DRILLING OF THICK COMPOSITE STRUCTURES WITH PILOT HOLE USING A TWIST DRILL

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Abstract

The drilling process is widely used in the assembly of composite structures. The twist drill is the most commonly used cutter as for metallic structures. Delamination at the hole exit is considered as the major defect during drilling of composite laminates. A solution to minimize these defects at the exit of the hole is to drill using a pilot hole. This process called reaming eliminates the chisel edge effect which is important when drilling composite structures. This paper presents an analytical and a numerical model that calculates the critical thrust force at delamination when drilling composite materials. This model does not take into account the chisel edge effect but only the principal cutting edge effect of the twist drill. The numerical model validates the analytical model. Comparison between the presented models and the experiment was made and a close correlation between results is obtained. This study can be used to minimize drilling delamination at the exit of the hole.

1. Introduction

The structures used in aeronautical and space contain nowadays a large percentage of composite materials. This growing interest is due to the strength/mass ratio relatively high for these materials compared to metals. Drilling is a commonplace operation to make bolted or riveted assemblies of composite structures in aeronautical. Special aeronautical parts, such the case of assembling the wing and the fuselage, have a relatively large thickness (greater than 10 mm). Drilling of thick composite structures using a conventional twist drill produces defects at the exit of the hole. These defects diminish the strength of the structure to failure. A solution to minimize these defects is to drill a pilot hole. The present paper focuses on the drilling of thick composite structures with pilot hole using a twist drill in order to minimize the defects at the exit of the hole.

The drilling of composite materials produces defects at the entry, at the wall and at the exit of the hole [1]. Delamination at the exit of the hole is considered to be the major defect [2]. The mechanisms involved in initiation and propagation of delamination at the hole exit were identified by Rahmé et al. [3]. Matrix cracks are initiated under the chisel edge of the twist drill and interlaminar delamination is then propagated by the main cutting edges. Tsao et al. [4] developed an analytical approach for the determination of the position of the onset of delamination during the drilling of composite laminates.

The defects at the exit of the hole are directly related to the axial cutting force which in turn depends on the tool geometry and the feed rate per tooth [5]. Delamination at exit side, can be controlled by taking into account the relationships between machining parameters and forces and torque [6]. The size of the delamination zone has been showed to be related to the thrust force developed during drilling [7]. The optimal drilling thrust force is defined as the minimum force for which delamination is initiated [8]. This critical thrust force was predicted by several authors. Rahme et al. [9] showed the effect of the chisel edge on the critical thrust force at delamination when drilling thick composite material with a twist drill. Lachaud et al. [10] proposed a model which links the axial penetration of the drill bit to the conditions of delamination (crack opening mode I) of the last few plies. Rahme et al. [11] showed the effect of various parameters on the critical thrust force at delamination. Hocheng et al. [2] presented the expression of the critical thrust force at delamination when drilling with a twist drill and other special drills as saw drill, core drill and candle stick drill.

According to Jain et al. [12], the contribution of chisel edge to the thrust force is often up to 40-60%. They deduced that, with a pilot hole, the delamination can be reduced significantly since the chisel edge no more interacts with material. Moreover, the chisel edge width has been identified as an important factor contributing to the thrust force and hence delamination [13]. Tsao et al. [14] determined the optimal range of chisel edge length with respect to drill diameter in order to avoid delamination.

Nowadays, the common used method in order to drill holes for rivets and bolts assembly in thick composite structures (20, 30 or 40 mm thickness) is composed of three steps:

- Drilling of pilot hole,
- Reaming of the hole (drilling with pilot hole),
- Countersinking the head of rivet or bolt.

In this paper, the drilling of thick composite plates using a conventional twist drill with pilot hole is studied. An analytical model of predicting the critical thrust force at delamination is developed when drilling composite structures using a twist drill with a pilot hole. This model is based on fracture mechanics. Another numerical model is developed using finite elements method. Both models are validated by punching tests.

2. Analytical model

During drilling when the drill approaches to the exit, the thickness of non-drilled material remaining under the drill decreases progressively. This leads to a reduction in the rigidity of non-drilled plies and therefore bending of last plies. According to Rahme et al. [3], the cracks at the exit of the hole are initiated under the chisel edge and propagated under the action of the two main cutting edges of the twist drill. The exact shape of the delaminated surface at the exit is difficult to be predicted. Drilling with pilot hole minimizes the defects produced by the chisel edge. The diameter of the pilot hole equals the diameter of the chisel edge. A smaller diameter will not completely cover the length of the chisel edge. At the same time, drilling a pilot hole of diameter greater than the diameter of the chisel edge produces also delamination. In this paper, the diameter of the pilot hole is taken equal the length of the chisel edge and designed by 2b (Figure 1).

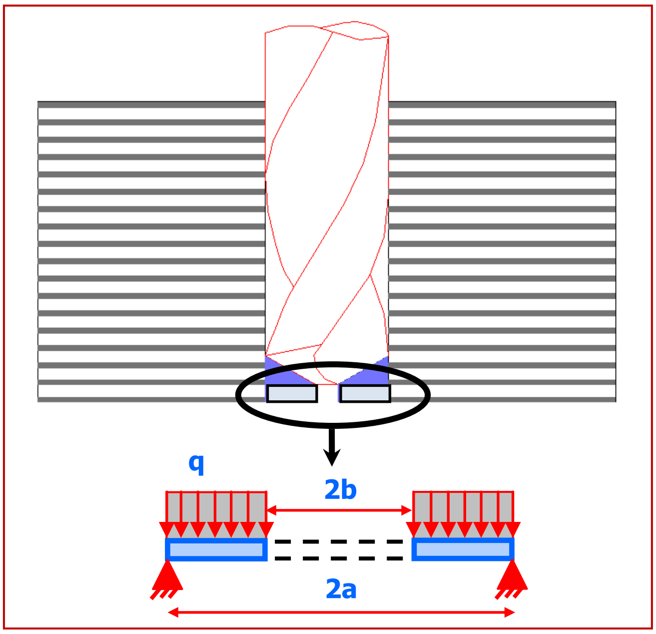


Figure 1. Analytical model for drilling thick composite plates with pilot hole.

At the exit of the hole, the thickness of remaining non-drilled plies under the drill decreases progressively when the drill approaches to the exit surface. According to Rahme et al. [3], the laminate does not resist to the circumferential bending moments. As consequent, the part of the plate located under the main cutting edges is modelled by a simply supported thin circular orthotropic plate with a pilot hole as shown in Figure 1. The thickness of this plate is assumed small with respect to the hole diameter and the shear effect is then neglected. The outer diameter of this plate equals the diameter of the drill (2a). The inner diameter (diameter of the pilot hole) is also similar to the length of the chisel edge (2b). The effect of the main cutting edges is represented, in this paper, by a uniformly distributed loading q on the plate. The choice of this loading is related to the geometry of the main cutting edges in rotation.

An energetic approach based on the virtual work principle is applied to the plate under the drill in order to find the critical thrust force at delamination F_C.

During drilling, the motion of the drill can be associated to a small displacement dx. The thrust force of drilling produces an external work on the plate which is function of the distance dx. This work tends to produce bending of the plate and to propagate the cracks later. The conservation of energy can be written as :

$$\delta W = \delta U + \delta U_d \tag{1}$$

The radius of the drill (a) is the parameter which varies virtually. Consider δa the fictitious length of the cracks. Then, the elementary virtual work δW of the external forces is :

$$\delta W = \frac{\partial W}{\partial a}\delta a = \frac{\partial\left(\iint_S F\, dS\right)}{\partial a}\delta a \tag{2}$$

Where S is the surface of the plate.

The virtual variation δU of the potential energy U can be obtained by :

$$2U = \int_S \left[M_{xx}\frac{\partial^2 w}{\partial x^2} + M_{yy}\frac{\partial^2 w}{\partial y^2} + 2M_{xy}\frac{\partial^2 w}{\partial x\, \partial y}\right] dS \tag{3}$$

Moreover, the variation of the energy absorbed by the propagation of cracks is given by δU_d. This energy U_d is the product of the critical restitution energy corresponding to mode I (G_{IC}) and the circular surface :

$$U_d = G_{IC}\,.S = G_{IC}\pi\, a^2 \tag{4}$$

To find the work and the potential energy, the deflection w(r) of the simply supported circular plate of diameter (2a) must be calculated as a function of the thrust force. Using the plate theory developed by Timoshenko (1959) applied to axisymetrical circular plates, the equilibrium equation of the plate is given in polar coordinates for small deformations as :

$$\frac{d}{dr}\left[\frac{1}{r}\frac{d}{dr}\left(r\,\frac{d\,w(r)}{dr}\right)\right] = \frac{Q}{D} \tag{5}$$

Q is the shear at any point of the plate as function of the load q. For an orthotropic material, D is given by:

$$D = \frac{1}{8}(3D_{11} + 3D_{22} + 2D_{12} + 4D_{66}) \tag{6}$$

With :

$$\left|D_{ij}\right| = \sum_{k=1}^{n}\left(\overline{Q_{ij}}\right)_k\left(\frac{Z_k^3 - Z_{k-1}^3}{3}\right) \tag{7}$$

And Q_{ij} are the terms of the rigidity matrix of the plate.
Solving equation 5, the deflection w(r) of the plate at any point is obtained as:

$$w(r) = \frac{-q}{8D(\vartheta^2-1)(b^2-a^2)}\Bigg[\Bigg(2a^2b^2(1+\vartheta)\ln\frac{b}{a} + (b+a)\Big(\Big(-\frac{1}{2}\vartheta-\frac{3}{2}\Big)a^2 + r^2(\vartheta-1)\Big)(b-a)\Bigg)(1+\vartheta)b^2\ln\frac{r}{a} + (a^2-r^2)(\vartheta-1)\Bigg(b^2(1+\vartheta)\ln\frac{b}{a} + \frac{1}{4}\Big((3+\vartheta)b^2 + \Big(-\frac{1}{2}\vartheta-\frac{5}{2}\Big)a^2 + \frac{r^2}{2}(1+\vartheta)\Big)(b^2-a^2)\Big)\Bigg)\Bigg] \tag{8}$$

When ν is the Poisson’s ratio taken 0.3 in the paper based on material characterization tests. The deflection is replaced by its value in equation 2 and equation 3. Solving analytically equation 1 for F_C, the critical thrust force at delamination is obtained :

$$F_C = 16\pi D(a^2-b^2)^2(\vartheta-1)^2\sqrt{\frac{128\,G_{IC}}{b^4(\vartheta+1)K}} \tag{9}$$

Where :

$$K = \Bigg[\Big((-9D'+24D)\vartheta^3 + (9D'+24D)\vartheta^2 + (48D_{66}-24D+21D'-16D_{12})\vartheta - 16D_{12} + 3D' + 16D_{66}\Big)\frac{b^4}{48} + \frac{\big((24D-9D')\vartheta^2+18D'\vartheta-16D_{12}+16D_{66}-24D+3D'\big)(\vartheta+1)a^2b^2}{24} + \frac{Da^4}{2}(\vartheta-1)\Bigg]\ln\Big(\frac{b}{a}\Big)^2 + \frac{b^4(a^2-b^2)(\vartheta+1)}{4}\Bigg[-4D(a^2+b^2)(\vartheta-1)\ln b + \Bigg(\Big(3D-\frac{9D'}{8}\Big)\vartheta^3 + \Big(5D-\frac{9D'}{8}\Big)\vartheta^2 + \Big(-5D+\frac{25D'}{8}-\frac{8D_{12}}{3}+\frac{8D_{66}}{3}\Big)\vartheta + \frac{8D_{66}}{3} - \frac{8D_{12}}{3} + \frac{7D'}{8} - 3D\Bigg)b^2 + \Bigg(\Big(D-\frac{3D'}{8}\Big)\vartheta^3 + \Big(3D+\frac{3D'}{8}\Big)\vartheta^2 + \Big(D+\frac{11D'}{8}+\frac{4D_{66}}{3}-\frac{4D_{12}}{3}\Big)\vartheta - 5D + \frac{5D'}{8} + \frac{4D_{66}}{3} - \frac{4D_{12}}{3}\Bigg)a^2\Bigg]\ln\frac{b}{a} + \frac{(a^2-b^2)}{96}\Bigg[48Db^4(a^2+b^2)(\vartheta^2-1)\ln\Big(\frac{b}{a}\Big)^2 - 48Db^4(a^2-b^2)(\vartheta^2-1)\ln b + \Bigg(\Bigg(\Bigg(13D-\frac{39D'}{8}\Bigg)\vartheta^4 + 78D\vartheta^3 + \Big(88D+\frac{99D'}{4}-26D_{12}+26D_{66}\Big)\vartheta^2 + (-78D+42D'-44D_{12}+44D_{66})\vartheta - 101D + \frac{81D'}{8} - 26D_{12} + 26D_{66}\Bigg)b^4 - 2\Bigg(\Big(D-\frac{3D'}{8}\Big)\vartheta^2 + \Big(8D-\frac{3D'}{4}\Big)\vartheta + 7D - \frac{27D'}{8} - 2D_{12} + 2D_{66}\Bigg)(\vartheta-1)^2a^2(a^2+2b^2)\Bigg)(a^2-b^2)\Bigg] \tag{10}$$

And :

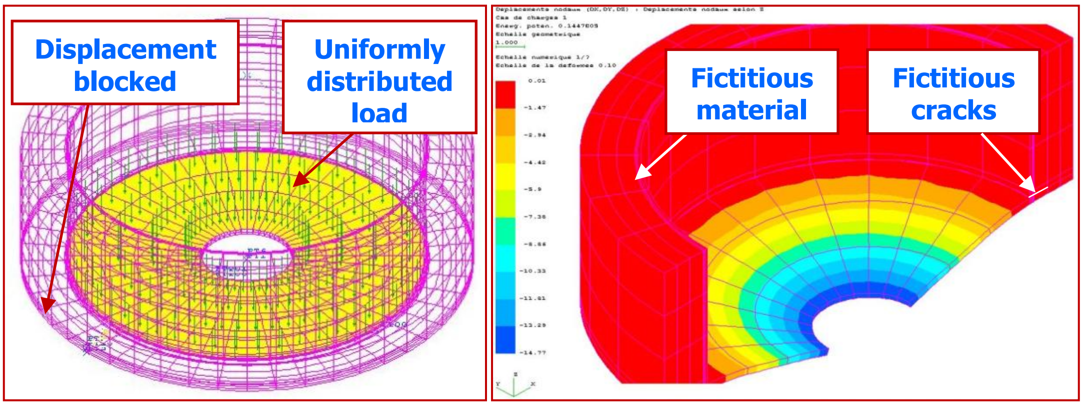
$$D' = \frac{(D_{11}+D_{22})}{2} + \frac{(D_{12}+2D_{66})}{3} \tag{11}$$

3. Numerical model

In this section, a numerical model based on the finite elements method is developed to validate the analytical model. This axisymetrical model was developed under Samcef. The same as for the analytical model, fictitious cracks are originally created by adding fictitious material on the circumferential boundary of the plate (Figure 2). These cracks are used to calculate the restitution energy along the crack corresponding to a given external load. Moreover, the model predicts the decomposition of the restitution energy with respect to different opening cracks modes. The same material and the same stacking sequences used in experimentation are considered in this section. In this model, mode II and III corresponding to opening cracks are neglected. The restitution energy is calculated using the virtual crack extension method (VCE) integrated in Samcef software. This restitution energy for mode I is determined for each node in front of the circumferential crack. The maximum value of the calculated restitution energy is selected. In the analytical model, constant restitution energy was taken. In reality for an orthotropic material, the resistance of one ply under the drill against delamination is not constant. The fibres resist in tension in the longitudinal direction more than in transverse direction.

The calculation of the maximum restitution energy is found for a number of plies non-drilled remaining under the drill varying from 1 to 6 and in function of the applied external load. A program under Linux and using the script TCL Shell is developed in order to run the calculation under Samcef several time. When the calculated maximum restitution energy equals the critical one, then the corresponding applied external load corresponds to the critical thrust force at delamination.

The boundary conditions of the model are presented in Figure 2-a. Figure 2-b shows half of the modelled hole. To model the simply supported plate, the thickness of the fictitious material is taken enough thick so that the fixed nodes are sufficiently far from the fictitious cracks. When the distance between the fictitious cracks and the fixed nodes becomes smaller and smaller, the model will be corresponding to the clamped circular plate.



(a) b)

Figure 2. Numerical model for drilling thick composite plate with pilot hole. (a) Boundary conditions and (b) Deflection of one ply remaining under the drill.

4. Experimental validation

In the experimental part, in order to find experimentally the critical thrust force, punching tests have been realized using tension/compression machine (Instron 8862). Carbon fiber reinforced epoxy polymer plates (CFRP) T800/M21 of thickness 20 mm are used. Quasi-isotropic of sequence $[90°,+45°,0°,-45°]_{S10}$ plates are made in the laboratory. The thickness of one ply is 0.25 mm. For this material, the critical restitution energy G_{IC} corresponding to propagation of cracks is taken equal to 800 J/m^2. This value is found by experimentation using the standard ISO 15024. In this paper, standard sharpened twist drill (DIN 1897) tapered without thinning of the chisel edge of diameter 15.8 mm is used to punch the remaining non-drilled plies. This twist drill was also used to drill a blind hole with pilot hole. The number of plies remaining non-drilled varies from 1 to 6 plies. The diameter of the pilot hole is taken equal to the length of the chisel edge 3.9 mm.

Figure 3 shows a punching test on the composite plate using a twist drill and the corresponding setup. The same setup was also used to drill the pilot hole and the blind hole.

The curve of the applied force by the machine during the punching test is saved as function of the displacement (Figure 4). The maximum force on the curve corresponds to the critical thrust force at delamination. The punching test is repeated by varying the number of non-drilled plies remaining under the drill. Finally, a curve of the critical thrust force is drawn in function of the number of delaminated non-drilled plies.

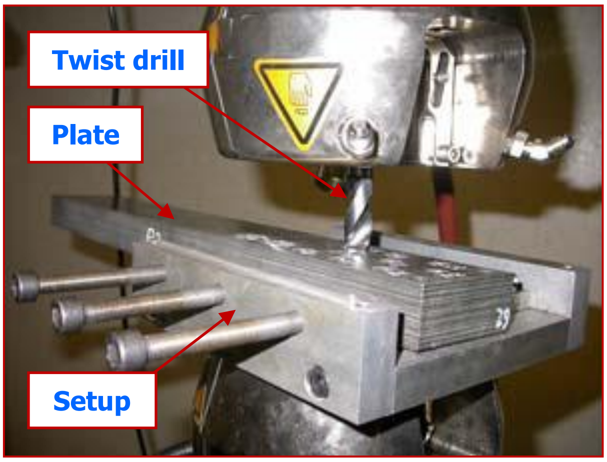


Figure 3. Experimental punching tests using Instron tension/compression machine.

Figure 4 shows the curve of the thrust force during the punching test of one non-drilled ply remaining under the drill. The thrust force increases in function of the drill displacement and reaches in this case a maximum value of 260 N. This value corresponds to critical thrust force at delamination for one non-drilled ply.

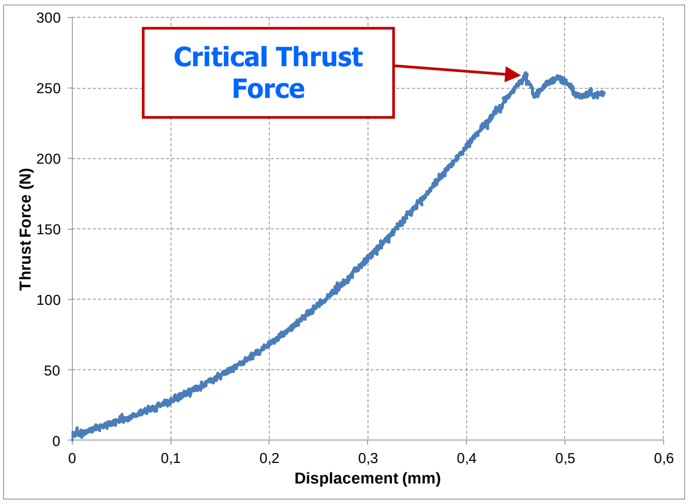


Figure 4. Punching test, curve of the thrust force for one ply remaining under the drill in function of the displacement.

5. Results and discussion

The results of the previous sections are presented in this paragraph. The critical thrust forces at delamination found analytically and numerically are compared with the experimental results. The critical thrust force is drawn in function of the number of delaminated plies remaining under the drill. Figure 5 presents the comparison for critical thrust forces at delamination of composite structures when drilling with pilot hole of modelling with experimentation. The model is characterized by a simply supported plate subjected to a uniformly distributed load. The numerical model validates the analytical model. An error of 4% between the models is found for one delaminated ply and a maximum error of 24% is obtained for five delaminated ply. This last error for five delaminated ply may be due to the fact that the analytical model doesn't take into account the shear.

The results of analytical model validate the choice of the boundary conditions and the external loading. Indeed, the results of experimentation and modelling are close. For six plies under the drill, the results are very close with an error of 8%. On the other hand, for two delaminated plies, a maximum error of 28% is found. However, the proposed analytical model is always conservative since it presents critical thrust force at delamination less than the results found in experimentation.

Finally, the results of this paper can be used to determine the critical cutting conditions at delamination when drilling with pilot hole. Drilling with a feed rate per tooth smaller than the critical feed rate avoid delamination at the exit of the hole. At the same time, these results may be applied on the case when drilling with a step drill.

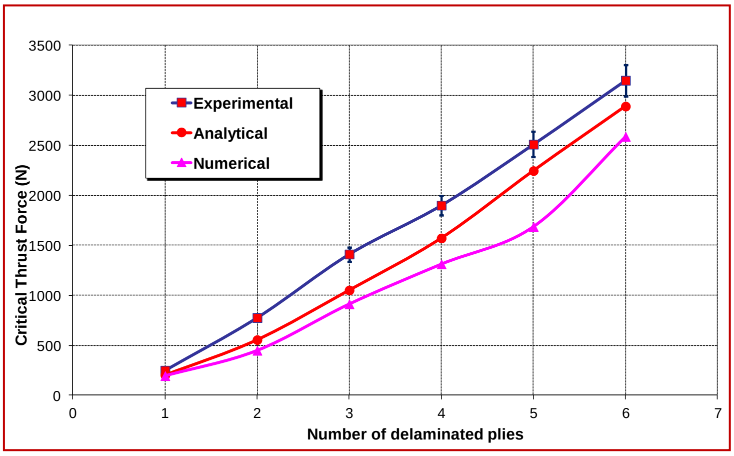


Figure 5 : Comparison between analytical and numerical model with experimentation tests.

6. Conclusion

A solution to minimize delamination at exit of the hole when drilling thick composite structure is to drill with a pilot hole. The pilot hole eliminates the effect of chisel edge which is important on delamination. In this paper, an analytical and numerical model is developed for drilling thick composite plates using a twist drill with a pilot hole. This model predicts the critical thrust force at delamination corresponding to propagation of the cracks. The numerical model validates the mathematical one. Punching experimental tests have been realized in order to validate the choice of the used boundary conditions and external loading. Close results have been found between theoretical and experiment. These results can be used to optimize the cutting conditions when drilling with a pilot hole. They can also be extended to find the critical thrust force at delamination when drilling with step drills.

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- The modeling of the manufacturing process,
- The virtual machining,
- The ermerging of new manufacturing methods.

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