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Quantifying Edge Defects in Drilled FRP Composites

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QUANTIFYING EDGE DEFECTS IN DRILLED FRP COMPOSITES

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ABSTRACT

Fiber Reinforced Polymer (FRP) composites are being increasingly used as replacements for metals in engineering applications. Though these composites are manufactured in near-net shape, machining is often necessary for integration and assembly. The most common machining operation performed on these materials is drilling. A commonly observed defect in drilling is edge defects which include incomplete fiber cutting. This report discusses a model which estimates edge defects during FRP drilling. Results predicted by the model are compared to experimental observations and possible techniques to characterize defects in FRP drilling are discussed.

Keywords: FRP composites, drilling, edge defect.

INTRODUCTION

The use of fiber-reinforced composite materials in engineering applications has been increasing steadily over the past years. A composite material can be defined as "a multiphase material that has been engineered to consist of more than one material type" (Callister, 1999). Composites usually consist of a hard reinforcement material embedded in a soft matrix. Based on the type of reinforcement, they can be classified as fibrous and particulate. The focus here is entirely on Fiber Reinforced Polymer (FRP) composites. FRPs are made of individual lamina which is a layer of parallel fibers set in the polymer matrix. FRP laminates are characterized by the order of orientation of the reinforcing fibers of the individual layers, which also largely determines the strength and application of the laminate (Jones, 1999).

FRPs are being increasingly used as replacements for metals in many engineering applications as they provide higher strength-to-weight ratios and as they can be designed locally to have optimal engineering properties. FRP panels are used extensively in the construction of aerospace structural members (Ffield, 2005).

Although FRPs can be manufactured to near-net-shape, some features such as holes can only be generated by machining operations. Drilling is extensively performed in composite panels that are used as aerospace structural members (Ffield, 2005). There are more than a million drilled holes in modern commercial aircraft. This being the case, the precision of drilled holes is of vital importance. Imprecision in the form of edge defects, burrs, local delamination etc. increase the cost and labor input of manufacturing, as well as decrease the quality of the final part. Currently, manual deburring is performed on drilled parts in the aerospace industry to remove these edge defects. Conventional approaches to minimizing defects include the use of clamps and backup material. This is not entirely acceptable as many structures such as, for example, those with blind holes cannot easily accommodate these changes due to the complexity and accessibility of the workpiece.

Numerical and analytical models are well suited for studying machining of FRPs to minimize defects. Though empirical models are easy to utilize and provide useful data, they cannot be entirely relied upon given the wide range of material properties inherent in composites. Analytical models on the other hand, attempt to establish a relationship between material properties and machining behavior, and the same model can be used for various material combinations. Due to high anisotropy and heterogeneity, composites pose several challenges for accurate modeling. These modeling issues have been discussed in Vijayaraghavan and Dornfeld, 2005.

This report discusses the imprecision at the hole edges while drilling FRPs and presents an analytical model to characterize the same (Vijayaraghavan, 2006). The objective of this work was to understand what affects hole quality and improve it by design. The report argues that the delamination of composite layers during the final stages of drilling leads to edge-defects around the drilled hole due to incomplete fiber cutting. It attempts to quantify these defects using a simple plate-mechanics model. Following the model discussion, results from the model are compared with experimental observations. Various techniques to characterize defects during FRP machining are then discussed. The paper concludes by offering suggestions for future work in this area.

LITERATURE REVIEW

There has been considerable work in the past decade studying the machining of FRP materials. Komanduri et al (1993) studied the orthogonal machining of FRP and concluded that fiber orientation is the major influencer of the machining behavior. Gordon and Hillery (2002) presented a detailed review of work in the machining of composite materials, though they do not focus much on drilling and delamination.

Hocheng and Dharan (1990) presented the first model that attempted to predict the occurrence of delamination during drilling of fiber reinforced composites. Two modes of delamination failure were identified, push-out during drill exit and peel-up during drill entry. During push-out delamination, the uncut-thickness decreases as the drill is fed through the material and at a critical point the drilling thrust force exceeds the inter-laminar bond strength resulting in delamination. Peel-up delamination occurs in the same mechanism, with the cutting action introducing a peeling force upwards forcing the layers to delaminate.

Jain and Yang (1994) revisited the work of Hocheng and Dharan and took into account anisotropy effects to determine the critical thrust force. Lachaud et al (2001) also used a similar fracture energy approach as the previous work, but modeled the drilling forces as a distributed load and took into account material anisotropy. Zhang et al (2001) presented a detailed study where the nature of delamination and improper fiber cutting during drilling were discussed. Based on extensive experiments, an empirical relationship was developed to predict the extent of delamination as a function of process parameters, material properties and drilling thrust force.

MODEL FORMULATION

The model explains edge defects during drilling by considering the cutting of the lamina in the workpiece that have been delaminated due to the axial thrust force. As the model is a first-order estimate, the Hocheng-Dharan (1990) model is used to predict the onset of delamination. From the Hocheng-Dharan model, the critical force for delamination, F_A^*, is:

$$F_A^* = \frac{8G_{IC}Eh^3}{3(1-v^2)} \tag{1}$$

where G_{IC} is the inter-laminar fracture energy, E is the fiber modulus, h is the thickness and v is the Poisson's ratio of the delaminating lamina.

Thus, the delamination thrust force is a function of the material properties of the laminate. As drilling continues after delamination, the delaminated lamina will suffer bending due to the thrust force of the drill. Hence, when the lamina gets cut, it is elastically extended, assuming that the deformation behavior of the lamina is small-strain linear-elastic. The bending and cutting of the matrix can be ignored, as the brittle fibers are responsible for the edge defects. Hence, delamination during drilling results in elastically extended fibers being cut. After the cutting happens, the cut fibers "springback" and it is apparent that lesser material than required has been removed, resulting in edge defects. This model does not actually capture the material removal process and assumes that all material in the feed-direction of the drill is removed by the cutting action. A schematic of this phenomenon is shown in Figure 1.

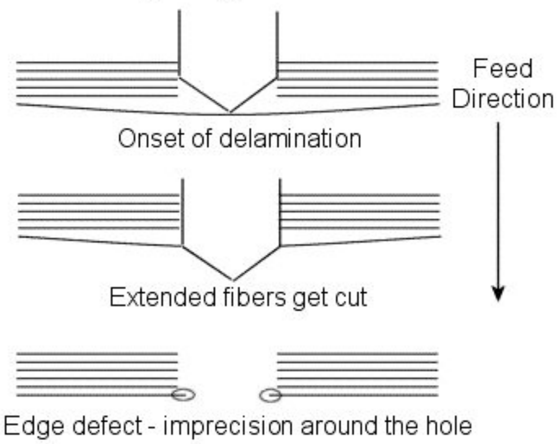

FIGURE 1: EDGE DEFECT SCHEMATIC.

To obtain a quantitative measure of the edge imprecision, the delaminated composite laminate is considered as a clamped plate under the load of a concentrated force. Keeping with the assumptions of the Hocheng-Dharan model, the composite is modeled as a clamped isotropic and homogeneous circular plate. The size of the plate is given by the extent of delamination (the delaminated zone). The thrust force causes the bending of the laminate. The displacement, *w(r),* due to bending as a function of the distance from the centre, *r*, is given as (Timoshenko, 1959):

$$w(r) = F_A(a^2 - r^2)/16\pi D \tag{2}$$

where F_a is the axial thrust force, *a* is the size of the delaminated zone and *D* is the rigidity modulus.

Using this relationship, the length of the fiber when under the influence of the thrust force just before cutting can be estimated as can the length of the fiber that is removed. Assuming uniform elastic extension, the length of the remaining fiber after cutting can be calculated as well as the size of the defect. The following treatment shows the defect calculated for the longest fiber section across the hole. The notation used is as follows:

L – Original length of the fiber, measured from the centre to the edge of the delaminated zone
l_{defl} – Length of the fiber as deflected
l_c – Length of fiber removed by drill

Using the arc-length formula:

$$l_{defl} = \int_0^L (1 + w'(r)^2)dr \tag{3}$$

$$l_c = \int_0^d (1 + w'(r)^2)dr \tag{4}$$

Hence, the fraction of fiber cut is l_c/l_{defl} and the remaining fiber length after the drill has been removed is $l_d = L \cdot (1 - l_c/l_{defl})$. Based on the radius of the required hole, the length of the defect, l_b can be calculated. This is normalized by the size of the hole and the normalized defect around the hole is expressed as $r_b = l_b/d$. The normalized defect is highest for the longest fiber section across the hole and it decreases moving away from this fiber to the extremities of the hole.

These calculations are also shown pictorially in Figure 2.

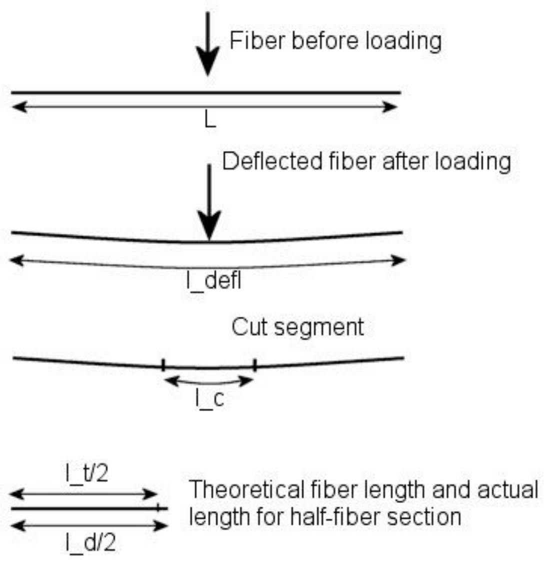

FIGURE 2: FIBER CUTTING.

APPLICATION OF THE MODEL

Hole Geometry

Using the model, the geometry of defects around a hole drilled through an FRP lamina can be seen in Figure 3. It can be seen that the defects are maximum for the fiber sections that are longest across the hole and that the resultant hole is elliptical and not circular as intended. Lachaud et al (2001) also discuss the observation of this kind of a defect during drilling. This corresponds to the case of using a 5mm drill with a High Modulus CFRP (Carbon-Fiber Reinforced Polymer) workpiece with a thrust force of 200 N, assuming a constant delaminated zone size of 2.5*r* (where *r* is the drill radius).

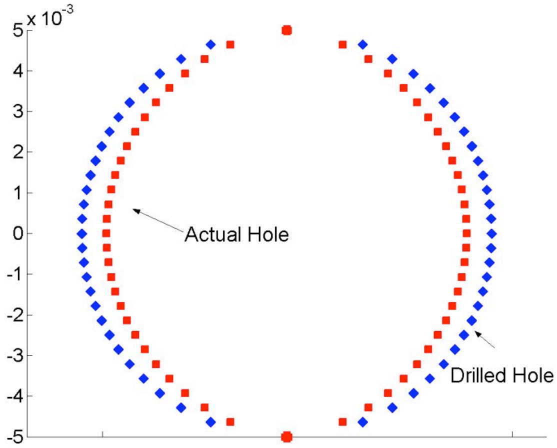

FIGURE 3: HOLE GEOMETRY PREDICTION.

Effect of Thrust Force

It can be seen from the model that the relative imprecision around the hole increases with the thrust force. This is studied in Figure 4, where the relative imprecision r_b is plotted as a function of varying thrust force and drill radii. The material is HM-CFRP and a constant delamination zone size of 2.5*r* is assumed.

From the figure, it can be observed that the relative imprecision increases monotonically with increasing thrust force. The relative imprecision also increases with increasing hole radii, implying that the absolute imprecision will increase even more rapidly with increasing hole radii. It can also be noted from the figure that until a critical thrust force which corresponds to the critical delamination force, the model predicts that no defects will occur.

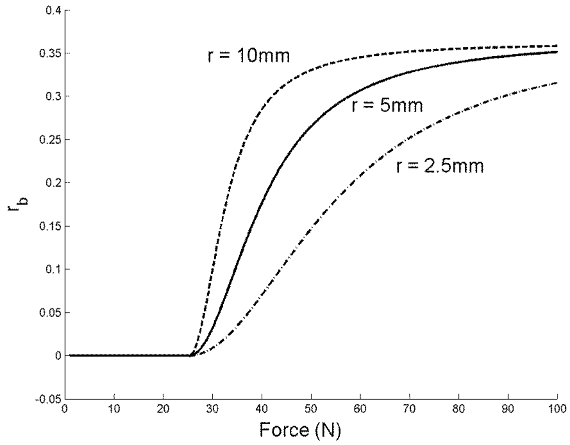

FIGURE 4: EFFECT OF FORCE AND 'R'.

Effect of Process Parameters

From a practical point of view, it is important to study the effect of drilling parameters like feed on the extent of edge imprecision. Several studies have established the relationship on feed and thrust force in drilling. Shaw (1957) proposed the following relationship between feed and thrust force:

$$F_A = k_1 (fd)^{(1-a)} + k_2 d^2 \tag{5}$$

where F_A is the axial cutting force, *f* is the feed in mm/sec and *d* is the diameter of the drill in mm. *a*, K_1 and K_2 are experimentally determined constants. Won and Dharan (2002) used Shaw's equations to model the relationship between feed and thrust force for drilling High Modulus CFRP with a Carbide drill. The thrust force was measured for experiments with varying drill sizes and the feed. From this data, the coefficients of Shaw's equations were calculated for this material, and are as follows: a = 0.4011, K_1 = 31.31, K_2 = -.0571.

Using this data, the effect of feed on the defect size can be studied. Figure 5 shows the effect of increasing feed on r_b for three different drill radii. As feed increases, so does the thrust force and hence, r_b. Thus a relationship between process parameters and defect size can be realized, and this information can be used to set limits on process parameters in order to minimize defects. As before, the material used is a high-modulus carbon fiber-polymer (HM-CFRP) and a constant delamination width, k=2.5 is assumed.

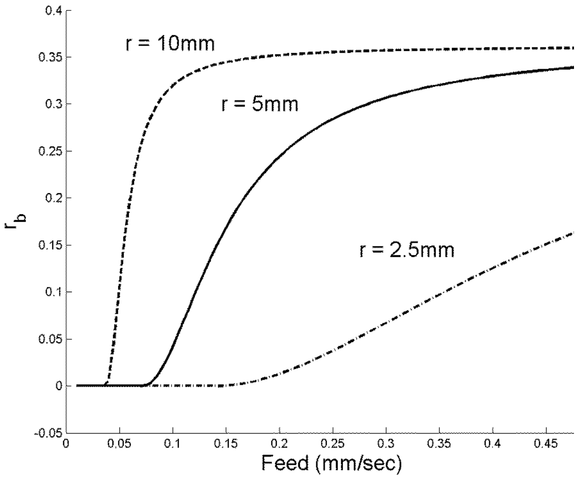

FIGURE 5: EFFECT OF FEED AND 'R'.

Effect of the Delaminated Zone

From the model it can be seen that the uncut fiber length depends on the size of the delaminated zone. Hence it is important to accurately characterize the size of the delaminated zone in order to have an effective model. Figure 6 shows the variation of the edge defect with changing force for two constant delaminated zone sizes. It can be seen that the defects markedly increase with increasing delaminated zone size.

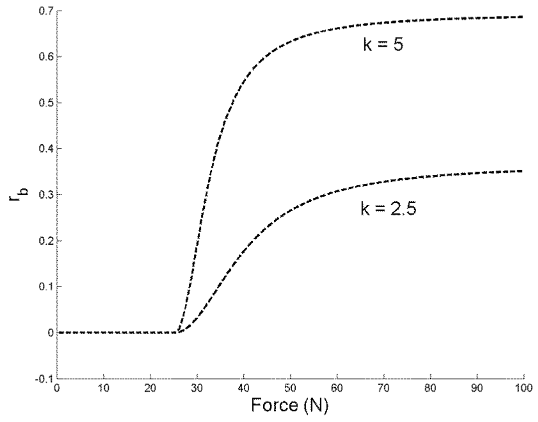

FIGURE 6: EFFECT OF DELAMINATED ZONE SIZE.

Existing work (Hocheng, 1990; Jain, 1994; Lachaud, 2001) characterizing the delamination of FRPs during drilling employ Linear Elastic Fracture Mechanics (LEFM). While LEFM successfully predicts the critical thrust force for the onset of edge defect initiation, it is not adequate for predicting the length of the delaminated zone. LEFM prescribes that when the critical strain energy release rate is achieved in the material during drilling, the delaminating crack propagates indefinitely resulting in an infinite delaminated zone. From practical observations it is quite clear that this is not the case and that the delaminated zone is limited to only a small region immediately around the hole and not to the entire workpiece that is being machined.

Experimental observations by Hocheng (1988) and Zhang et al (2001) show that the size of the delaminated zone is related to the thrust force during drilling. Hocheng (1998) measured the size of the delamination zone for drilling through different FRP composites including Graphite/Epoxy and Glass/Epoxy and used a linear-fit to explain the relationship between the thrust force and the delaminated zone size. Zhang et al (2001) measured the size of the delaminated zone as a function of thrust forces for drilling CFRP using a 5.5mm drill. This is shown in Figure 7. Using this information, the edge defect can be calculated as a function of both thrust force and delaminated zone size, which is shown in Figure 8.

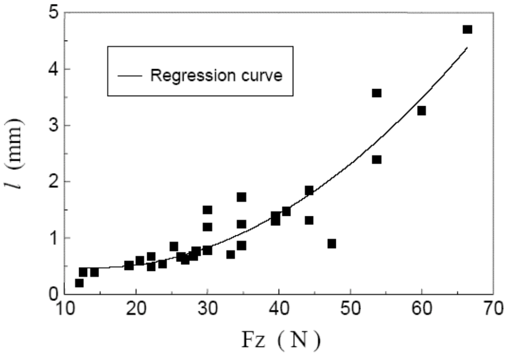

FIGURE 7: DELAMINATED ZONE VARIATION WITH THRUST FORCE (ZHANG ET AL, 2001).

The results indicate that the increase of the edge defect is sharper when the delaminated zone varies as a function of thrust force.

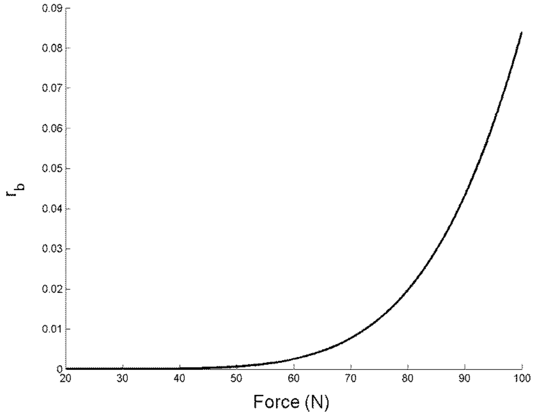

FIGURE 8: DEFECT VARYING WITH THRUST FORCE APPLIED TO DATA FROM ZHANG ET AL (2001).

EXPERIMENTAL COMPARISONS

Based on studying drilled CFRP samples, it is apparent that it is difficult to accurately measure the size of the defect around a drilled hole. This is because defects are not uniform as the model predicts them to be. Actual defects around a drilled hole include phenomena such as fiber pull-out which can be very difficult to model. During measurement, it is also difficult to differentiate between fibers of different lamina. Due to this, the uncut-fibers around the hole cannot be attributed solely to the phenomena the model is trying to capture. Thus, quantitative measurements are not very accurate and a qualitative assessment of the model is performed.

The model predicts an elliptical defect profile around the hole, which was seen in Figure 3. Also, the model predicts that the size of the defect increases with increasing feed. This can be seen in Figures 9 and 10, which are two cases of drilling through HM-CFRP material at low (.1mm/rev) and high (1mm/rev) feeds, respectively.

The experimental observations also show that there is significant downward bending of the uncut fibers due to the drill feed. Hence, the defects are out of the cutting plane which may also cause debris accumulation and improper mating during assembly.

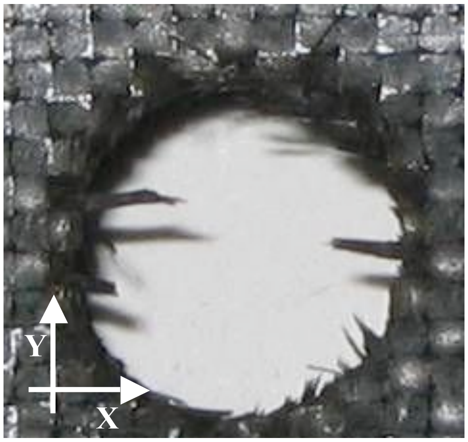

FIGURE 9: DEFECT IN LOW-FEED DRILLING.

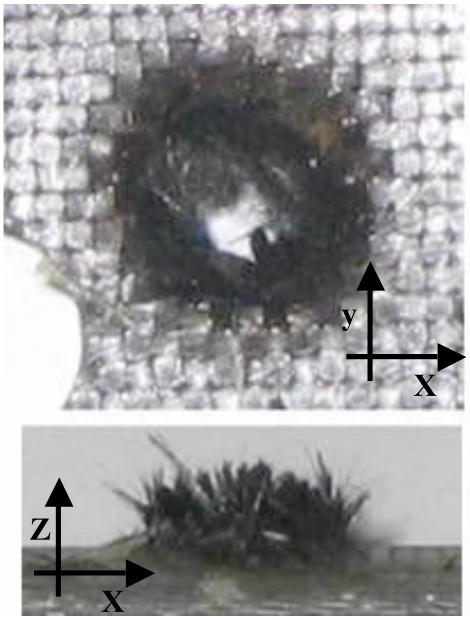

FIGURE 10: DEFECT IN HIGH-FEED DRILLING.

TECHNIQUES TO QUANTIFY EDGE DEFECTS IN FRP MACHINING

Measuring the defects around a hole edge during FRP machining is challenging due to several reasons, including the out-of-plane nature of the defects and the brittle fibers breaking during measurement. Also, sometimes the defects themselves may not be of concern, but the debris they cause during assembly may be an issue. It is again instructive to draw comparisons between FRP drilling and metal drilling to better understand techniques for quantitative characterization as metrology and process control methods for metal machining are more advanced.

Non-contact optical techniques have been successfully demonstrated to measure edge-defects formed during micro-drilling (Ko, 2004). Since these methods do not rely on the properties of the material being machined, they are ideal for application in the case of FRPs. Ko and Park (2004) demonstrated that the Conoscopic Holography method is best suited as it can capture very small features, which is very important in the case of FRPs as the fibers can be only a few-hundred microns in diameter. It is also possible to use the Conoscopic method to obtain 3D profiles of the burr. This information, along with the mechanical properties of the fibers can be used to estimate the behavior of the edge defects during assembly.

Ultimately, a standardized method to formally characterize the tolerable defect around an edge is needed for optimal manufacturing with minimal waste of effort from over-precision. Several characterization methods have been used for metal burrs (Gillespie, 1996; Kato; Berger, 2004) and these can be adapted and extended to include FRP machining as well.

CONCLUSIONS AND FUTURE WORK

Although the model does not precisely predict the defects around a hole, it is offered as a “first-step” in quantifying defects generated in FRP machining. It will be possible to make a better prediction after taking into account the complex non-linear phenomena that take place during FRP machining. Although empirical methods may be currently better suited to predict defects, analytical models that take into account material properties are useful in material design.

Future work includes reformulating the model by taking non-linearity effects into consideration. This would necessitate revisiting the derivation of the critical thrust force for delamination and including non-linear factors such as material and geometric non-linearity, as well as transverse shear deformation which is important in laminated polymer composites. With a non-linear approach, it will also be possible to arrive at an analytical estimate of the delaminated zone size. Also, using some of the techniques outlined in the previous section, experimental tests have to be employed to assess the accuracy of the model. More sophisticated models can also take into account cutting dynamics; however, given the complexity of the drill geometry and the different phases in the workpiece, these models will need numerical approaches to arrive at practical solutions to this complex problem.

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