Delamination analysis after carbon/epoxy plate drilling

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SUMMARY

Drilling of carbon fibre reinforced plates – CFRP – causes typical damages such as delamination and others. These damages, that cannot be visually detected, can cause the premature collapse of structures. Damage assessment is usually carried out using non-destructive inspections like radiography and ultrasonic C-scan.

Damage extent can be evaluated by the use of damage criteria. One of them – delamination factor – was proposed by Chen, establishing a ratio between the maximum damaged diameter and the hole nominal diameter. Another one – damage ratio – was presented by Mehta comparing the damaged area with the hole average area. Both ratios allow for comparison between different drilling conditions.

In this paper the images obtained are processed and analyzed using standard techniques from Computational Vision together with a processing platform already developed. An experimental evaluation using radiographic and C-scan images to obtain the referred ratios will be presented.

INTRODUCTION

The use of laminate composites in structures is under a considerable increase. The advantages of their use are related with a considerable weight reduction and consequent improvement of dynamic characteristics, in the case of aeronautics, automobile, railway and naval industries. Drilling is a widely used technique as it is always needed to assemble components in more complex structures. Drilling is a complex process which is characterized by the existence of "extrusion" and cutting mechanisms, the former performed by drill chisel edge that has null or very small linear speed and the latter by the existence of rotating cutting lips at a certain speed.

As composites are non-homogeneous and anisotropic, drilling raises specific problems that can affect parts strength and fatigue life [1, 2, 3]. Typical damages after drilling are push-out delamination, intralaminar cracking, fibre/matrix debonding and thermal damage. Due to their abrasiveness, composites drilling cause high tool wear, leading to the need of frequent tool changes that affect the production cycle. From all these problems, delamination is the most serious as it reduces severely the load carrying capacity of laminated composite structures and must be avoided. Delamination is a defect that occurs in interlaminar regions, that is to say, in the contact plan between adjacent layers. Delamination mechanisms are classified in push-out and peel-up, according to the laminate region where they occur, exit or entry side, respectively. Push-out delamination (figure 1) is a consequence of the compressive thrust force that the drill always exerts on the workpiece. The laminate under the drill tends to be drawn away from the upper plies, breaking the interlaminar bond in the region around the hole. When the loading exceeds the interlaminar bond strength delamination occurs, before the laminate is totally penetrated by the drill.

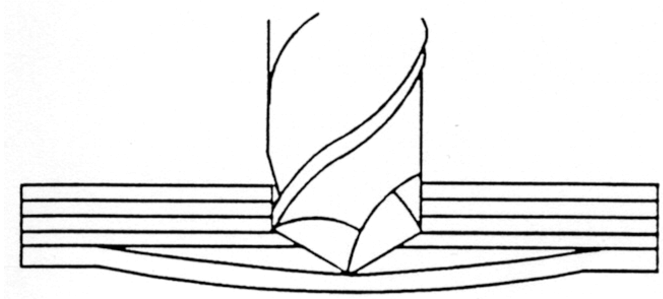


Figure 1 – Push-out delamination at exit.

Several drilling techniques, based in an adequate selection of tool geometry and cutting parameters, have been proposed with the aim to minimize delamination [1, 2, 4, 5].

Tsao and Hocheng [6] evidenced the importance of a pilot hole by measuring a 25 to 50% reduction on thrust force during drilling with a pilot hole strategy. The pilot hole diameter should be able to cancel the chisel edge effect which is largely responsible for the extrusion mechanism the occurs during laminate drilling, turning it possible to have delamination-free holes.

After laminate holes are drilled, it is important to establish criteria that can easily compare the delamination degree of various processes, even though they can only be applied to composites with the same lay-up regarding orientation and number of plies. Chen [7] proposed a comparing factor that enables the evaluation and analysis of delamination extent in laminated composites. That ratio was called the Delamination Factor *(F_d)* and it was defined has the quotient between the maximum delaminated diameter (D_{max}) and the hole nominal diameter (*D*),

$$F_d = D_{\max} / D \quad . \tag{1}$$

Mehta et al. [8] have suggested a different ratio, named Damage Ratio (D_{RAT}), defined as the ratio of Hole Peripheral Damage Area (D_{MAR}) to Nominal Drilled Hole Area (A_{AVG}), i.e.,

$$D_{RAT} = D_{MAR} / A_{AVG} \quad . \tag{2}$$

This hole damage evaluation method is based on the existence of damage images and pixel counting of the digitized damage area, as described in [7], or from digitized radiographs [8].

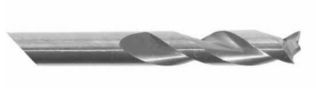
Tsao and Hocheng [9] used ultrasonic techniques and computerized tomography for the evaluation of delamination damage in carbon/epoxy composite plates. The photographs obtained from the use of those techniques allow the measurement of delamination extent considered as an average of six measurements along the delamination perimeter. The authors concluded that feed rate is an important factor in delamination, as higher feeds cause higher thrust force, thus increasing the risk of damage occurrence around the hole.

MATERIALS AND METHODS

In order to perform the experimental work a carbon/epoxy plate was fabricated from pre-preg with a stacking sequence of $[(0/-45/90/45)]_{4s}$, giving the plate quasi-isotropic properties. The laminate was cured, in a hot plate press, under 3 daN/cm^2 pressure and 140ºC 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. Cutting parameters were selected according to tools manufacturer advice. Four types of drills were experimented for comparison: twist, c-shape, dagger and step. The twist drill was used in two conditions: first without a pilot hole and then with a pilot hole of 1.1 mm diameter. Drills characteristics as well as machining parameters are shown in table 1.

Table 1 – Drilling tools and conditions.

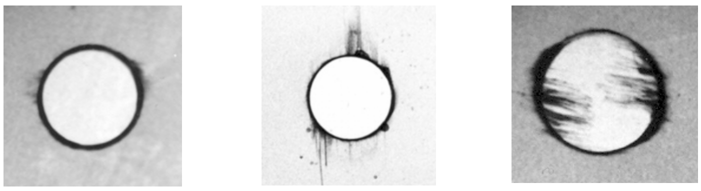
Tool		Point angle	Cutting speed [m/min]	Feed speed [mm/rot]
Twist drill		118º	80	0.05
Twist drill with 1.1 mm pilot hole		118º	80	0.05
C-shape drill		------	80	0.05
Dagger drill		30º	38	0.05
Step drill		118º	80	0.05

Radiography is a well recognized and documented method that is applied in industry for assessment of the soundness of materials and components. The technique is based on different absorption of penetrating radiation by the object being inspected.

Radiography is suitable on the detection of delaminations only if a contrasting fluid is used. With such purpose di-iodomethane was considered. This product is a chemical reagent with a density of 3.32, radio-opaque, which is the important characteristic for the objective of its use.

To obtain a radiographic image, the contrasting fluid is poured into an appropriate container and the plate is immersed for one and a half hour in a dark chamber. After time elapsed, the plates are cleaned and placed over a film. The exposition time is 0.25 seconds.

Developed films were used for the measurement of delaminations around the hole. Figure 2 shows some radiographies from holes made with twist, c-shape and dagger drills.



a) b) c)

Figure 2 – Radiographies of drilled parts: a) twist drill; b) c-shape drill; c) Dagger drill.

Ultrasonic techniques are most frequently used for non-destructive inspection of composites. Ultrasound inspection technique is based on the analysis of the changes that happen in the sound wave caused by material discontinuities.

In this paper, C-Scan method, an ultrasonic inspection with sweeping commanded by a motorized X-Y table, was used. The ultrasonic scanning was made with *Ultrapac II* equipment and a 5 MHz transducer. The parameter used for the measurement of the echo was time-of-flight (TOF). The result, given in a colour scale, can be related with the depth from the transducer at which the wave hits an obstacle that causes its reflection.

The use of Computational Vision has the purpose to reckon from the images obtained either by radiography or C-Scanning, information regarding damaged area or diameter. This process has the advantage of reducing operator dependence to measure the dimensions wanted, thus increasing reliability. An existing processing and image analysis platform was used [10, 11]. This platform turned possible the use of some standard Computational Vision techniques [12, 13, 14] to accomplish the required values regarding damage measurement around the drilled hole.

According to the kind of image considered, different processing and analysis sequences need to be established. For radiographic images, the first step was the selection of the interest zone. This step was manually executed and has just the objective of reducing computational time involved in the following steps. The second step was the pre-processing of the sub image by a smoothing filter to reduce sudden changes of intensity thus reducing existing noise. Next step on the smoothed image was the segmentation of the interest areas. In many cases, this step results in a large number of segmented areas, so it is needed to eliminate those who were not relevant. Noise areas were eliminated by the application of erosion and dilation morphologic filters. After this processing step, each image is mainly the concern damaged area plus its background. In the final step, a region processing and analysis algorithm is applied to differentiate the several regions in each image, and for each region a certain number of measurements is presented. In figure 3 an example of area identification and measurement results for a radiographic image is shown.

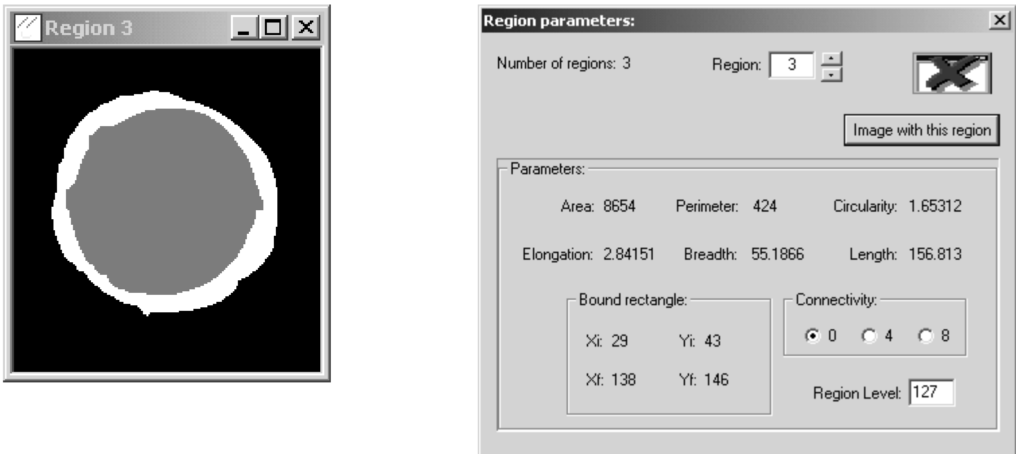


Figure 3 – Example of area identification and measurement results in an image obtained by radiography using Computational Vision techniques.

For C-Scan images the processing and analysis sequence was slightly different. The first step was, as before, the selection of the interest zone. Each colour image was then converted into grey levels. After this conversion was done, the pixels that were not included in the interest zones were removed. For this operation a segmentation operation was used by selecting an adequate threshold level of grey. So, pixels below that level are classified as noise and removed. After this operation was completed, the images were binarized and subjected to the application of morphological filters to get homogeneous regions. Final processing step is the same as for the radiography images, and consists in the application of the region processing and analysis algorithm to obtain the desired measurement. In figure 4 an example of interest zone, area identification and results is presented.

The results from these measurement procedures give the possibility to determine the values of the damaged area according to two different criteria, the delamination factor proposed by Chen [7] and the damage ratio proposed by Mehta et al. [8].

RESULTS AND DISCUSSION

As carbon/epoxy plates are opaque, visual inspection is not able to satisfactory assess the damage extension that can exist between inner plies of the laminate. So, it is fundamental to use other imaging methods when it is necessary to inspect drilled parts. The techniques described above were applied for damage evaluation of the plates used in this work. Both kinds of images – radiographic and C-scan – were processed according to the appropriated sequence.

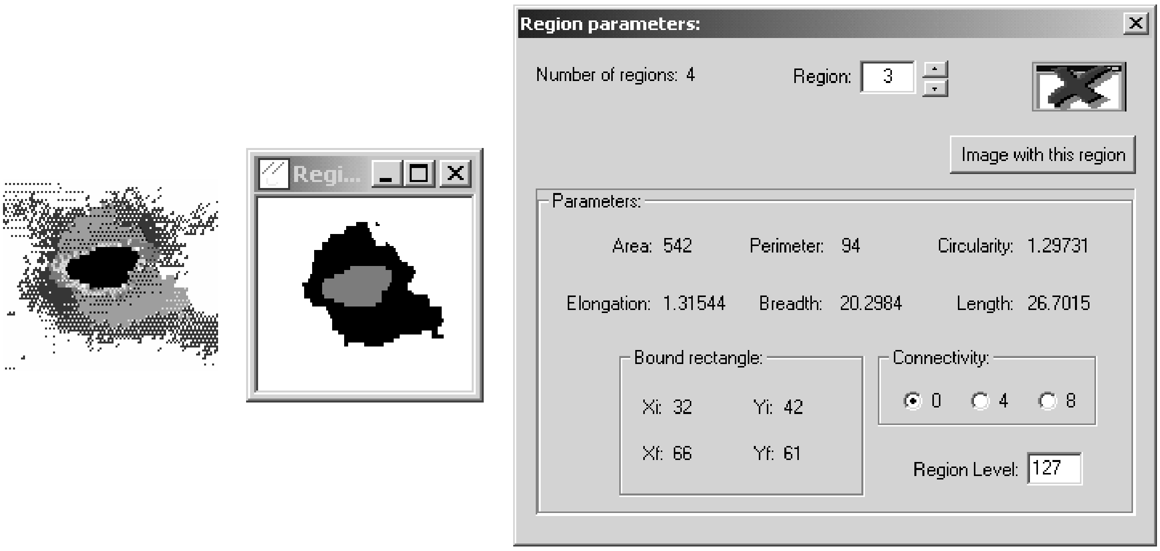


Figure 4 – Example of interest zone, area identification and measurement results in an image obtained by ultrasonic C-scan using Computational Vision techniques.

Images obtained by radiography were processed using appropriate Computational Vision techniques to give information that allows the determination of delamination factor and damage ratio. Departing from the shape of a radiographic image, that is nearly circular, and using the processing steps described before, it is possible to have a number of results including drilled area (dark grey in figure 3), damaged area (light grey in figure 3) and maximum damaged diameter.

Images from ultrasonic inspections were only used for the determination of damage ratio using the processing and image analysis platform depicted. As can be seen in figure 4, the images obtained by C-scan are not circular. This can be a consequence of the beam diameter used, leading to the existence of noise regions.

The results of the damage criteria referred, equations (1) and (2), can be seen in figure 5. For every criteria the best result, that is to say, with less delamination around the hole was obtained with c-shape drill. This effect shows that the drill geometry has an influence on the delamination value. The peculiar geometry of c-shape drill, pre-tensioning the fibre prior to cut, has enabled the achievement of delamination values around 1.1, for every criteria used. The delamination results of dagger drill were better when considering the damage ratio than when considering the delamination factor. That can be the result of the existence of a main direction for delamination when drilling with dagger drill, but with less extent when the damaged area is to be considered. In fact, for twist and c-shape drills, the damage was more regularly distributed around the hole (figure 2).

The use of a pilot hole has reduced the delamination in about 3%. For the step drill, the transition angle of 180º has caused the opposite effect, increasing delamination. The use of a step drill with a smoother transition angle (like 90º) could be helpful. Also, according to [9], a smaller pilot diameter than the one of the drill used – 3.4mm – would be preferable.

CONCLUSIONS

Carbon/epoxy laminates were drilled with four different drill geometries, one of them with the additional use of a pilot hole. The results considered in this study were the measurements of delamination by the use of two existing criteria, delamination factor, F_d, and damage ratio, D_{RAT}. In order to apply the criteria mentioned, the damage around the hole was evaluated by the use of two techniques – radiography and ultrasonic scanning – and the resulting images were analysed by a computational vision technique in order to provide the areas and diameters of the damaged region around the drilled hole.

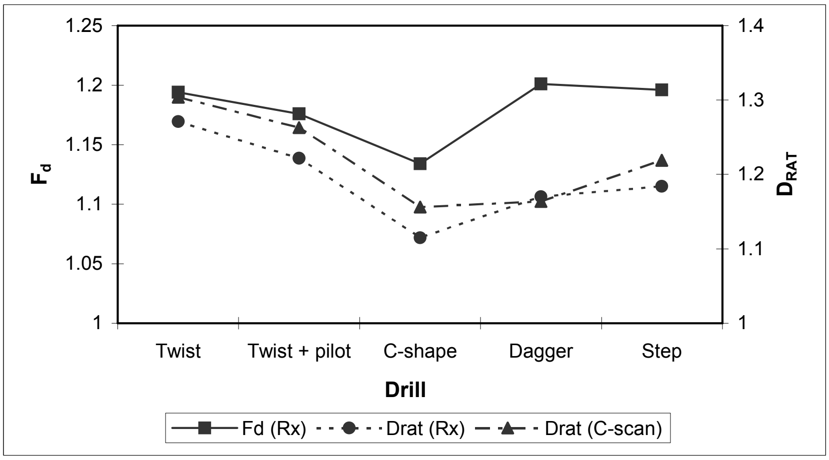


Figure 5 – Delamination factor (F_d) and damage ratio (D_{RAT}) results with radiography and C-scan images.

From the results presented, it is possible to draw some conclusions:

- The drill geometry has an influence on the delamination extent;
- Considering the damage around the hole, the c-shape drill seems to be the most appropriate tool for composite laminates drilling;
- The use of a pilot hole has some beneficial effects reducing the damage around the hole;
- The use of Computational Vision techniques was useful in the determination of the damage caused by drilling. The processing and analysis sequences here presented can be used for the measurement of damage in other composites, like those using glass or aramid fibre as reinforcement.

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