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Experimental analysis of GFRP laminates subjected to compression after drilling

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ABSTRACT

This paper presents an experimental study of drilling-induced delamination on the compressive properties of woven glass fiber-reinforced epoxy composites. In the drilling of laminated composites, interlaminar cracking or delamination has a detrimental effect on compressive properties. The onset of delamination and the extent of the damage are governed by the cutting forces developed during the drilling process. High cutting forces, in turn, result from the use of improper drilling parameters. This study investigates the effects of feed rate and spindle speed on delamination and residual compressive strength. The composite laminates were cut into the standard dimensions of compression after impact specimens. The drilling of composite specimens was conducted at three different levels of spindle speed and feed rate based on general full factorial design. Analysis of variance was used to find the percentage contribution of the drilling parameters and it was found that feed rate has the most significant influence on the residual compressive strength. A polynomial regression model was also developed to express the residual compressive strength as a function of the selected process parameters.

1. Introduction

Glass fiber reinforced plastics (GFRPs) are characterized by having a combination of high specific strength and high stiffness. As a result of these remarkable properties, GFRPs have attracted increasing attention for use in many industries [1]. However, GFRPs have specific characteristics that affect their machining behavior. The mechanisms of cutting composite materials are considerably distinct from those observed during cutting isotropic materials. The application expansion of composite materials calls for the use of different types of machining operations; of which conventional drilling with twist drill is one of the most commonly used processes in the assembly of composite sub-components. However, different damage types occur during drilling such as delamination, fiber pull-out and matrix burning which degrade mechanical properties of the composite structures [2,3,4].

One of the most common damage mechanisms in GFRPs is delamination, where the layers of the material separate from each other. Delamination is caused by the low interlaminar strength of the composite laminate and high transverse cutting forces [5]. El-Sonbaty *et al.* [6] identified two forms of delamination called 'peel-up' at the drill entrance and 'push-out' at the exit side of the workpiece, as shown schematically in Fig. 1. Peel-up occurs as the drill enters the laminate. After the cutting edge of the drill comes into contact with the laminate, the cutting force acting in the peripheral direction is the driving force for delamination. It generates a peeling force in the axial direction through the slope of the drill flute resulting in separation of the layers from each other at the top, forming a delamination zone. The peeling force is a function of tool geometry and friction between the tool and workpiece. Push-out is the delamination mechanism occurring as the drill reaches the exit side of the material, where the uncut thickness is smaller and the resistance to deformation decreases. At some point, the load exceeds the interlaminar bond strength and delamination occurs. This happens before the laminate is completely penetrated by the drill. A different drill geometry and cutting conditions can reduce the delamination by lowering the thrust force. In practice, it has been found that the delamination associated with push-out is more severe than that associated with peel-up [7–9].

Delamination reduces the strength and stiffness, thus limiting the life of a structure. Furthermore, it causes stress concentration

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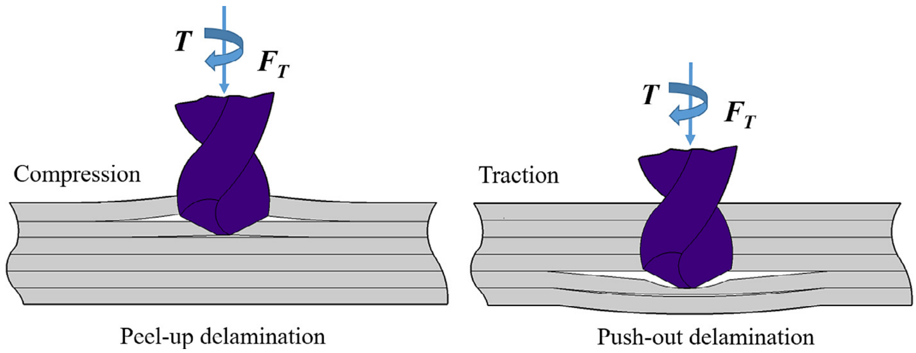

Fig. 1. Delamination mechanisms in the drilling of laminated composites; peel-up at the entrance and push-out at the exit side.

in load-bearing plies and local instability, leading to a further growth of delamination that results in a compressive failure of the laminate. In these two cases, delamination leads to a redistribution of structural load paths that, in turn, precipitates structural failure. Hence, delamination indirectly affects the final failure of the structure and its life [10,11],. Depending on the size of the delamination, it can reduce the static and fatigue strength and the compression buckling strength. In order to quantitatively measure the amount of delamination, Chen [12] proposed a method to obtain the value of the conventional delamination factor that assumes the form as Eq. (1).

$$F_d = \frac{D_{\max}}{D_0} \tag{1}$$

The conventional delamination factor is not appropriate because the crack size does not properly represent the damage magnitude. Furthermore, this procedure does not indicate the damaged area. A novel approach to measure the delamination factor was proposed by Davim *et al.* [13], namely, the adjusted delamination factor, which is calculated through Eq. (2). The first part of Eq. (2) shows the size of the crack contribution and the second part shows the damaged area contribution.

$$F_{da} = \alpha \frac{D_{\max}}{D_0} + \beta \frac{A_{\max}}{A_0} \tag{2}$$

where A_{max} is the area related to the maximum diameter of the delamination zone (D_{max}), and A_0 is the area of the nominal hole (D_0). The parameters α and β are used as weights in the parts of Eq. (2), defined as below:

$$\beta = \frac{A_d}{A_0 - A_{\max}} \text{ and } \alpha = 1 - \beta \tag{3}$$

Replacing Eq. (3) into Eq. (2) yields:

$$F_{da} = F_d + \frac{A_d}{A_{\max} - A_0}(F_d^2 - F_d) \tag{4}$$

Different parameters used in preceding equations are illustrated in Fig. 2.

In order to reduce delamination, it is necessary to develop procedures to select appropriate cutting parameters, because an unsuitable choice could lead to unacceptable material degradation. Several researchers investigated the effects of input variables, feed rate, cutting speed, point angle of twist drill bit, etc. on drilling-induced delamination. Davim and Reis *et al.* [14–18] conducted a series of experiments on different composite materials including GFRPs, carbon fiber reinforced plastics (CFRPs), and metal matrix composites to understand the effects of drilling parameters on delamination and other characteristics of these materials. Their results show that delamination increases with increasing feed rate and cutting speed. The effect of feed rate on delamination is more

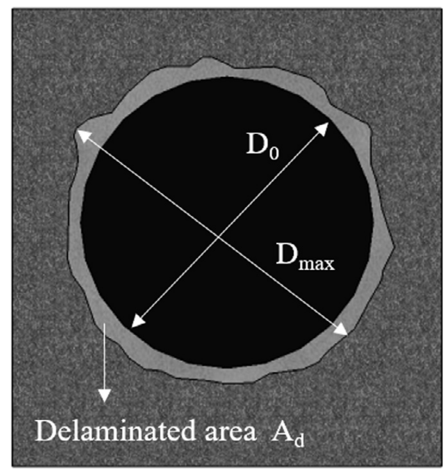

Fig. 2. Schematic of the measurement of the delaminated area A_d and maximum diameter D_{max}.

than that of the cutting speed. In contrast, the works conducted by Khashaba *et al.* [19,20], show that delamination decreases with increasing cutting speed during drilling of woven-ply GFRP composite laminates. Gaitonde *et al.* [21] also reported that delamination decreased with cutting speed during high-speed drilling of thin woven-ply CFRP composite laminates. They also observed that delamination increases with increasing drill point angle. However, Kilickap [22] observed that the delamination tendency decreases with increasing point angle of twist drill during conventional drilling of UD-ply GFRP composite laminates. To summarize, almost all researchers reported that drilling-induced delamination increases with increasing feed rate at any different cutting speeds using various drill bits, while two different behavior for cutting speed and drill point angle effects were reported.

Several researchers studied the effect of cutting parameters on mechanical properties of drilled composite laminates. Persson *et al.* [23] investigated the effect of drilling-induced damages on the strength and fatigue life of carbon/epoxy laminates subjected to static and fatigue loads. They observed that drilling-induced damages significantly reduced the static and fatigue strengths of pin-loaded laminates; the effects on the strengths of compressively loaded laminates were less pronounced. Kishore *et al.* [24] studied the effect of cutting speed, feed rate, and drill point geometry on residual tensile strength of the drilled unidirectional glass fiber reinforced epoxy composites. They observed that feed rate has the least influence and cutting speed has the maximum influence on residual tensile strength, and it increases substantially with an increase in cutting speed. In contrast, Zarif *et al.* [25] observed that feed rate has the most important effect and cutting speed