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Concept of Delamination Strength in Drilling of Composites

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Abstract

The aim of this paper is to present the novel concept of *delamination strength* in drilling of fiber-reinforced polymer matrix composite laminates. Delamination strength is proposed here as a material characterization property in the drilling of fiber-reinforced composite laminates (FRCL). The experimental set up comprises a machining center and solid carbide twist drills. The materials used for the study is carbon fiber-epoxy composite material of overall laminate thickness 8.8 mm containing unidirectional carbon fibers. Two specimens, each of different ply thickness, are employed in the tests. A series of drilling experiments are performed and the delamination parameters at relevant stages of the drilling process are measured. The strength is found to be constant for a given fiber-reinforced laminate material. Other results show that the size of the final delamination crack is dependent on the ply number at which it initiates as well as a delamination drilling *index.* The average value of the delamination drilling index obtained for a woven laminate indicates that the delamination crack front travels fastest in the 28-ply material followed by the 57 ply, with the woven material showing the least propagation speed. As a laminate property that couples the flexural and energy release properties of the material, the drilling delamination index, along with the concept of delamination strength, describe the drilling delamination crack growth behaviour of fiber-reinforced composite laminates in a simple and compact fashion while indicating fair agreement with other linear models reported in the literature.

Keywords: Composites, drilling, delamination strength, index

1. Introduction

Fiber-reinforced composite laminates (FRCLs), though used in a variety of engineering applications, are prone to delaminations during drilling. Many researchers have tackled the delamination problem from different angles: e.g. Davim & Reis (2003) proposed a new and comprehensive approach to selecting cutting parameters for damage-free drilling of carbon fiber-reinforced epoxy composites. Their approach was based on a combination of Taguchi's techniques and the analysis of variance. Their objective was to establish a correlation between cutting velocity and feed rate, and between cutting velocity and delamination. They claimed to obtain this correlation by multiple linear regression. However, it is not known whether their results have been independently verified. Others are: Zhenchao, Kaifu , Yuan, Shunuan, & Hui (2014): a model for predicting the critical thrust force based on linear elastic fracture mechanics and plate bending theory; Yibing, Runze, Tishun, & Yongming (2014): delamination growth under fatigue loading; Obinna, Krishna, Zhifang, & Tapabrata (2014): delamination detection based on error and noise polluted natural frequencies; Liu & Islam (2013): a model for mixed-mode delamination of composite laminates; Won & Dharan (2002): the effects of different drill geometries on delamination damage; Sackey & Owusu-Ofori (2004): determinination of an index to characterize delamination behaviour in drilling and Shukla & Khanna (1993), who studied the nature of the fiber closing forces on the advancing delamination crack; they obtained results that indicate a straight-line relationship between crack size and time. Dipaolo (1996) obtained similar results as Shukla, with crack arrests and re-initiation appearing as a remarkable feature of their crack growth pattern.

For a given material the single most important factor that can be controlled to limit delamination is the thrust force, being itself is a function of many other factors., which include (1) cutting speed, (2) hole/tool diameter, (3) tool design/geometry, (4) tool wear, (5) material hardness, (6) laminate properties and type of composite material (unidirectional, woven, stacking order), (7) crack propagation energy of material, (8) and whether it is tool entry or exit that is taking place.

The objective of this research is to build upon the works of Sackey & Owusu-Ofori (2004), Shukla & Khanna (1993) and Dipaolo (1996), by introducing a concept of *drilling delamination strength* to deepen understanding of the delamination phenomenon in drilling of fiber-reinforced composite laminates.

2. Initial considerations

The authors define drilling delamination strength, P_c/n, at a ply level, as the maximum resistance that a composite laminate can put up against the external delaminating thrust force at that ply level. P_c is the force value of the strength and n the corresponding ply number. For example, a delamination strength of 24 $N/_1$ means that a minimum force of 24 N is required to cause delamination in the first ply of the material. The direction of the thrust force is assumed perpendicular to the plies. Clearly, the quantity P_c/n should desirably be as high as possible to minimize delamination. Resistance to delamination is generally expressed mathematically as (Ho-Cheng and Dharan, 1990):

$$P_c = B\sqrt{2G_{IC}D_C} \qquad (1)$$

where D_c = flexural rigidity of material under the drill, P_c = critical load acting on the laminate, G_{IC} = energy release rate of the laminate and B = a constant.

Equation 1 indicates that delamination strength depends on the G_{IC} and D of the material ahead of the drill tool, inferring that two things must happen for delamination to occur:

1. a flexing out (dependent on D_c.), and
2. inter-laminar cracking causing delamination propagation (dependent on G_{IC}.).

High values of D_c and G_{IC} indicate strong laminate resistance to delamination, implying P_c/n, will be correspondingly high. Thus, while D_c primarily determines where delamination may occur (i.e., ply location); both G_{IC} and D_c, chiefly G_{IC}, determine how far and fast a delamination crack travels.

Many external factors that affect delamination adversely do so by influencing an increase in the external thrust force value (but the delamination strength, P_c/n, being a material property, remains constant). A higher thrust force causes more delamination by ensuring that delamination occurs at a higher value of H so that, from Equation (2) the delamination crack size, a, consequently increases.

3. Experimental procedure

The experimental set up comprises a machining center and solid carbide twist drills. The materials used for the study are: 57- and 28-ply carbon fiber-epoxy composite material of 8.8 mm laminate thickness containing unidirectional carbon fibers of type T-300 and type T-700 respectively. A series of drilling experiments are performed and the delamination parameters (a & H defined below) at relevant stages of the drilling process were measured. The following equation for a drilling delamination index, S is recalled from Sackey and Owusu-Ofori (2004):

$$S = \frac{a}{H} \qquad (2)$$

where a = the crack size, H = distance from exit plane at onset of delamination. S may be intrinsically related to the energy release characteristics *(G_{IC})* and the stiffness of the yet uncut portion of the laminate directly under the advancing tool.

4. Results, observations and discussion

4.1 Index S and delamination strength

The average value of the drilling delamination index obtained from the data for the woven laminate, 2.58 mm/mm, indicates that the delamination crack front is traveling at an average of 2.58 times the rate the tool is feeding into the work. Ideally, this value should be as small as possible. The average values of the drilling delamination index obtained for the 28-ply and the 57-ply unidirectional laminates are respectively, 4.38 and 3.73 mm/mm.

Although its precise relationships to G_{IC} and D_c, are yet to be determined through further experiments, it is easy to see from Equation (1) that the drilling delamination index is clearly a property of the laminate. It effectively links or couples the amount of delamination crack movement in the lateral direction (determined primarily by G_{IC} and represented in magnitude by a) with the amount of flexing in the axial direction (determined by D_c, and represented by *H).*

A dynamic form of Equation 1 is obtained by modeling variation in D_C linearly as

$$D_C = D_0\,(1-n/k) \qquad (3)$$

and intuitively representing S, by correspondence, as $S = D_0/k$,

where n (ply number after delamination) = 0, 1, 2, ……k, and k = ply number from exit plane where delamination starts.

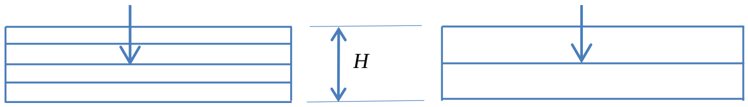
Then Equation 1 becomes

$$P_{c/n} = B\sqrt{2G_{IC}S(k-n)} \qquad (4)$$

Thus the drilling delamination S, has been incorporated in the delamination strength as intuitively expected.

4.2 Comparison of 28-Ply laminate and 57-Ply laminate

The differences observed in the drilling delamination behavior of the unidirectional (*UD*) specimens are chiefly due to differences in ply thickness (or number of plies), since laminate thickness is the same in each case. In the 28-ply laminate, delamination initiates at the top of second ply from the bottom whereas in the 57-ply it does so at the top of fourth ply from the bottom.



(a) 57-ply: n = 2, k = 4 (b) 28-ply: n = 1, k = 2

Figure 1. Comparison of the relationship of the ply flexure, *k*, *n*, and location, *H*, where delamination initiates for (a) 57-ply laminate and (b) 28-ply laminate

If G_{IC} is assumed constant and *Pc/n* is written as

$$P_{c/n} = B\sqrt{(k-n)}$$

,

where Q = $B\sqrt{2G_{IC}S}$,

Then for the 57- ply laminate,

$$P_{c/2} = Q\sqrt{(4-2)} = Q\sqrt{2}$$

,

and for the 28-ply laminate

$$P_{c/1} = Q\sqrt{(2-1)} = Q,$$

showing the former to be of higher delamination strength. This modeling result agrees with the finding noted earlier, that with the same laminate thickness the 28-ply specimen suffers more damage than the 57-ply laminate under similar conditions.

Alternatively if delamination initiates in the last ply from the bottom it will do so at a higher value of *H* in the 28-ply specimen. If delaminations occur in this manner, then both cases will register delamination as occurring in their respective last ply; however, in the 28-ply laminate delamination would have started at a higher value of *H* (Equation 2), and the 28-ply laminate would experience greater delamination damage. This is because the greater single-ply stiffness of the last ply of the 28-ply laminate enables it to bend with a larger curvature than in the 57-ply laminate, other things being equal. Moreover, the initial delamination crack size of the 28-ply laminate (a continuous, uninterrupted growth) is likely to be greater in this case.

5. Concluding remarks

The *drilling delamination strength* proposed in this work builds upon the earlier concept *of drilling delamination index*. The two concepts work in conjunction to accommodate the vast number of factor combinations which characterise the material-process system in regard to delamination crack initiation and propagation. A key finding from the last two equations is that ply thickness has a bearing on delamination strength. This deepens our understanding of the delamination phenomenon in drilling. Thus the delamination strength characterization, building upon the concept of drilling delamination index (a laminate property that couples the flexural and energy release properties of the material), describes the drilling delamination crack growth behaviour of fiber-reinforced composite laminates in a simple, compact and comprehensive fashion, while indicating fair agreement with the linear models of Dipaolo (1996) and Shukla and Khanna (1993).

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