Advanced School on Sandwich Structures 2008
ASSS 08
A. Torres Marques (Editor)

DRILLING PROCESS OF CARBON/EPOXY LAMINATES – THRUST FORCES STUDY AND MODELING

Luis M. P. Durão [1], Marcelo F. S. F. de Moura [2] and António T. Marques [2]

[1] ISEP/CIDEM – Instituto Superior de Engenharia do Porto
R. Dr. António Bernardino de Almeida, 431 – 4200 Porto – Portugal
e-mail: lmd@isep.ipp.pt

[2] DEMEGI / FEUP – Faculdade de Engenharia da Universidade do Porto
Rua Dr. Roberto Frias, s/n – 4200-465 Porto – Portugal
mfmoura@fe.up.pt
marques@fe.up.pt

INTRODUCTION

For the past decades composite materials are increasing their importance as one of the most interesting group of materials, due to their unique properties of low weight, high strength and stiffness. Although earlier development was related with aerospace and aeronautical industries, recent years had seen the spread of their use in many others like automotive, transport, energy, construction and sport goods.

One of the main machining operations needed for part assembly in structures is drilling, as it is necessary to use bolts, rivets or screw when joining different pieces. Generally, it is accepted that drilling can be carried out using conventional machinery, with adaptations. As composites are non-homogeneous, drilling causes some difficulties. Normally some damage in the region around the hole circumference is evident, after operation is completed. Delamination is one of the most frequent damage as it reduces bearing and fatigue strength of the composite part [1]. Besides that, composites machining can cause several damage modes such as delamination, fibre pull-out, matrix thermal degradation and others [2]. Delamination, or any other damage, is an unwanted outcome. The main mechanism responsible for delamination is the indentation effect of the quasi-stationary drill chisel edge which pushes aside the material at the centre as it penetrates into the hole [3] – figure 1.

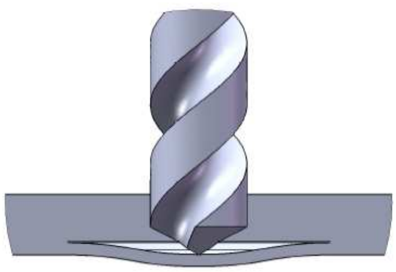

Figure 1 – Delamination mechanism

Normally, two kinds of delamination are identified: peel-up delamination and push-out delamination. In this work the authors are concerned with the latter only. Delamination can be reduced by a cautious selection of drilling parameters – cutting speed and feed rate –, drill material – tungsten carbide instead of high speed steel – and drill bit geometry, as evidenced by several papers published on this subject [4-11].

A reduction in thrust force normally leads to less delamination. This outcome is evidenced by the Hocheng-Dharan model for delamination onset [12] that relates the thrust force necessary for delamination onset with the uncut thickness and mechanical properties of the material. The well known resulting expression of this model is

$$F_{crit} = \pi \left[\frac{8 G_{Ic} E_1 h^3}{3(1-\upsilon_{12}{}^2)} \right]^{1/2} \quad (1),$$

where the critical thrust force for the onset of delamination (F_{crit}) is related with properties of the unidirectional laminate like the elastic modulus (E_1), the Poisson ratio (ν_{12}), the interlaminar fracture toughness in mode I (G_{Ic}) and the uncut plate thickness (h).

Other possible approach to reduce delamination is the pilot hole strategy [13, 14]. The intention is to reduce the thrust force during drilling by dividing the drilling in two steps. The pilot hole cancels the chisel edge effect, reducing the risk of delamination.

EXPERIMENTAL WORK

In order to perform the experimental work, a carbon fibre/epoxy plate was fabricated from pre-preg with a stacking sequence of $[(0/\text{-}45/90/45)]_{4s}$, giving the plate quasi-isotropic properties. The laminate was cured, in a hot plate press, under 3 kPa pressure and 140 ºC for one hour, followed by air cooling. The final thickness of the plate was 4 mm. Drilling experiments were executed in a machining centre *OKUMA MC-40VA*. All drills are made of K20 carbide and have a diameter of 6 mm. Four types of drills were experimented for comparison: twist, Brad, Dagger and a specially designed step drill – figure 2.

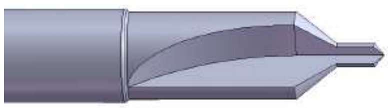

Figure 2 – Special step drill

For the holes where twist drill was used, three different pilot hole diameters were used – 1.5, 2.0 and 2.5 mm – with a spindle speed of 3000 rpm and a feed rate of 0.04 mm/rev. A summary of the relevant drilling parameters can be found in table 1.

Table 1 – Relevant cutting parameters

	Unit	LOW	MEDIUM	HIGH
Cutting Speed	m/min (rpm)	40	60	80

Feed rate	mm/rev	0,02	0,04	0,1

During drilling, thrust forces were monitored with a Kistler dynamometer. Results from experimental work are compared with a Finite Element Model for drilling simulation, already presented by the authors [15].

FINITE ELEMENT MODEL

The model uses three-dimensional brick solid elements available in the ABAQUS® software library. 8-node interface finite elements, compatible with solid elements, are placed at the interfaces between differently oriented layers where delamination is prone to occur. These interface elements incorporate a mixed-mode cohesive damage model based on Fracture Mechanics to simulate damage onset and propagation [16]. The final shape of the modelled plate is a cylinder of 16 mm diameter and 4 mm thickness, distributed in 14 layers. In order to reduce computational time, layers 13 and 14 represent a homogenized aggregation of material. Details of the model can be found elsewhere [17]. Results that are considered relevant during a simulation corresponded to two outcomes from the model - thrust-displacement curve and maximum thrust force; delamination onset, when stress in a certain point vanishes, due to material discontinuity. Figure 3 shows a comparison of the experimental thrust-displacement curves for the case of a twist drill and the corresponding curve from the FE model.

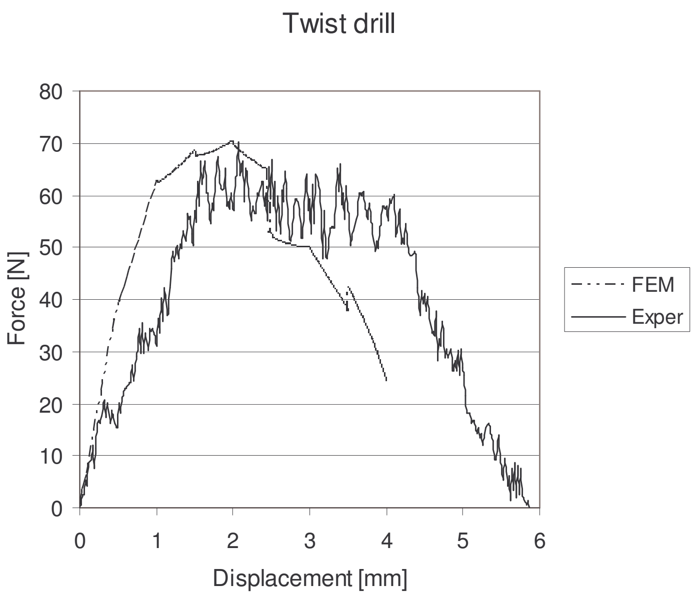

Figure 3 - Thrust force displacement with a twist drill [17].

With this Finite Element Model, good agreement was achieved between existing analytical models for delamination onset thrust force [11], enabling extra data about the location of the delamination onset in terms of uncut plies.

CONCLUSIONS

Based on the experimental work here presented it is possible to draw some conclusions:

- a correct selection of cutting parameters in order to reduce thrust force and, consequently, delamination around the hole, is possible.
- besides the selection of cutting parameters, the choice of a dedicated tool can be useful. A drill bit geometry that reduces the indentation effect of the chisel-edge is preferable. The use of a pilot hole has a similar effect in terms of delamination reduction.
- the FE model was able to reasonably predict not only the thrust force for delamination onset and the maximum thrust force during drilling, but also the uncut thickness at which this phenomenon will occur.

ACKNOWLEDGEMENTS

This work is supported by FCT – Fundação para a Ciência e Tecnologia, under project number PTDC/ PTDC/EME-TME/66207/2006.

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