Analytical models of composite material drilling

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Abstract Drilling of composite material structures is widely used for aeronautical assemblies. When drilling, damage to the composite laminate is directly related to the cutter geometry and the cutting conditions. Delamination of the composite materials at the hole exit as directly related to the axial force ($F_Z$) of the cutter is considered to be the major such defect. To address this issue, an orthotropic analytical model is developed in order to calculate the critical force of delamination during drilling and a number of hypotheses for loading are proposed. This critical axial load is related to the delamination conditions (propagation of cracks in the last layers) and the mechanical characteristics of the composite material machined. A numerical model is also drawn up to allow for numerical validation of the analytical approach. A comparison between these analytical and numerical modelings and experimental results from quasi-static punch tests led to the choice of the loading hypothesis closest to the experimental conditions. The selection of corresponding load permits to model the drilling critical thrust force on delamination and then to optimise the cutting conditions. The dimensions and geometrical shape of the cutter are of considerable importance when it comes to choosing this load. The present article focuses on the case of the twist drill, which is commonly used to drill thick plates. However, this work can be adapted to different cutter geometries.

Keywords Drilling · Composite materials · Delamination · Analytical models · Numerical models

1 Introduction

Composite materials are widely used to build aeronautical structures. Drilling is currently implemented for assembly by bolts or rivets as well as for structural repairs. The twist drill used for metallic materials is very commonly used to drill composite structures [1]. A number of studies have been conducted into the quality of machining during the drilling operation. Hocheng et al. [2] calculated the critical thrust force for a number of tools in order to minimise the drilling defects. Rahmé et al. [3] developed an orthotropic analytical model when drilling a composite material. Furthermore, Rahmé et al. [4] studied the different defects of the composite material drilling. Indeed, Roudge et al. [5] and Ramulu et al. [6] studied the machining of multi layers materials containing composite material. In these studies, delamination at the exit of holes drilled through a composite plate is considered to be a major defect. These defects have been identified as due to the delamination of layers, cracks in the matrix and breakage of fibres. Rahmé et al. showed that the cracks at the hole exit are initiated under the web of the twist drill and propagated by the main cutting edges.

A number of authors [7–9] have modelled the critical thrust force of delamination during drilling in relation to the thickness remaining under the cutter, using numerical and
analytical approaches. Hocheng et al [10] consider the thrust force of the drill as being the cause of delamination and developed a relation between the critical force of delamination, the mechanical characteristics of the material and the thickness remaining under the cutter. They assume an isotropic behaviour of the material and a surface of circular cracks under the cutter. This hypothesis leads them to use the classic theory of bending of thin circular plates embedded at the ends and subjected to a concentrated point load to determine the critical force of delamination. Rahmé et al. [3], Piquet [11] and Lachaud et al. [12] calculated the critical force of delamination for an orthotropic material. They modelled the un-machined part of the plate remaining under the cutter into a thin circular plate embedded at the ends with a diameter equal to that of the cutter and subjected to a uniformly distributed surface load. An analytical model allows the critical axial force of delamination applied by the cutter to be modelled in relation to the critical energy of propagation of cracks in mode I for a given thickness.

In the present study, a similar approach based on classical plate theory [13] allows the critical force of delamination during drilling of composite materials with orthotropic behaviour to be predicted. Numerical modelling using the finite elements method was developed using Samcief to validate the analytical hypothesis retained. A number of loading hypotheses (loading cases) were tested and compared in order to propose the model closest to reality for a given cutter/material couple. Furthermore, a special measurement of the delamination force allows to validate the analytical modelling. The material used for this study is a thick plate of carbon epoxy (T800/M21) comprising 80 layers with a quasi-isotropic layering sequence.

Finally, this work contributes to choosing a loading hypothesis corresponding to the maximum critical force of delamination. This hypothesis may lead to an idea as to the element of the active part of the cutter that has the preponderant role in delamination. In addition, using special tools reduces delamination [14,15]. The results of the present article can thus be used as a database to then develop improved cutter geometry to machine composite materials. At the same time, a number of authors [16,17] developed a model to predict the thrust force as a function of spindle speed, feed rate and drill diameter. These models can be related to the calculated critical thrust force in order to determine the critical cutting conditions.

2 Analytical approach

During drilling and when the drill approaches the exit, the remaining thickness of material under the cutter becomes reduced, which leads to impaired rigidity of the un-drilled layers. This contributes to deformation of the last layers due to bending and a resultant propagation of cracks in the matrix, thus causing delamination. Figure 1 shows delamination and the ripping of fibres on the last layer of the thick plate. The exact shape of the delaminated surface is hard to predict.

The analytical approach applied to drilling is based on a number of assumptions. Initiation of cracks is assumed to be due to pressure of the cutter on the last layers. Propagation of the cracks is directly related to the normal stresses perpendicular to the plane of the layers [3]. As a result, the kinetic energy of propagation applied within the scope of a mode I linear elastic fracture mechanism allows initiation of delamination to be predicted. To do so, the part of the plate located under the cutter on exit was modelled as a thin circular orthotropic plate embedded at the ends and with a diameter equal to that of the cutter (Fig. 2). This approach does not take into consideration the global deflection of the plate. It is just applied to a reduced thickness of material under the cutter for a number of layers of less than or equal to eight. In the present article, a number of loading hypotheses are proposed and a compar-