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ORIGINAL ARTICLE

Effect of puncher profile on the precision of punched holes on composite panels

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Abstract As structural materials, assembly for a composites panel cannot be avoided. Typically, composite panels are assembled using a fastener through a drilled hole. The main problem of drilling is delamination, which affects the strength of the assembly. In addition, the cost of drilling is high because of severe wear on drill bits. The main goal of this research is to develop a new punching operation method as an alternative to drilling during hole preparation. In this study, we investigated the effect of different puncher profiles on the quality of punched holes on composite panels. Six types of puncher profiles with minimum die clearance (1 %) were fabricated. Three quality aspects, namely, precise hole diameter, incomplete shearing, and delamination factor were measured. The conical shape puncher produced the lowest defect in terms of delamination and yielded an acceptable amount of incomplete shearing compared with the other punchers.

Keywords Composites panel · Punching · Puncher profile · Hole quality

1 Introduction

Composite materials are now widely used to replace certain metals in manufacturing applications, particularly in the aerospace industry [1, 2]. These materials are used mainly because of their light weight, reliability, and strength, especially in critical and high-precision applications. The assembly of composite structures as structural materials cannot be avoided. Mechanical joint efficiency is largely dependent on the quality of produced holes. The evaluation of the quality of drilled fastener holes must include the general geometry of the hole and the condition of the hole surface. Therefore, the quality of the hole can be characterized on the basis of a few criteria, including delamination factor, out-of-roundness, cut neatness, and surface roughness [3–5]. Delamination can decrease bearing strength and material durability by reducing the structural integrity of the material, resulting in long-term performance deterioration [4]. Mechanical fastening efficiency is largely dependent on the precision and accuracy of drilled holes. Therefore, out-of-roundness, cut neatness, and hole edge quality are crucial.

Drilling-induced damage, such as spalling, delamination, edge chipping, fiber pullout, crack formation, and excessive tool wear, may affect structural integrity [6–8]. Hence, improved methods of quality holes production are needed to ensure the integrity of fasteners without compromising the advantages of composite strength characteristics. In addition, drilling is considered time consuming because drilling tools need to be changed frequently [9]. For an aircraft, thousands of holes need to be produced. Therefore, time is important. In addition to drilling, other methods of producing holes on composites include electrical discharge machining [10, 11], laser machining [12], ultrasonic machining [13], and abrasive waterjet machining [12, 14]. Comprehensive review of the drilling can be found in [15, 16]. Punching is another method used to produce holes, particularly on metal. However, on composites, this technology is still new, and only a few published works on this topic can be found. Campbell [17] reported the potential of using a punching operation to produce

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holes. Qiao et al. [18] managed to produce holes using shear punching on metal-based composites. Comparison between drilling and punching on the laminates composite panel has been made based on wear [19]. The holes produced using punching has better quality as the puncher less wear compared to the holes produced by drilling.

The main objective of this research is to conduct a feasibility study on the replacement of drilling with punching. Previous research on this topic covered the effect of die clearance and multistage puncher on holes quality. Notably, such research achieved promising findings [20, 21]. Both studies used flat top puncher. Relative to the drilling process, the damaged/affected area for punching using flat puncher still wide and at the same time, deviation between entry and exit holes diameter is still large. By introducing multistage puncher, only load required for the punching reduces, but the quality of the hole is about the same. Thus, in the present study, we focus on the effect of different puncher profiles on the quality of punched holes.

2 Methodology

The methodology can be divided into four stages, namely, design and fabrication of the puncher, experimental setup, specimen analysis procedure, and parameter evaluation.

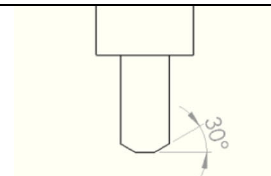
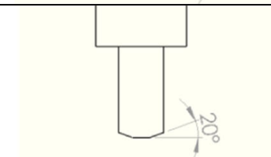
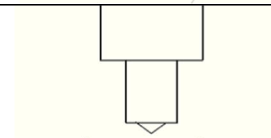
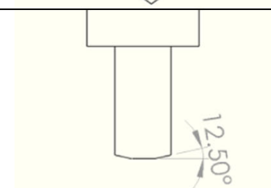
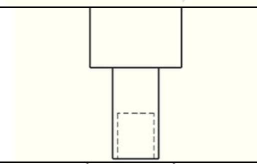
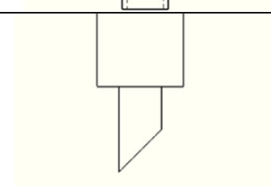
2.1 Puncher profile

In this experiment, six different puncher profiles were fabricated: single shear shape, double shear shape at 12.5°, 20° and 30°, conical shape, and inverted cup shape (Table 1). Generally, puncher can be divided into two sections, namely, puncher head and puncher body. A minimum die clearance of 1 % was implemented for the die; the puncher diameter was (∅5.0 mm ± 0.15 mm), and the die diameter was (∅5.068 mm ± 0.182 mm). The punchers were made of tool steel grade D2. For the purpose of this study, the punchers were hardened to 62 HRC.

2.2 Experimental setup

The tool punch and die were set up and installed on the Instron 3367 Universal Testing Machine (UTM), as shown in Fig. 1. The punch travel speed of the UTM is 5 mm/s, which is half of the speed adopted in the industry (10 mm/s). The tool punch was installed at the crosshead, whereas the die was placed at the bottom of the sample grip. First, the composite panel should be precisely located on the UTM before the punch was moved down to cut the composite panel. The specimens were tested at least three times for each type of tool geometry.

Table 1 Puncher profiles

No.	Puncher Profile	CAD
1	30° Double Shear	
2	20° Double Shear	
3	Conical Shape	
4	12.5° Double Shear	
5	Inverted Cup Shape	
6	Single Shear	

2.3 Specimen analysis procedure

A machine vision camera is one of the tools used to capture image quality. This technique is extensively used in factories to inspect components, such as hard disks, for defects. In this study, an EXXO night vision webcam was used to obtain

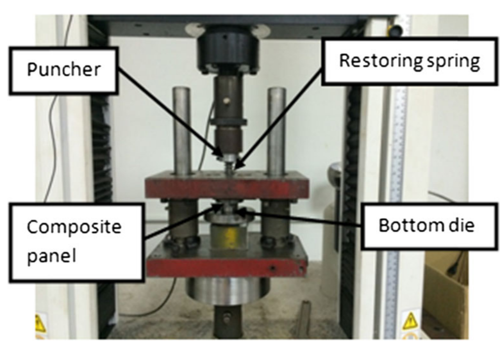


Fig. 1 Experimental setup

quality images and to ensure that no shadows were produced. Figure 2 shows the machine vision camera setup.

Then, the captured image was analyzed using the KLONK Image Measurement software. For scale reference, an ordinary ruler was used (Fig. 3). This is the standard procedure in performing image processing using this software.

2.4 Parameter evaluation

For a hole, precision is usually measured based on the correctness of holes size, which is usually quantify the diameter both entry and exit. Another aspect is on the cleanliness of the holes. In the punching of the metal, most likely the height of burr formation will be taken into account. But for the composite panel, cleanliness may be evaluated from different aspect. Finally the effect of the holes making process to the strength or integrity of the holes or affected area resulted from the operation, which is important for the assembly purposes. In this research, the precision of the holes will be evaluated based on the entry and exit holes diameter, incomplete shearing, and delamination factor to represent correctness, cleanliness, and integrity of the produced holes, respectively.

2.4.1 Measurement of entry and exit diameters

First, calibration was conducted using the ruler placed along the image of the sample. Then, the perimeter of the surface diameter of the hole was drawn manually using the KLONK Image Measurement software. Finally, the values of the entry and exit diameters were generated automatically by the operating software. Figure 4 shows the illustration of the entry and exit diameter.

2.4.2 Measurement of incomplete shearing

First, calibration was conducted using the ruler placed along the image of the sample. Then, the perimeter of the surface diameter of the hole was drawn manually using the KLONK Image Measurement software. The value of the area drawn

Fig. 2 Machine vision camera

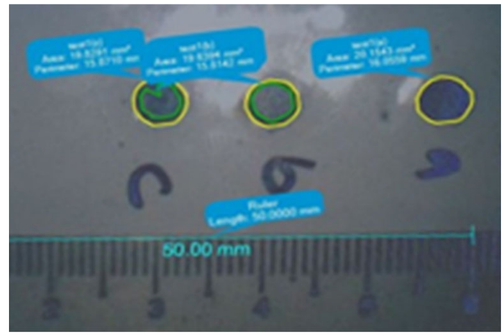


Fig. 3 KLONK Image Measurement software image

was also generated automatically by the operating software. This area value was considered the holes area, A (Fig. 5a). Then, the perimeter of the clean holes area was also drawn manually, similar to that for the holes area. The value of the clean holes area drawn was generated automatically by the operating software. This area value was considered the clean holes area, A_c (Fig. 5b). Finally, the ratio of incomplete shearing was calculated using the following equation [20]:

$$\text{Ratio of incomplete shearing} = \frac{A - A_c}{A} \times 100\%.$$

2.4.3 Measurement of delamination factor

First, the images were analyzed using Alicona IFM. Then, the inner and outer surface diameters of the hole were drawn using the available features measured using Alicona IFM (Fig. 6). The inner and outer diameters were considered the nominal holes diameter and maximum delaminated diameter, respectively. The delaminated factor could be calculated using the following equation derived by Miguel et al. [22]:

$$F_d = D_{max} / D_o.$$

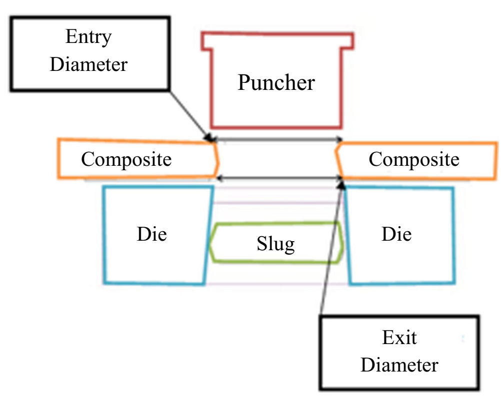


Fig. 4 Schematic diagram of punching process

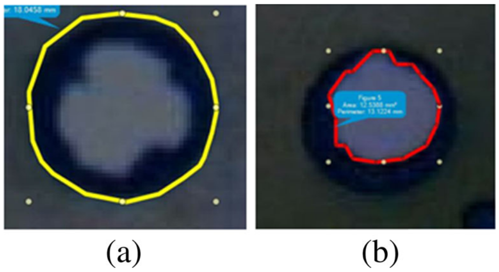


Fig. 5 Definition of (**a**) hole area, A and (**b**) clean hole area, A_c

3 Results and discussion

In this section, we focus on the deviation of the entry and exit diameter of the holes, incomplete shearing, and delamination factor. The graph in Fig. 7 shows that the average value of the entry diameter increases. Almost all the types of tool geometry punch have a small deviation in the diameter of the entry. For puncher 2 (20° double shear) and puncher 3 (conical shape), the diameters of their entry are close to their punch diameter, that is, 4.98 and 5.03 mm, respectively. By contrast, for puncher 1 (30° double shear), puncher 4 (12.5° double shear), and puncher 5 (inverted cup shape), the diameters of their entry have a larger deviation compared with their punch diameters, that is, 4.89, 5.12, and 5.41 mm, respectively. The punch tip profile that initiated the punching results in a balanced load distribution. In this way, punching proceeds smoothly and results in improved holes accuracy. Punchers 1 and 4 have unsuitable degrees of chamfering for this operation. Therefore, a large deviation in terms of holes accuracy can be observed. A similar case can be observed for puncher 5 with an inverted cup shape.

Depending on the diameter of the entry, the deviation of the punch diameter can be measured, as shown in Fig. 8. The deviations of the 30° double shear punch and conical shape punch are close to zero, that is, −0.38 and 0.59, respectively. However, this pattern is not observed for punchers 1, 4, and 5, as the deviations are larger, that is, −6.21, 2.52, and 8.13 %, respectively. The negative value indicates that the diameter of the entry is less than the diameter of the puncher. This may happen due to severe incomplete cut of the fibers. Since the measurement of the holes is based on the image, it therefore affects the final measurement of the diameter. Notably, the tolerance range of the puncher is ⌀5 mm ± 0.15 mm.

Figure 9 shows the effect of puncher geometry on the exit diameter. The trend of the graph shows that the differences in the exit diameters of the tools are slightly different. However, Fig. 10 shows that the differences in the deviation of the exit diameter from that of the die diameter are considerably large. Puncher 3 shows a high deviation value of 15.46 %, whereas puncher 2 shows a low deviation value of 6.54 %. However, the exit diameter produced by each type of tool geometry does not tend to follow the die diameter because the value is not within the tolerance range of the die diameter, that is, ⌀5.068 mm ± 0.182 mm. Puncher 5 broke during punching because of misalignment between the puncher and the die. As stated previously, puncher geometry also affects holes accuracy. However, in this case, the conical shape puncher with a sharp edge produces a less accurate hole compared with the double shear type puncher that presents better accuracy because of the contact between the puncher edge and the die edge.

Figure 11 shows the effect of puncher geometry on the completeness of the sheared section. The incomplete shearing ratios vary between these tools. Laminate composites consist of a multilayer fiber that is arranged at different orientations for each of the alternate layer, commonly between 0° and 90°.

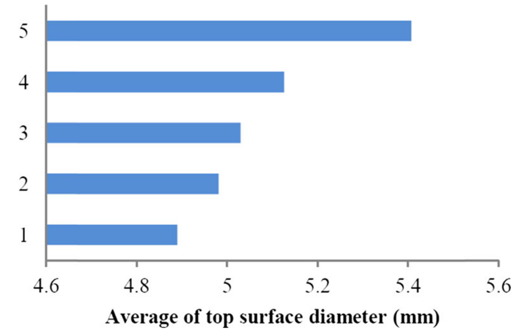


Fig. 7 Average entry diameter for different puncher profile

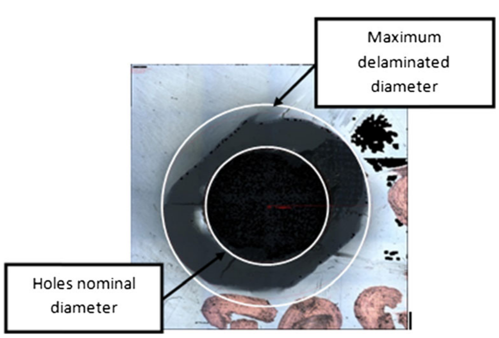


Fig. 6 Image of delaminated area on composite panel

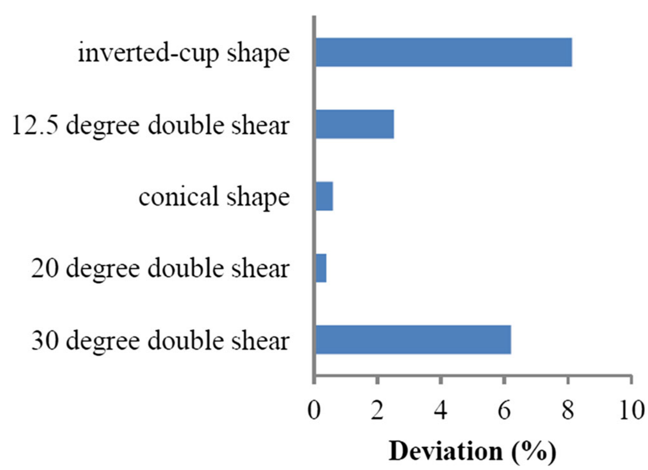


Fig. 8 Deviation of entry diameter for different puncher profile

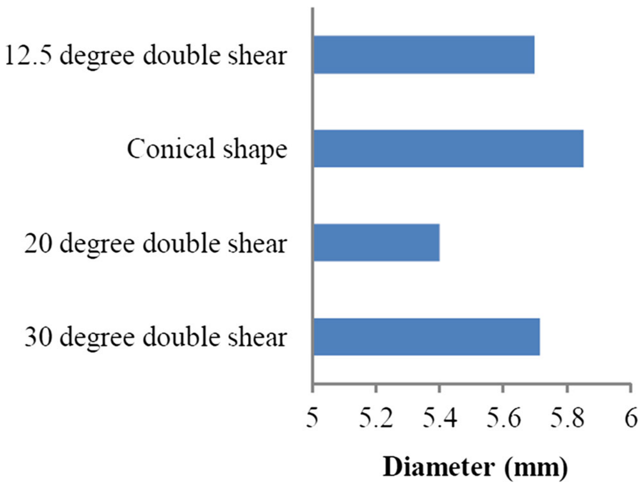


Fig. 9 Average entry diameter for different puncher profile

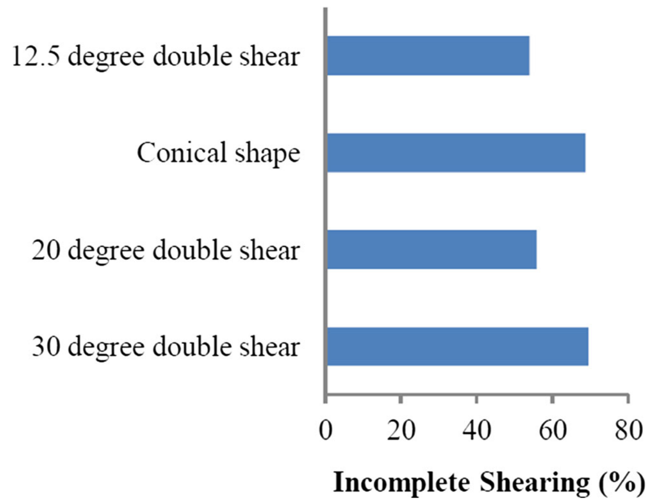


Fig. 11 Incomplete shearing in % for different puncher profile

From the study, increasing the tapered edge from 12.5° to 30° results in increasing incompleteness of the shearing. Therefore, net shearing throughout the hole is difficult to determine. In this study, puncher 4 (12.5° double shear) shows a low average value of incomplete shearing, that is, 53.98 %.

Delamination is critical for holes production on composite panels because it may affect the structural integrity of these panels. Therefore, delamination must be eliminated or at least minimized. Figure 12 shows the effect of puncher geometry on the delamination factor. The trend of the graph shows the same pattern as that for incomplete shearing. Moreover, the value of the delamination factor between punchers is slightly different, and different types of geometry yield different results for the composite panel. Puncher 3 (conical shape puncher) shows the lowest value of delamination, whereas puncher 5 (inverted cup shape) shows the highest value of delamination. Higher value of delamination factor represents that the damaged area or affected due to punching is higher. Therefore, in terms of delamination, we conclude that puncher 3 is the best puncher that can be used to produce holes on composite plates because this puncher profile produced little damage around the hole after the punching operation. In addition, the value of the delamination factor of puncher 3 is nearest the ideal value, that is, 1. Again, the introduction of sharp tip helps in reducing the affected area as the tip initiates pre-breaking of the panel.

Figure 13 shows the effect of puncher geometry on the load required to conduct the punching operation. The average values of the maximum load required for complete punching show that the differences in the four types of punchers are slightly high. Moreover, the conical shape puncher shows the lowest load required to produce holes on the composite, approximately 12.2 kN. For conical shape puncher, the existence of the sharp tip helps in initiating pre-breaking prior to the larger penetration of the main puncher, while the double shear puncher with 20° tapered edge depicted the highest load, approximately 13.8 kN. Interestingly, the same types of puncher with larger tapered edge result in lower load as shown in Fig. 13.

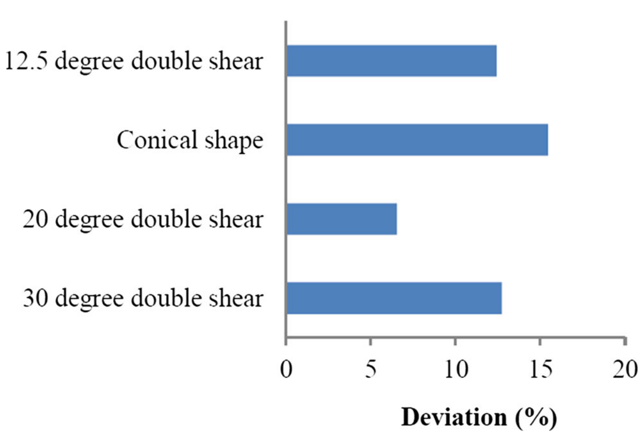


Fig. 10 Deviation of exit diameter for different puncher profile

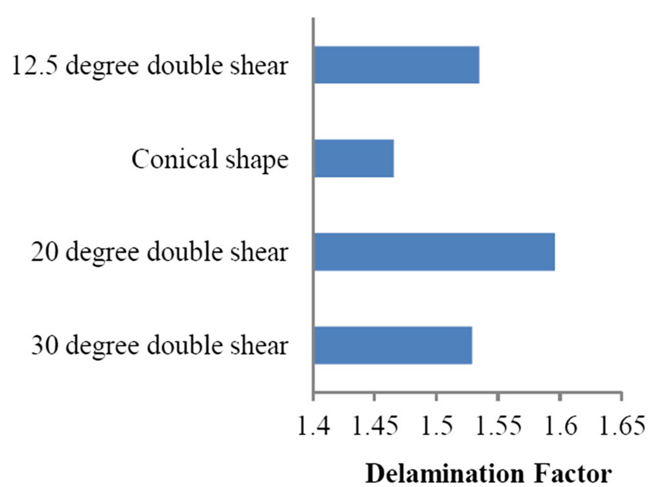


Fig. 12 Delamination factor for different puncher profile

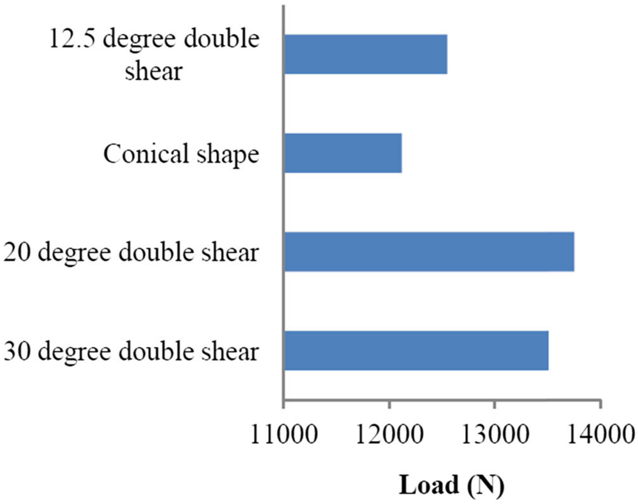


Fig. 13 Required load for punching at different puncher profile

4 Conclusion

The main objective of this research is to investigate the effect of puncher profiles on the quality of punched holes on composite panels. This is one of the assessments of the practicality of the proposed method as an alternative to the drilling method in making holes. Six puncher profiles were proposed. Based on the observations, the puncher no. 2 (20° double shear) achieves the best holes quality in terms of the accuracy of the entry diameter, which is closest to the punch diameter, and the exit diameter compared with the die diameter. Another quality indicator measured was the completeness of shearing throughout the hole. In this case, the results show that the double shear type puncher yields the best shearing quality. Furthermore, the damaged area produced by this puncher around the hole on the composite plate is low because the delamination factor produced is also low. The conical shape puncher yields the lowest delamination. Notably, a relationship is observed between the load required and the delamination factor. In overall, the conical shape puncher gives the best option among the proposed puncher profile. In future works, shearing efficiency and its effect on composite material composition, fiber orientation, and number of layers will be further examined. In addition, the effect of punching to the integrity of the panel will be explored in the future.

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