 N) it is lower, but still it is advisable to use carbon fiber due to its lower cost compared with boron fiber. Boron fibers are six times costlier than carbon fibers. Also boron fibers have more density of 2.34 g/cm^3 than carbon fibers which leads more weight of the structures. As thickness of lamina from bottom increases the critical thrust force increases. The variation is nearly linear for carbon fiber phenol composites. Comparison between different composites for critical thrust shows that glass and Kevlar composites with epoxy matrix are having closer values of critical thrust force. The term containing ratio of bending stiffness values was neglected in previous model. The plot for difference in critical thrust obtained by two models shows that value increases with thickness and it will become significant at higher thicknesses. Though percentage difference remains constant for each material, its value is different for different materials as shown in fig. 5.

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