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ORIGINAL ARTICLE

Hole integrity of carbon fibre reinforced epoxy composites using combined punching and drilling techniques

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Abstract

Drilling is the most common technique in the hole making of composite panels. Based on the previous study, punching was proposed to replace drilling. This study aims to investigate the effect of hole-making techniques, i.e. new combined technique and conventional drilling technique to the hole quality and performance by conducting experiment based on surface roughness and bearing strength, respectively. The surface roughness measurement was performed oversampling with 3.6-mm thickness at four quadrant points along the hole wall. A bearing test was conducted according to ASTM D5961 procedure-A double shear with a single-pin fastener. The failure modes resulting from an experiment are quantified and compared. It was found that there is a slight difference in the initial ply failure load (IPFL) between the conventional drilling and both combined technique for 0.65% and 7.90%, respectively. However, the difference is still low, i.e. less than 10%. The results confirmed that the use of the combined technique is almost similar to the conventional drilling alone in terms of bearing strength, failure mode, and surface roughness.

Keywords Hole integrity · Punching · Drilling · Bearing strength

1 Introduction

The use of a mechanical joint in composite structures has been used steadily in recent years due to ease of access in assembly for inspection, maintenance, and repair work compared with the bonded joint [1, 2]. However, due to structural discontinuities in joint geometry, the load transmitted via fastener gives rise to the stress concentration around the hole-fastener boundary and might cause the premature failure of the entire structures [3, 4]. Since most of the existing method which produces holes in a laminated composite is drilling that involved direct contact between the workpiece and cutting tool (except for those related to an unconventional method), the tool being used faced extreme tool wear [5]. The defect in hole-making processes associated with drilling-induced damage due to the tool wear, including the time needed to regrind the tool, caused the manufacturing cycle time and production cost increase [6]. The input process parameters like tool geometries, tool materials, and cutting parameters affect directly to the hole quality. Hole quality can be characterized based on a few criteria, including delamination factor, out-of-roundness, cut neatness, surface roughness, damaged surface layer, fibre fracture, burr formation, and crack [7, 8]. However, in composite laminates, damage due to delamination is a great concern in drilling. For example, it was reported that the rejection of composite parts of the final assembly in the aircraft industry is high as 60% due to drilling-induced delamination damages [9].

Apart from hole quality, tool wear also influences the frequency of tool-regrinding and tool changes during machining, thereby, uneconomical production cycle and manufactures cost [10]. It is also stated [11] that high temperature and tool wear are other considerations while machining hard material. The productivity rate of machine tools and machining costs depends on the failure of cutters, which is due to intense machining processes as a result of the increase in dynamic force, cutting speed, the magnitude of feed rate, and depth of cut [12]. Therefore, machine tools must go through many cutter replacement processes that ultimately result in a decrease in output and economic

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efficiency. The wear mechanism and development in machining material can differ due to many aspects; however, among all the possible wear, only abrasion, surface damage, and sometimes adhesion are significant in FRP machining [13]. Different authors have been studying different machining parameters concerning to wear during CFRP drilling. It shows that the tool wear during cutting CFRP occurred is due to the abrasive hard grain of carbon fibre broken into pieces which rubbed against the tool flank. The author also found that the rubbing is more intense as the cutting speed increase [14].

The effects of increasing cutting speed on drilling characteristics of CFRP were studied [15]. The results showed that the tool wear increases significantly as cutting speed increases. On top of that, they also found that the average torque is slightly higher for multifaceted compared with twist drill. They concluded that tool wear is the primary reason these changes in force. The research done [4] showed that the use of low feed during machining contributes to the rapid wear of the cutting edge. They used high-speed steel (HSS) drill mounted to vibratory drilling and conventional drilling to evaluate the thrust force, flank wear, and delamination factor on glass fibre-reinforced plastic composites. The experimental results indicated that the tool wear reduces as feed rate increases from 0.04 to 0.2 mm/rev. The worn of the conventional drill bit during dry high-speed drilling of carbon composites was studied [16]. As a result, the abrasive wear has been found the main factor that causes WC drill bit to deteriorate. Moreover, it has been observed that as the cycles increase, the delamination and surface roughness also increase.

An experimental investigation of the effect of tool wore at the exit delamination when drilling CFRP was done [17]. The author, in his research, used a 6-mm diameter of high-speed steel twist drill bit with a 181° point angle. The results showed that there is a correlation between tool wear and the thrust force. The thrust force is higher with increasing wear; thus, the delamination is more liable to occur. Moreover, they were also comparing sharp drills with the worn twist drill and found that the delamination can be suppressed for worn twist drill bit by using the lower feed. Regarding tool geometry influence on composite material drilling, the author [18] investigates the effect of drill geometry and process parameters when drilling small hole diameter on thick CFRP, and they observed that the drill geometry and feed are the two main factors affecting drill life. CO_2-based laser cutting also can be applied for high intensity and precision cutting of polymer-based composite [19].

Finally, the behaviour of coated versus uncoated drills was studied [20]. The author conducted an experiment using three different drill bits (uncoated, diamond coated, and AlTiN coated) on CFRP. The experiment was aimed to investigate the effect of the coated material of drill bit to the wear. As a result, the diamond-coated drill bit was found to reduce the wear among others. They claimed that the edge rounding wear was the main wear type in all types of drills used. Also, the investigation of cutting performance in CFRP drilling using three different coated materials on Co-cemented tungsten carbide (WC-Co) drills was done [21]. They used three coated materials, namely, microcrystalline diamond (MCD), nanocrystalline diamond (NCD), and dual-layer composite MCD/NCD on WC-Co drills. The experimental results showed that the MCD/NCD coated has a minor influence on the average thrust force and demonstrated higher resistance to wear.

Thus far, the researcher has learned that the tool wear encounter during machining depends on several factors, related to the various machining parameter (such as feed and cutting speed), tool geometry (such as tool angle and the shape of the drill bits), and tool material (different type of tool material, coated material, etc.). Now, manufacturers are focusing their attention toward the development of new material for the cutting tool to extend tool life, and thus, better performance. Any tool or work material improvements that increase tool life would be beneficial. However, instead of developing new material for cutting tools, another approach should be considered.

From previous studies, punching showed great potential in the hole making on laminated composite compared with drilling in terms of time, speed, versatility, and cost [22, 23]. Additionally, tool wear in punching is not an issue. However, there is a significant drawback using punching as hole making in laminated composites such as hole quality and performance. Since thrust force is the most significant factor that contributes to delamination in the drilling operation, it is almost similar to punching operation which used shear to cut through a laminated composite. As a result, the punching force might exceed the interlaminar bond strength and cause severe delamination damage at the hole. Compared with the punching on metal, studies of punching on composites are limited in number because producing holes on composite panels was typically done by multiple stages of drilling [24, 25]. It was also pointed out that there is no extended study that could improve the quality of the punched hole in composite compared with metallic materials.

Therefore, another approach based on a combination of two manufacturing processes (punching and conventional drilling technique) applied independently during hole making on laminated composites may provide a new substantial solution to the limitation of punching alone. By using this approach, the hole quality and performance (bearing strength of the hole) of punching should reasonably improve by the combined technique (punching + conventional drilling). This present study is focusing on the feasibility of a new combined technique which is an attempt to improve the punching technique.

2 Experimental procedure

2.1 Specimen

The material used is carbon fibre epoxy prepreg using autoclave for curing. The laminate panel with a 3.6-mm thickness consists of 26 layers of unidirectional carbon fibre with fibre orientations [45/135/90_2/0/90/0/90/0/135/45_2/135]. Woven fibreglass that places at the top and bottom carbon laminate is used for preventing metal joining from galvanic corrosion and delamination issues. These composite laminates are used for main aircraft applications, such as wing structure (leading edge flaps) and spoilers. The specimen is obtained from one of the aircraft manufacturing industry in Malaysia. The specimen coupon was prepared using a BOSCH hand grinder with a tungsten carbide grit-edge blade. A dummy wooden block was used to clamp the laminates during hand grinding to avoid damage on the surface. A horizontal belt sanding machine was used to refine the cutting edge and achieve a precise dimension. A total of 15 specimen coupons were prepared with the standard geometric parameters, width-to-bolt diameter (W/D) and edge distance-to-bolt diameter (E/D) ratio of 3.8 and 3.6, respectively. Two types of techniques were used to make a hole in the specimen coupon, namely, combined technique and conventional drilling technique. There were three groups of specimen coupons, and each group consisted of five specimens nominally identical for repeatability. Two of the three groups of specimen coupons used a combined technique with different sizes of die clearance of puncher at the first stage and were drilled independently concentric to the punched hole during the second stage. While the last group used conventional drilling techniques as a single shot drill. The geometric parameters used in this experiment were constant for all specimen coupons, as illustrated in Fig. 1 and Table 1.

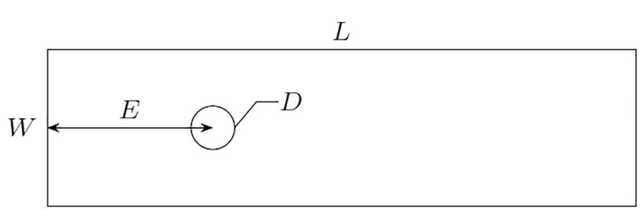

Fig. 1 Specimen geometries

Table 1 Specimen geometry and pin dimension

Parameter	Standard dimension, mm
Fastener or pin diameter, d	10
Hole diameter, D	10
Thickness, t	3.6
Length, L	135
Edge to hole centre distance, E	38
Width, W	36
E/D ratio	3.8
W/D ratio	3.6

3 Experiment setups

3.1 Punching

A laboratory test rig (Fig. 2) was designed for this investigation. The die placed on the rig was with an Instron 3367 Universal Testing Machine (UTM) with a punch travel speed of 5 mm/s. For this experiment, five coupons were punched with a die clearance (C) of 25%, and another five coupons were punched with C = 30%. Table 2 gives the detail of the punch and die diameter at different die clearance.

3.2 Alignment of punched hole

Due to vibration during punching operation, the punched holes deviated slightly from the marking line. The drilling operation must be concentric to the centre of the hole punched to avoid uneven stress concentration at the boundary of the drilled hole. Hence, the Mitutoyo Crysta Plus M443 Coordinate Measuring Machine (CMM) was used to determine the centre of the punched hole with a precision of ± 0.0001 mm. All specimens were measured, as demonstrated in Fig. 3. The punched coupon was held by a clamp to ensure

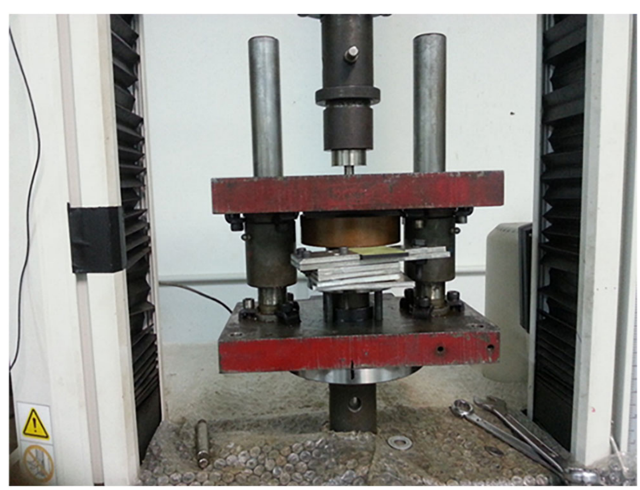

Fig. 2 Laboratory die rig

Table 2 Puncher and die clearance

Punch diameter (mm)	Die diameter (mm)	Clearance, C (%)
5.00	6.70	25
5.00	7.04	30

precise measurement of the geometry. The data collected is then transferred to MCOSMOS Mitutoyo Controlled Open Systems Software. All the data collected is recorded for the next use in a conventional drilling operation.

3.3 Conventional drilling

The data collected using CMM is then used to precisely position the drill bit in an OKUMA MX-45VA CNC milling machine. The position of the centre of the hole was set in a CNC program. All ten punched specimen coupons (5 mm in diameter) were drilled according to the suggested geometry by ASTM D5961 Procedure A. The clamp-on working table envelope of the machine was used to hold the specimen coupon as shown in Fig. 4. The drilling process was performed at spindle speed of 2600 RPM and feed of 0.05 mm/rev using a 10-mm diameter of twist drill (tapered web drill) bit made of tungsten carbide material. These cutting parameters were suggested by one of the aircraft manufacturing industry in Malaysia. Another five specimens were drilled through a hole in a dry condition using the same drilling parameter purposely for comparison with the combined technique, all fifteen specimens, as shown in Fig. 5.

3.4 Surface roughness test

The mean surface roughness parameter (Ra) of all drilled hole wall specimens were measured using Mitutoyo SV-3000CNC Series 178-CNC Surface Measuring Instruments with

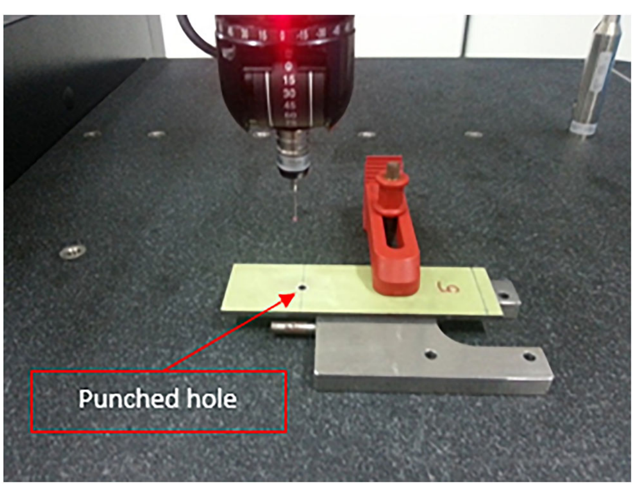

Fig. 3 CMM measuring probe setup

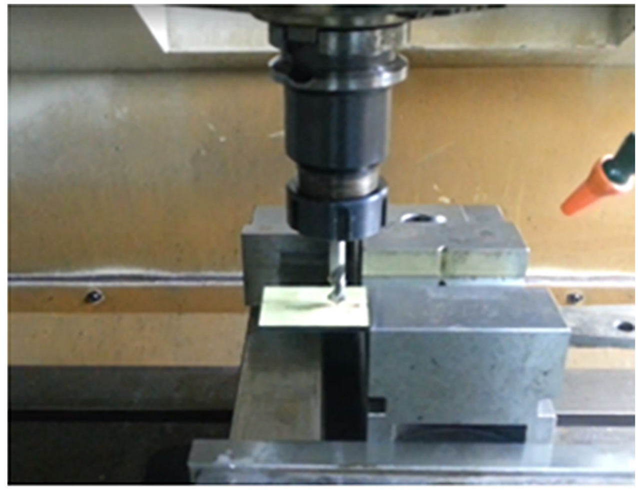

Fig. 4 Conventional drilling operation

miniature bore stylus probe (112/2623) of 2-μm radius as shown in Fig. 6. The surface roughness measurement was performed over a sampling length of 3.6 mm along with the thickness of the hole wall. The cut-off value was taken at 0.8 mm. The hole surface was scanned along with the hole depth at the 4 quadrant points. Four readings were taken at 90° to each point along the hole, and the average value is reported.

3.5 Mechanical testing (bearing test)

This test was conducted to determine the mechanical and failure mode behaviour of the holes under tensile loading. This test was aimed to establish a comparison between the cutting processes under constant specimen geometry configuration. In this experiment, ASTM D5961 procedure-A double shear with single-pin fastener was followed. The modified test fixture used in this experiment does not allow any external displacement transducer to be placed on a specimen surface due to geometrical constraint of the fixture. Because of these, the load-specimen displacement was continuously measured by internal displacement transducer recorder (internal load cell) built-in system of an INSTRON 3367 UTM through the data acquisition system. The specimens and the pin images were captured before and after the experiments to analyze any damage or failure.

The testing fixture was mounted on an INSTRON 3367 Universal Testing Machine with 30 kN loading capacity. The pin was inserted into the bolt-hole without washer between the composite specimen and the testing fixture. The specimen is mounted at approximately 4 cm between the hole centre and the upper section of the specimen, which clamped to the machine crosshead, while the other end fix at the testing fixture. Then, the experiment was carried at room temperature in a tensile loading at a rate of 1 mm min^{-1}, as shown in the schematic diagram in Fig. 7.

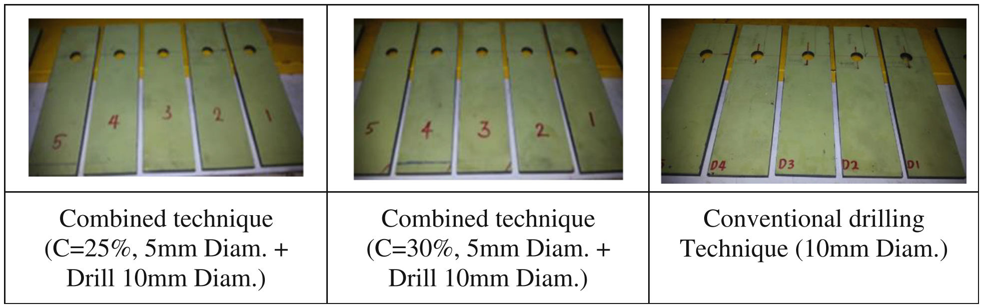

Fig. 5 Specimens with different cutting techniques

The experiment was tested monotonically to failure. In bearing stress, bearing strain, and bearing at initial ply failure (IPF), F^{IPF} is calculated from the test results by using the standard Eq. 1 and Eq. 2, and the bearing at IPF can simply be extracted from the bearing stress vs bearing strain curve. The highest value of bearing stress in the bearing stress against bearing strain curve represents the bearing at IPF.

$$\sigma^{br} = \frac{P}{K.D.t} \tag{1}$$

$$\varepsilon^{br} = \frac{\delta}{K.D.t} \tag{2}$$

where σ^{br} is the bearing stress, ε^{br} is the bearing strain, P is load applied, δ is the extensometer displacement, D is the hole diameter, t is the specimen thickness, and K is a factor with a value equal to 1 for procedure-A. Identification of failure and damage pattern on the specimens resulting from the bearing test is recorded and compared for both hole-making techniques.

3.6 Visual inspection

A sample from the bearing test for each hole preparation technique was sectioned, and the imaged were capture using Andonstar ADSM201 HDMI 1080P Full HD USB Microscope to identify the failure damage of the laminate matrix. The test is known as non-destructive testing (NDT), where the characteristic of the sample is evaluated without causing damage.

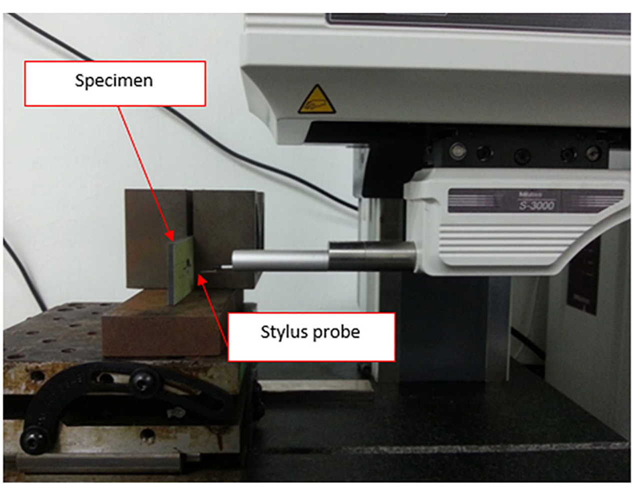

Fig. 6 Mitutoyo SV-3000CNC Series 178-CNC Surface Measuring Instruments for surface roughness measurement

4 Result and discussion

4.1 Bearing strength assessment

Based on research in the previous paper [26], there is a huge difference in the value of bearing strength at initial ply failure load (IPFL) and loading pattern which easily can be differentiated between the conventional drilling technique and the punching technique. Because of that, the result of this research is only focusing on bearing strength at the initial ply failure (IPF) region.

Figures 8, 9, and 10 show the load versus displacement curve of all specimens for each hole preparation technique during the bearing test. The test is conducted according to the ASTM D5961 procedure-A double shear with a single pin loaded. The specimen was loaded until initial ply failure load (IPFL) was reached, and the load has dropped off about 30% from the IPFL, to provide a more representative failure mode assessment. It is observed from the load versus displacement curve (Fig. 8) that the curve passed through the origin and yielded in the linear trend until it reached the IPFL and dropped down instantaneously to the set limit. On the other hand, both curves (Figs. 9 and 10) show a similar trend (Fig. 8) despite having a difference in punch clearance at the beginning of the hole's preparation stage. Figures 8, 9, and 10 show the specimen failed in between 1.3 and 1.5 mm of displacement after the load being loaded. Noted that this displacement value is almost close to the value of displacement [26] where the IPF had occurred.

Based on the results being summarized Table 3, all of the five drilled specimens have achieved the IPFL of approximately 21.46 kN in average, followed by 21.32 kN and 19.83 kN for both combined techniques (C = 25% and C = 30%) with coefficients of variation, CV of 6%, 3%, and 1%, respectively. It shows that there is a slight difference in the

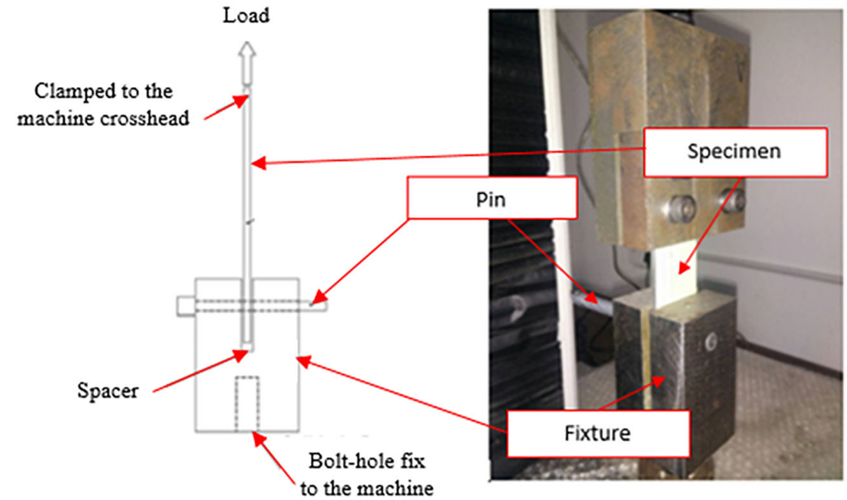

Fig. 7 Bearing test setup

IPFL between conventional drilling and both combined technique with 0.65% and 7.90% in comparison. However, the difference is still below 10%, which indicates that the result is considered within the acceptable range.

In relation to the previous research done [26], there is a massive difference in the IPFL between conventional drilling and punching. The reasons of the significant difference have been explained clearly in the previous research ([26]), which are caused by the damage induced at the hole-boundary such as delamination, fibre micro buckling, and matrix cracks that propagate through the laminated matrix due to punching during the hole preparation. By superimposed the conventional drilling with a large diameter (i.e. 10 mm) after punching (5 mm in diameter) in the combined technique, there is a great potential that the damage induced at the hole boundary during punching is diminished. Instead, the surface area of the hole boundary is replaced by the drilling characteristics. These results were demonstrated that punching on laminated composite could be improved by the help of conventional drilling while maintaining the strength of the hole close to the conventional drilling technique alone.

The slope of the stress against strain curves showed in Fig. 11, 12, and 13 provides the bearing stiffness/chord modulus of the hole.

Table 3 shows a summary of the experimental bearing result for all the tested specimens with two different types of holes preparation technique.

Based on the result summarized in Table 3, the average bearing strength at IPF for two types of hole preparation techniques can be extracted from the stress-strain curves. The highest average bearing strength at IPF obtained from the conventional drilling is 584.75 MPa, followed by 581.12 MPa and 540.33 MPa for both combined techniques with (C = 25% and C = 30%) standard deviation, SD of 35.30 MPa, 5.19 MPa, and 16.02 MPa, respectively.

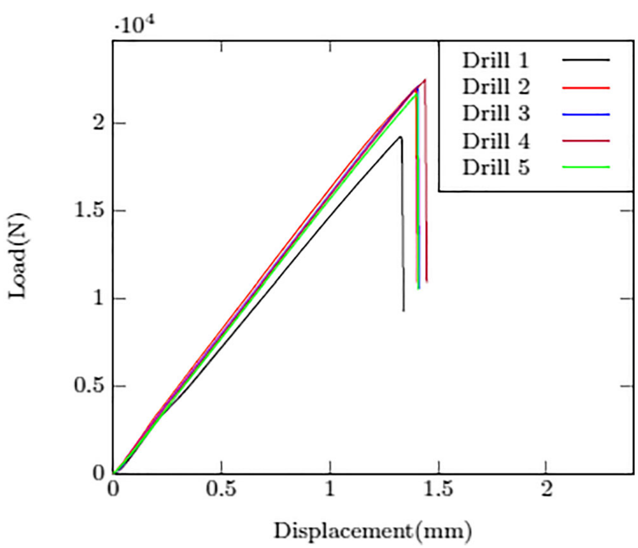

Fig. 8 Load versus displacement curve for conventional drilling technique (10-mm diameter)

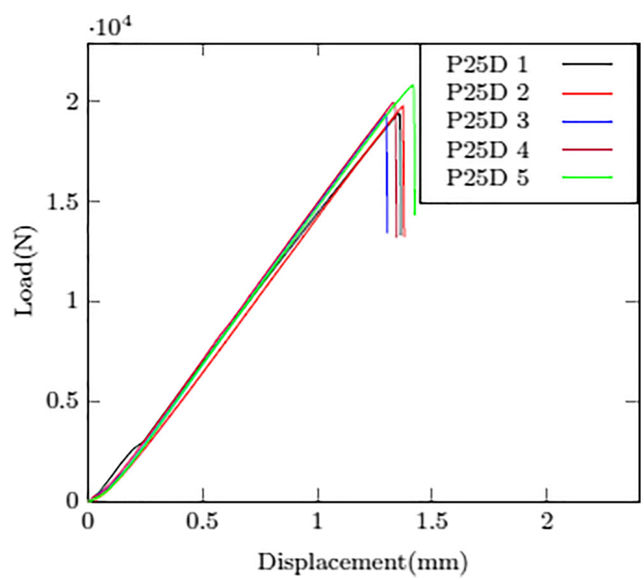

Fig. 9 Load versus displacement curve for combined technique (C = 25%, 5-mm diameter + conventional drill 10-mm diameter)

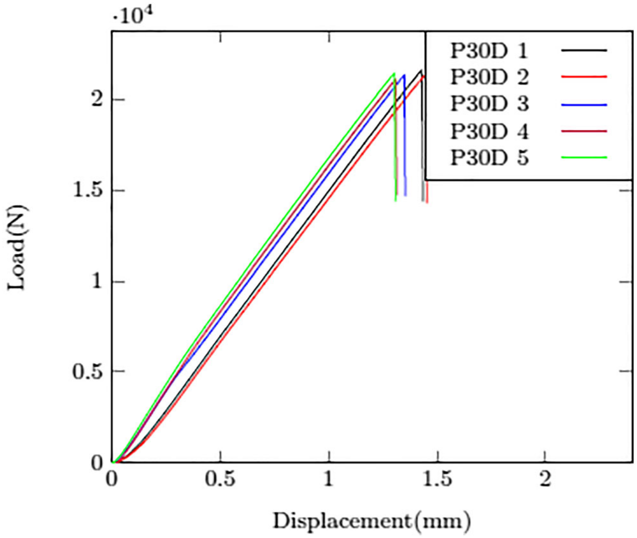

Fig. 10 Load versus displacement curve for combined technique (C = 30%, 5-mm diameter + conventional drill 10-mm diameter)

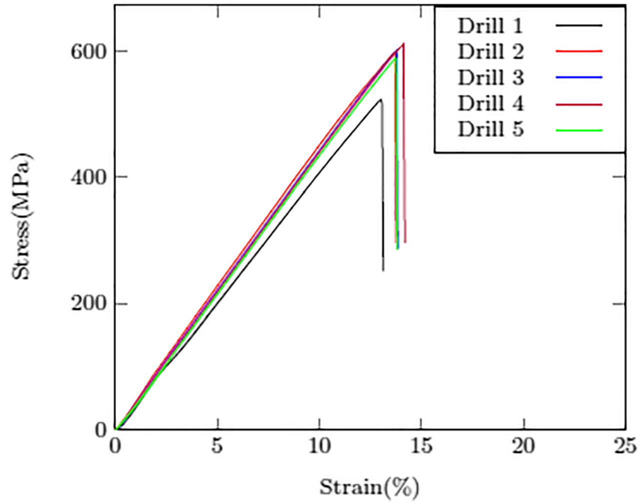

Fig. 11 Stress vs strain for conventional drilling technique (10-mm diameter)

Therefore, it shows that there is a slight difference in average bearing strength at IPF between the conventional drilling and combined techniques with (C = 25% and C = 30%) of 0.62% and 7.90% in comparison. The difference in the bearing strength at IPF of both techniques might be an indication of the damage induced in the test specimen during punching at the early stage of hole preparation for combined technique. The result also shows that the die clearance of punching in combined technique has a minor effect on the bearing strength at IPF.

The bearing chord stiffness, E^{br} summarized in Table 3 is obtained by calculating the slope between two specific bearing stress and bearing strain points corresponding to the linear portion of the stress versus strain curve using the relation: $E^{br} = \Delta\sigma^{br}/\Delta\varepsilon^{br}$, where $\Delta\sigma^{br}$ and $\Delta\varepsilon^{br}$ are the changes in bearing stress and bearing strain, respectively. The calculation of slope is carried out by regression method using Microsoft Excel. The average of bearing chord stiffness is reasonably consistent for each test case as referred to the coefficient of variation, CV. The combined technique with C = 30% attains the highest bearing stiffness of 44.44 GPa, followed by conventional drilling and combined technique with C = 25% of 43.76 GPa and 43.21 GPa. From the findings of combined technique (C = 30%), it was found that the variation between the bearing stiffness is almost the same except for one value that lies outside the acceptable range from the mean which caused the average of bearing stiffness to be slightly higher than the others. It might be due to an error occurred during the test. However, the difference between the bearing stiffness values for combined technique is relatively close to the conventional drilling technique.

Table 3 Experimental bearing results for each specimen

Specimen	Conventional drilling technique (10-mm diameter)			Combined technique (C = 25%, 5-mm diameter + drill 10-mm diameter)			Combined technique (C = 30%, 5-mm diameter + drill 10-mm diameter)		
	P^{max} (kN)	F^{IPF} (MPa)	E^{br} (GPa)	P^{max} (kN)	F^{IPF} (MPa)	E^{br} (GPa)	P^{max} (kN	F^{IPF} (MPa)	E^{br} (GPa)
1	19.20	523.23	41.52	19.39	528.51	41.30	21.58	587.96	44.43
2	21.98	598.98	44.63	19.72	537.52	43.16	21.34	581.51	43.85
3	22.06	601.26	44.32	19.32	526.69	44.41	21.29	580.09	44.34
4	22.43	611.37	44.32	19.90	542.37	43.61	21.05	573.52	44.54
5	21.61	588.92	44.00	20.97	566.56	43.56	21.38	582.51	45.06
Mean	21.46	584.75	43.76	19.83	540.33	43.21	21.32	581.12	44.44
SD	1.30	35.30	1.27	0.59	16.02	1.16	0.19	5.19	0.44
CV (%)	6	6	3	3	3	3	1	1	1

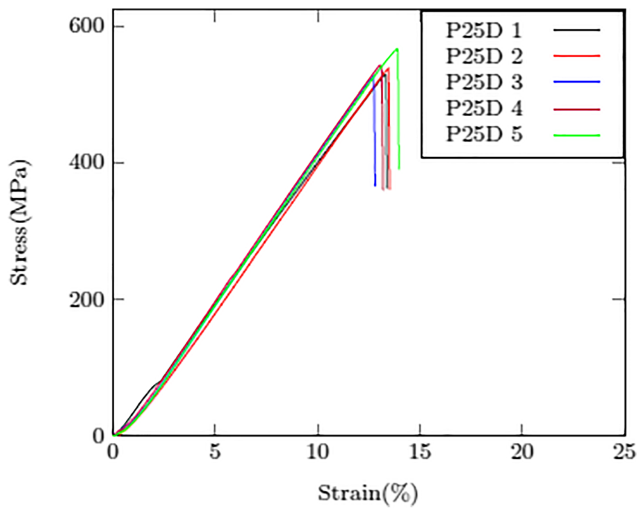

Fig. 12 Stress vs strain for combined technique (C = 25%, 5 mm diameter + conventional drill 10-mm diameter)

4.2 Failure mode assessment

The image of tested specimens with failure mode is illustrated in Fig. 14 as examples of the observation. The specimen is loaded until terminated at 30% right after reached IPFL. This is to prevent masking of the true failure mode by large-scale hole distortion, to provide a more representative failure mode assessment. The final failure of the hole specimens occurred when the damage near hole-fastener boundary displaced a certain distance from the end of the specimen. In this experiment, the displacement is in between 1.3 and 1.5 mm after the load is being loaded. The results of the investigation show that only bearing failure was observed for all 15 specimens being tested for the different hole preparation techniques. The result is consistent with the findings being reported [27, 28].

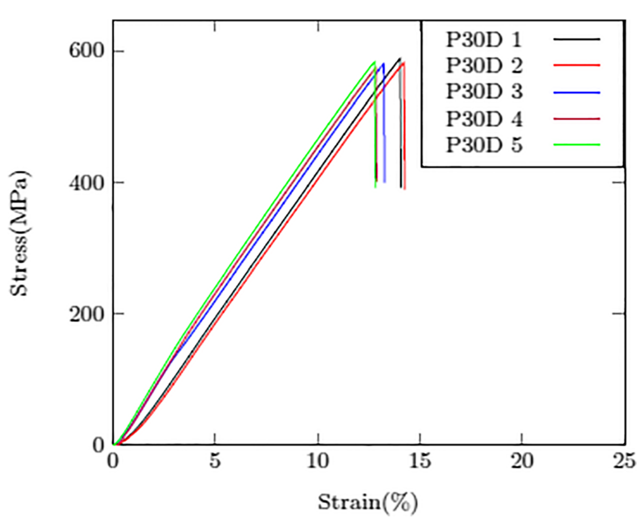

Fig. 13 Stress vs strain for combined technique (C = 30%, 5-mm diameter + conventional drill 10-mm diameter)

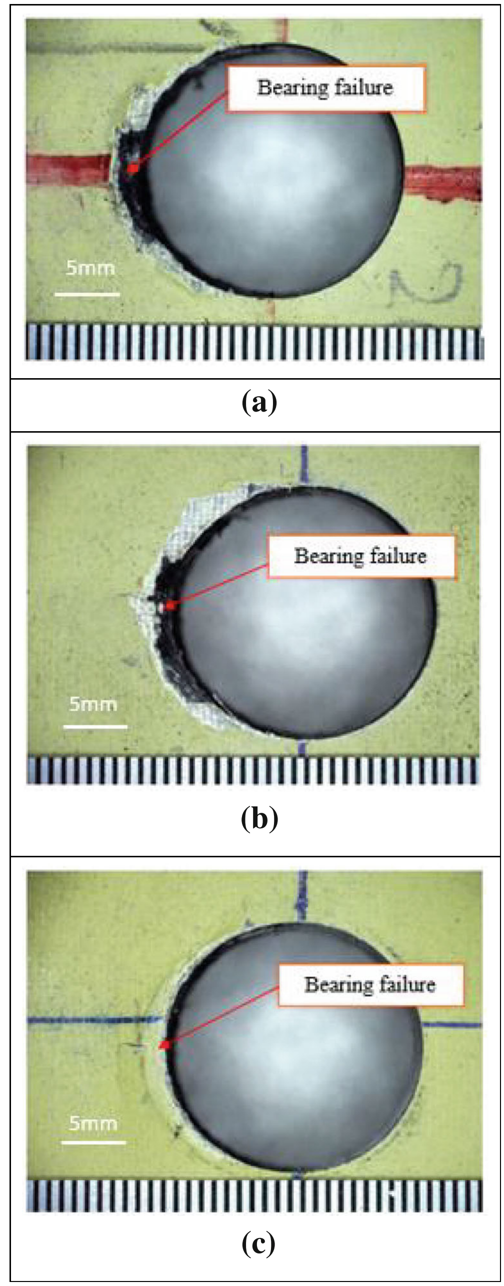

Fig. 14 Photograph of specimen failure for pin-hole bearing test (**a**) conventional drilling technique (10-mm diameter.) (**b**) combined technique (C = 25%, 5-mm diameter + drill 10-mm diameter) (**c**) combined technique (C = 30%, 5-mm diameter + conventional drill 10-mm diameter)

A sample from the bearing test for each hole preparation technique was sectioned, and the imaged were captured using Andonstar ADSM201 HDMI 1080P Full HD USB Microscope to identify the failure damage of the laminate matrix. An example of a macrograph of the cross-sectional hole is presented in Fig. 15.

Based on Fig. 15, it was observed that the damage accumulated in the laminate area adjacent to the loaded pin is

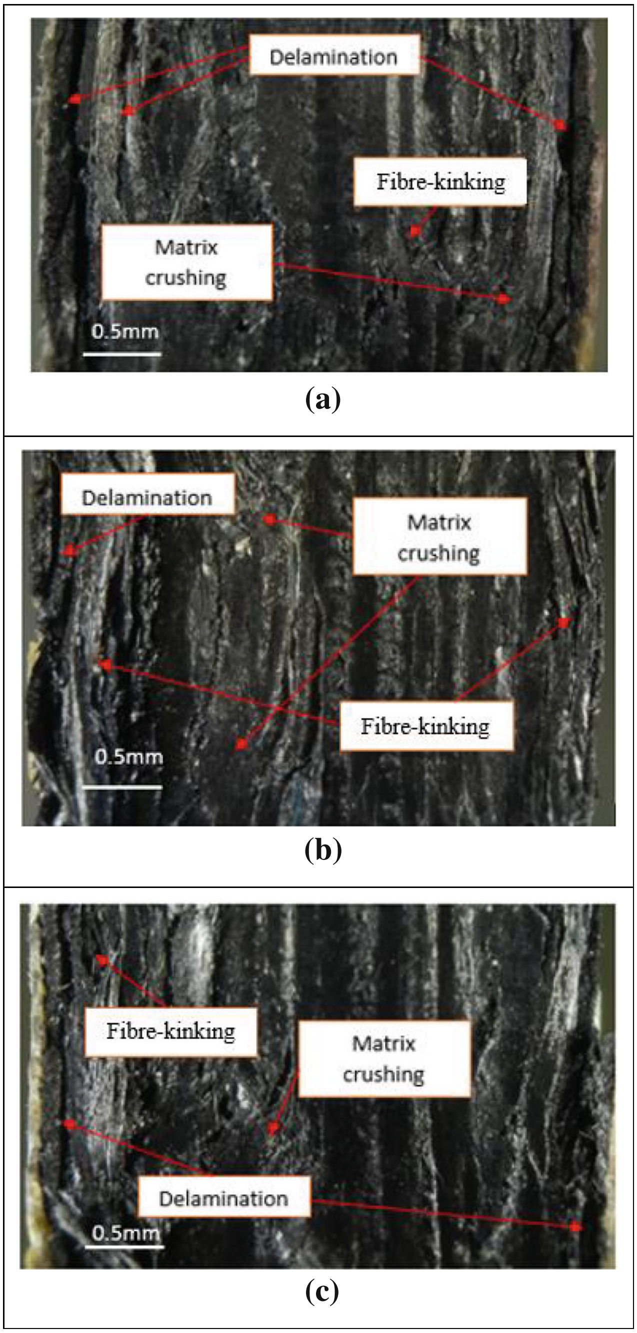

Fig. 15 Macrograph of the cross-sectional hole (**a**) conventional drilling technique (10-mm diameter), (**b**) combined technique (C = 25%, 5-mm diameter + conventional drill 10 mm diam.), and (**c**) combined technique (C = 30%, 5-mm diameter + conventional drill 10-mm diameter)

visible. Close examination revealed that the damage developed during the bearing test is delamination, matrix compression failure, and compressive fibre failure. An extensive crushed zone in these inner mat plies originated from fibre buckling due to compressive stress of the loaded pin parallel to the fibre. As a result, the fibres bend and eventually break at excessive compression and the kink form as shown in macrograph. This leads to shear cracking and causing several delaminations. These damage growths show a similar result for both types of hole preparation technique. The present of this damaged is always associated with bearing failure. This finding is consistent with the research done [29].

The result shows that all the specimens failed identically in bearing failure for both conventional drilling and the combined technique. This means that the punching at the early stage of the combined technique demonstrated an insignificant effect on the failure mode. Accordingly, the adoption of punching on composite laminates can be improved greatly in term of strength and quality by adding conventional drilling over the punching technique.

4.3 Surface roughness assessment

Many factors, such as spindle speed, feed rate, and depth of cut, affect the surface roughness of the workpiece. Moreover, at a lower feed rate and higher cutting speed, the fracture is less aggressive and easier to deal with due to a lower strain rate. Thus, to ensure finer surface roughness, all the specimens were drilled at constant drilling parameters recommended by the aircraft industry. The surface roughness measurement was performed over a sampling length of 3.6 mm along with the depth of the holes. The cut-off value was taken at 0.8 mm. The holes surface was scanned along with the hole's depth at the 4 quadrant points. Four readings were taken at 90° to each point along the hole, and the average value is reported in Table 4. Note that the value of surface roughness for punching at the first stage of combined technique is not presented in the table. This is due to the damage on the punching area which is severe, and the value measured is beyond the range. For this reason, the value of surface roughness for punching at an early stage for the combined technique cannot be meaningfully compared.

Based on Table 4, the quality of the hole in terms of surface roughness (Ra) for drilling technique is 1.704 followed by combine techniques (C = 25% and C = 30%) by 1.604 and 1.756, respectively. The average of the surface roughness for all hole preparations is below 3 μm which is considered preceding manufacturer standard. This is attributed to the damage induced during punching in combined technique is eliminated by the conventional drilling technique.

5 Conclusion

The strength and quality of the hole of the pin-loaded carbon fibre reinforced epoxy have been investigated experimentally. Performance of the new approach of hole-making technique was quantified. It was confirmed that the effects of punching technique from previous research [26] had been greatly improved by implement the combined technique. Some of the

Table 4 Experimental surface roughness results for each specimen

	Drilling technique (10-mm diameter)	Combined technique (C = 25%, 5-mm diameter + conventional drill 10-mm diameter)	Combined technique (C = 30%, 5-mm diameter + conventional drill 10-mm diameter)
Specimen	The average surface roughness of hole (4 points measurement) (μm)		
1	1.971	1.829	1.714
2	1.937	2.286	2.050
3	1.287	0.816	1.590
4	1.614	1.509	1.753
5	1.710	1.581	1.673
Mean	1.704	1.604	1.756
SD	0.277	0.536	0.175
CV (%)	16	33	10

critical observations and conclusions derived from the experimental studies are summarized as follows:

1. The value of bearing strength at IPF, bearing chord stiffness for combined technique, is close to the conventional drilling technique with below 10% difference in value. Also, both techniques (combined and conventional drilling) display similar loading curves trends which demonstrated that the hole has a similar characteristic.
2. Further analysis of failure mode showed that both techniques have failed in a similar manner which is in bearing failure mode. In conclusion, introducing the combined technique in the hole making on composite laminates grant a considerable improvement in punching technique in terms of bearing strength at IPF.
3. The value of surface roughness, Ra of combined technique, is close to conventional drilling, which is below 3 μm. This value of Ra is considered the preceding manufacturer. It can be concluded that the hole quality (surface roughness) of the punching technique has been greatly improved by implementing the combined technique.

In the future, further comparison can be made to other techniques such as low power CO_2 laser. Also, statistical analysis to determine the performance of the cut is another aspect that can be explored in the future. The effect of material properties, including structure behaviour to performance of the punching and drilling processes, is also an interesting aspect to be explored in the future.

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