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ORIGINAL ARTICLE

Bearing strength and progressive failure analysis of the punched hole of CFRP under tensile loading

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Abstract

Mechanical joints in composite structures are broadly used in many applications due to their accessibility for disassembly during maintenance. The capability of mechanical joints (bolted joints, pin joints, rivet joints, etc.) depends on the hole quality because the load transmitted via fastener gives rise to stress concentration around the hole-fastener boundary. This experimental study investigates the pattern on the effect of hole preparation techniques, namely, drilling and punching, on carbon-fiber-reinforced polymer with constant geometric parameters to the bearing strength and progressive failure analysis of the hole under tensile loading. A bearing test is conducted according to ASTM D5961 Procedure-A double shear with single-pin fastener using a modified fixture. The progressive failure modes resulting from the experiment are quantified and compared to those in literature. Results reveal clear differences in the bearing-response profiles plotted in the load–displacement graph between the drilling and punching techniques.

Keywords CFRP · Punching · Drilling · Bearing strength

1 Introduction

In recent years, composite materials have been widely used in the aerospace and automotive industries because of their high strength-to-weight ratio and have begun to replace metallic materials in many modern aircraft structures [1]. Composite materials are assembled as composite structures by mechanical joints via bolted connections, pin connections, and so on [2]. These joints require holes to assemble the structures. The strength of the joint depends highly on the hole quality, hole-fastener clearance, geometric size, and material size, among many other factors [3, 4]. However, hole quality is the most crucial in hole making, which causes high stress concentration around the hole-fastener boundary and limits the strength of the structures [5, 6]. Composite laminates are fundamentally unique compared to metallic materials, and this difference adds complexity to the machining process because numerous parameters need to be considered to achieve the required precision and accuracy. Consequently, approximately 60% of the drilled holes on composites are rejected at the primary stage [7]. In addition, as most of the composites are abrasive materials, the drilling cost is high because of repeated regrinding of the drill bit due to severe wear [8]. Thus far, drilling remains the main conventional technique to produce holes for laminate composites [9]. Substantial progress has been made in drilling to achieve the optimal hole quality on laminate composites.

Many studies have been conducted to analyze the effect of mechanical fasteners on the bearing strength of laminate composites. These studies are motivated by the failure initiation that frequently occurs in structural joints owing to stress concentration, fatigue, and fiber damage cause by drilling operations [10]. The damage induced by drilling include delamination, fiber pull-out, fiber fracture, matrix cracking, matrix burning, plastic deformation, and debonding [11]. The damage due to delamination (peel-up and push-down delamination) has become a major concern, and several studies have been conducted on this subject to minimize the damage [12–15]. Delamination depends on cutting parameters and drill geometry. The thrust force is highly influenced by cutting parameters, such as feed, which as it increases, also increases the delamination damage [16]. Several authors have

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investigated the associated effects of drill geometry on delamination. Their findings indicated that the thrust force changes with the drill geometry and that delamination can be minimized at a high feed if a suitable drill geometry is selected [17]. The influence of the cutting parameter toward tool wear and hole quality was studied in [18], which found a correlation between tool wear and delamination. The author states that increasing the cutting speed and feed to a certain amount will reduce tool wear and delay the push-down delamination. IşIk and Ekici [19] investigated the drilling parameter that influences surface damage on GFRP and found that the damage factor at both hole entrance and exit of the drilled hole can be reduced by increasing the cutting speed. However, increasing the feed increases the damage factor at the hole exit and decreases it at the entrance. Increasing the feed also elevates the thrust force, which lowers the bearing strength of the drilled hole because of the increase in delamination [20]. Aside from drilling, the punching technique shows potential in hole making on laminate composites [21]. In some cases, punching exceeds drilling in terms of time, speed, versatility, and cost. In industrial applications that require less precision and accuracy than the finished product, punching is a primary choice over other techniques. Various studies on punching on metallic materials have been carried out to obtain the optimum quality of the part. However, punching behavior in composites is uncertain and is still under discussion because of some contradicting results [22]. Numerous parameters influence metal punching characteristics, including clearance, tool geometry, stroke rate, blank holder force, sheet thickness, blank layout, material type, punch–die alignment, and friction [23]. The non-homogeneity, multi-phase structure, and anisotropic nature of composites lead to unavoidable severe damage (delamination, incomplete shearing of plies, fiber fracture, etc.) under bearing load and reduce structural capability [12]. The feasibility of punching on laminate composites using different puncher profiles was examined in terms of three quality aspects: precise hole diameter, incomplete shearing, and delamination factor [24]. The author found that the conical shape puncher gives the best option among the proposed puncher profiles. Given the increasing number of applications in various fields requiring many circular holes, punching may be a successful alternative to drilling. There are several research methods for strength analysis of the hole-fastener for composite structures. A prominent method is the ASTM D5961 Procedure-A double shear with single-pin fastener [25]. This test provides useful data on the bearing response exhibited by the specimen under load. An evaluation of the bearing strength characteristic of the hole is necessary to determine the limit that can be achieved before failure. Several studies have investigated the effect of the geometric parameter of laminate coupons on the bearing strength and progressive failure of hole fasteners. Increasing the edge distance-to-hole diameter ratio (E/D) and width-to-hole diameter ratio (W/D) was found to increase the bearing strength [26–28]. When E/D and W/D exceed a certain value (> 3), the progressive failure mode changes from shear-out or net tension to bearing failure [26, 28, 29]. Thus, the aim of the present study is to investigate the pattern on the effect of different hole-making techniques (drilling and punching) on a carbon-fiber-reinforced polymer (CFRP) composite to the bearing strength and progressive bearing failure of the hole under tensile loading.

2 Experimental procedure

2.1 Fixture fabrication

The test fixture used in this experiment was designed slightly different to the ASTM testing fixture. It is designed for the specimen to be loaded on a straight pin without clamp-up force supported in double shear. Figure 1 shows the test fixture fabricated according to ASTM D5961 Procedure-A. The spacer was designed to fit the thickness of the specimen, which minimized bending to avoid uneven stress concentration on the pin and prevented premature failure during the bearing test. The material used for the test was D2 tool steel. For the fabrication process, a block of D2 tool steel was cut according to the design using a power jigsaw, followed by a final surface finishing using a milling machine with a tungsten carbide cutter to eliminate burrs. A wire-cut machine was then used to fabricate the spacer, where the specimen was placed during the test. The pinholes were drilled parallel through the test fixture using a 5-mm HSS drill bit. In addition, an M12 tapped thru hole was prepared at the bottom of the test fixture for mounting purposes. The pin

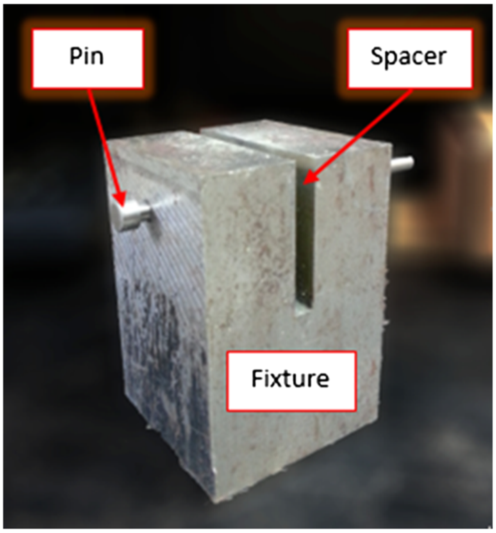


Fig. 1 The modified test fixture according to ASTM D5961 Procedure-A

material used in this experiment was a mold ejector pin made of the same material (i.e., D2 tool steel). This material gave adequate strength compared to the specimen coupon. Hence, the possibility of pin failure could be avoided.

2.2 Specimen

The material used was made of carbon-fiber epoxy prepreg cured via autoclave. The laminate panel was 3.6 mm thick and consisted of 26 layers of unidirectional carbon fiber with fiber orientation $[45/135/90_2/0/90/0/90/0/135/45_2/135]$s. Woven fiberglass was place on the top and bottom of the carbon laminate to prevent metal joining due to galvanic corrosion and delamination. To prepare the specimen coupon, the laminate panels were cut to size 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. Then, a horizontal belt sanding machine was used to refine the cutting edge and achieve precise dimensions of the specimen coupons. A total of 15 specimen coupons were prepared with the standard geometric parameter configuration and a width-to-bolt diameter (W/D) and edge distance-to-bolt diameter (E/D) ratio of 4. Two types of techniques were used in this hole-making experiment on the specimen coupon, namely, punching and drilling. There were three groups of specimen coupons, and each group consisted of five specimen coupons nominally identical for repeatability. The punching technique was used for two of the three groups of specimen coupons, with a different size of die clearance used for each punching group, while the drilling technique was used for the last group. The geometric parameters used in this experiment were constant for all specimen coupons. The present coupon dimensions differ from those in the ASTM standard, but this detail does not make the present analysis inappropriate. The geometric configuration of the experimental specimen for double shear single-hole with pin is illustrated in Fig. 2 and Table 1.

3 Experiment setup

3.1 Specimen holder

The specimen holder made of aluminum plate was designed to ensure accurate positioning of the specimen and precise hole punching. The holder consisted of 1 degree of freedom plate, which allowed for adjustment of the specimen position prior to the punching operation. The holder gripped the specimen to prevent tilting and horizontal movement during the operation. Special attention was given to maintain the specimen parameter (hole position) of each specimen coupon. The specimen holder was likewise designed in such a way that it could be mounted on the die. Figure 3 shows a specimen holder attached to a rig.

3.2 Punching

A laboratory test rig (Fig. 4) was specially designed for this investigation. The die placed on the rig was an Instron 3367 Universal Testing Machine (UTM) with a punch travel speed of 5 mm/s. As the punch traveled downward, the initial action was to clamp the specimen coupon. The bottom die was pressed by the top die to generate a holding pressure on the coupon. The punch proceeded further to cut the coupon successively. For this experiment, five coupons were punched with a die clearance (C) of 25%, which was subsequently changed to C = 30%. The procedure was repeated for another five coupons. Table 2 gives the detail of punch and die diameter at different die clearance.

3.3 Drilling

Dry drilling process was performed at room temperature, as shown in Fig. 5. In this study, a 5-mm HSS twisted drill bit was used to make the hole through the specimen coupon. Drilling was carried out using a milling machine with a constant feed of 3 mm/min at a spindle speed of 600 rpm. The specimen was flanked between a backing plate to minimize the delamination damage during the drilling process. The clearance of the drill hole specimen was about 0.01 mm.

3.4 Test standard

This experiment followed the ASTM D5961 Procedure-A double shear with single-pin fastener. The objective of the test was to obtain the bearing strength of the composite laminates. Compared to other procedures, this standard can avoid the induced bending moment under bearing load on the pin specimen. This bending is considered as secondary bending, where the high localized stresses are distributed non-uniformly through the thickness of the composite laminates. The test was based on an experiment conducted using the ASTM D5961 Procedure-C single shear with single-bolt

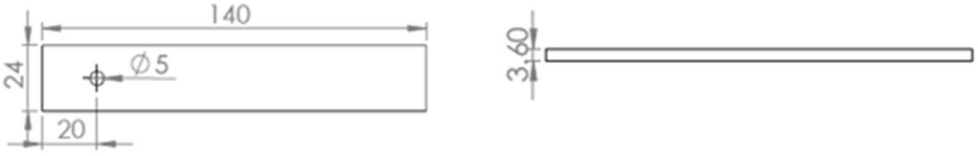


Fig. 2 Geometries of the coupon

Table 1 Specimen and pin dimensions

Parameter	Standard dimension, mm
Fastener or pin diameter, *d*	5
Hole diameter, *D*	5
Thickness, *t*	3.6
Length, *L*	140
Width, *W*	24

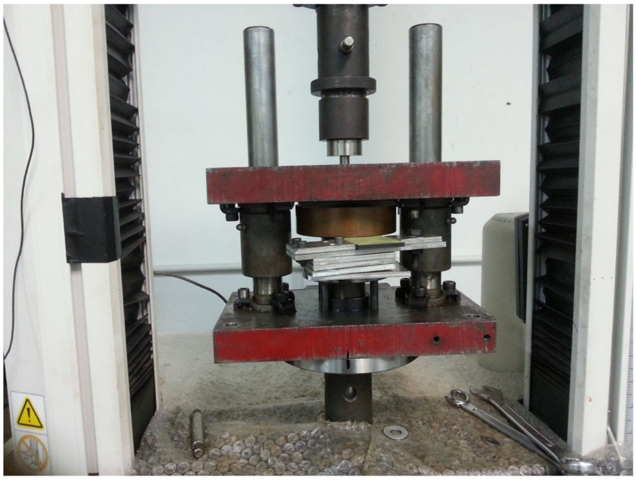


Fig. 4 Laboratory die rig placed on the UTM

fastener. The test was conducted to study the performance of hole-making via different techniques. The goal was to characterize and compare the graph patterns of bearing load induced by hole-making on composite specimens via the punching and drilling techniques. The test intended to identify the failure modes through a series of experiments performed using a new modified ASTM D5961 test fixture, as described previously. To avoid high stress concentration on the pin during the experiment, the fixture was not designed similar to the standard ASTM fixture. In contrast to the standard, the test fixture used in the current test set-up did not use any washer to support the specimen because the fastener itself was replaced by a pin with no thread, which did not require any washer. The modified test fixture used in this experiment did not allow any external displacement transducer to be placed on a specimen surface owing to the geometrical constraint of the fixture. Therefore, the load-specimen displacement was continuously measured by an internal displacement transducer recorder (internal load cell) built in the system of an INSTRON 3367 UTM through the data acquisition system utilizing Bluehill 2 Software. In addition, the specimens and pin images were captured before and after the experiments to analyze the damage and failure. The testing fixture was mounted on an INSTRON 3367 UTM with 30 kN loading capacity. The pin was inserted into the bolt hole without a washer between the composite specimen and the testing fixture. The specimen was mounted at approximately 2 cm between the hole center and the upper section of the specimen, which was clamped to the machine crosshead, while the other end was fixed to the testing fixture. Then, the experiments were carried out at room temperature with a tensile loading rate of 1 mm/min (Fig. 6). The experiments were tested monotonically to failure. Bearing stress/strength (σ^{br}) and ultimate bearing strength(F^{bru}) were calculated from the test results using the standards Eq. 1 and Eq. 2 as follows:

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

$$F^{bru} = \frac{P^{max}}{D.t} \tag{2}$$

where P, P^{max}, D, and t represent the load (N) at any data point, maximum load (N), bearing bolt-hole diameter (mm), and composite plate thickness (mm), respectively. The failure and damage pattern identified on the specimens resulting from the bearing test were recorded and compared for both hole-making techniques.

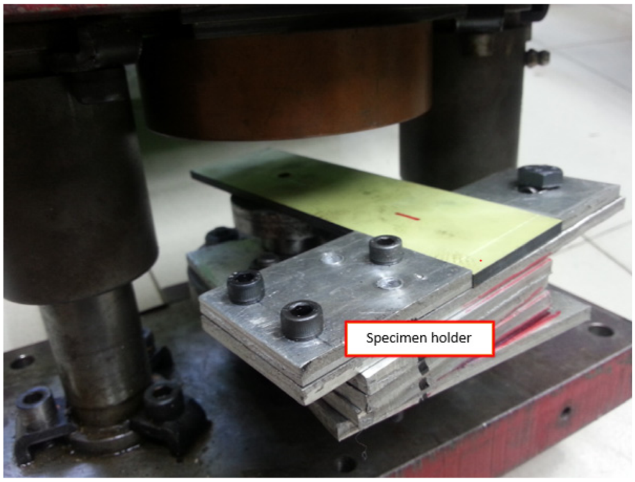


Fig. 3 Specimen holder used in the experiment

4 Result and discussion

4.1 Failure mode analysis

The failure propagation of the hole caused by contact stress at the hole boundary for the CFRP specimen coupons is shown

Table 2 Puncher dies clearance

Punch diameter (mm)	Clearance (%)	Die diameter (mm)
5.0	25	6.70
5.0	30	7.04

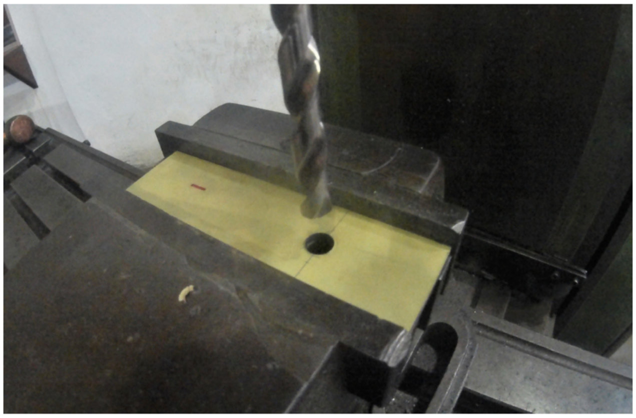


Fig. 5 Drilling operation setup on conventional drilling machine

in Fig. 7. The basic types of failure modes of composite bolted joints are tension, shear-out, tear-out, cleavage, and bearing. The fixture's geometric constraint makes it almost impossible to clearly observe the progressive failure that occurs during the test. Nonetheless, the failure mode of the specimen can be predicted based on the geometric parameter configuration. Previous research revealed that when the ratios W/D and E/D exceed a certain value (> 3), the failure mode noticeably changes from bearing failure to mix mode failure [26, 28, 29]. Their results show that the photographed images of failure, as tested on all 15 specimens.

Essentially, the specimens failed promptly at the initial stage of the test, followed by a sudden drop in load which caused the bearing failure to occur. This failure mode is the desirable type of failure in the joint mechanism of laminate composites because it provides prior warning before the final failure of the joints. At this stage, the specimen experienced initial ply failures (IPFs, Figs. 8, 9, and 10) and continued on to the pseudo yield until it reached the rupture point. At this point, the failure mode clearly shown by the photos is net tension failure, which is catastrophic and occurs without warning. Apparently, the propagation of the transitional failure mode as the load increased between the IPF and the final rupture could not be identified due to the geometric constraint of the fixture. The results indicated no

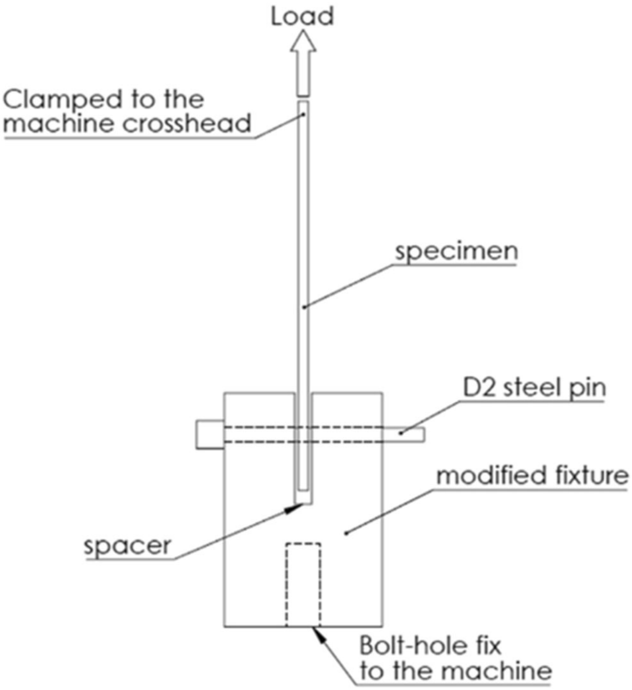
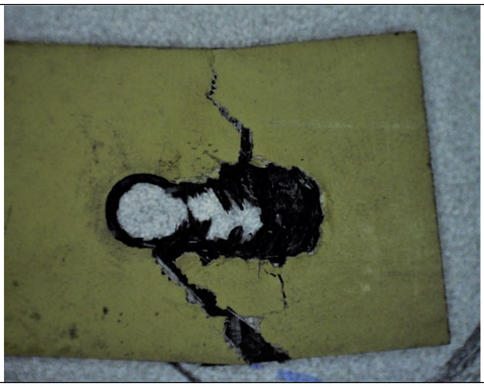


Fig. 6 Illustration of the experimental set-up

(a) drilling (final failure mode: net tension)

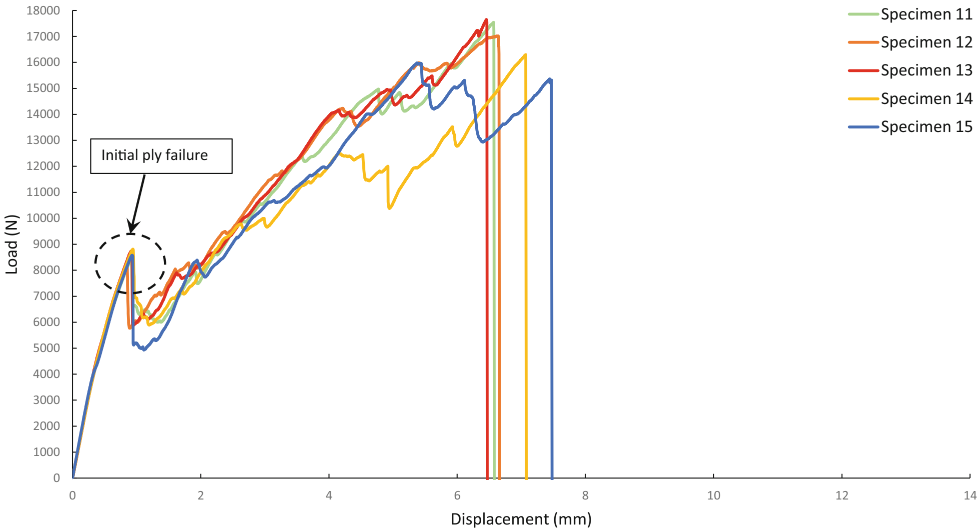


(b) punching C= 25 % (final failure mode: net tension)

(b) punching C= 30 % (final failure mode: net tension)

Fig. 7 Specimens failure at macroscopic level for bolt-hole bearing test. (**a**) drilling (**b**), punching C = 25%, and (c) punching C = 30%

Fig. 8 Load-displacement pattern for hole produced by drilling



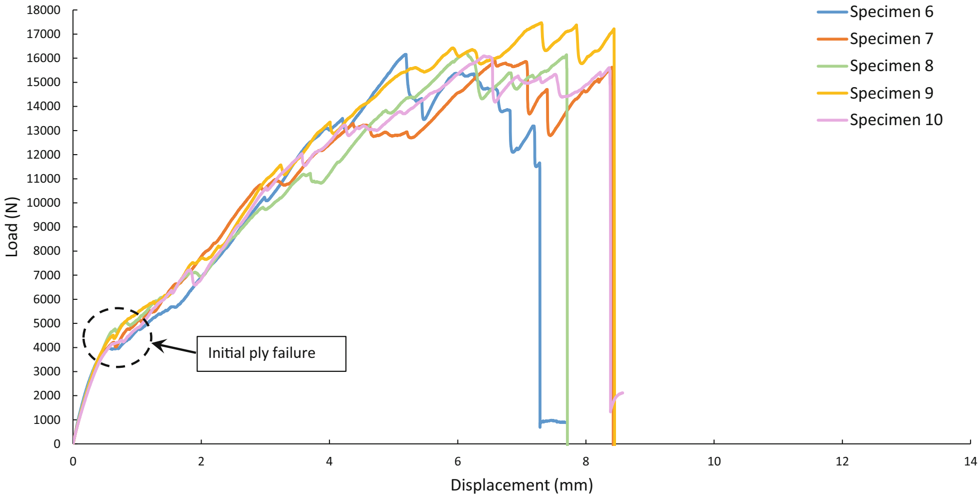
difference in failure mode for the punching and drilling techniques as a result of identical geometric parameters, a finding that was proven by the specimen photos as the final macroscopic source. The actual failure mode was more complex, with a great number of variables involved and consisting of more than two failure modes.

4.2 Bearing strength

The variation trends of load versus displacement by the punching and drilling techniques are plotted in Figs. 8, 9, and 10. As the load was applied to the specimen coupon, the displacement progressed in a linear trend until a sudden drop in load was observed, known as IPF. The results show that the IPF occurred at approximately 1 mm of displacement after the specimen was loaded. The specimen then evidently continued on to the pseudo yield, to the maximum load, and then gradually decreased until final rupture (only for the punched specimen). Both graphs for punching show the same pattern despite the difference in punch clearance ($C = 25\%$, $C = 30\%$). However, the graph for the drilling technique (Fig. 8) shows a difference in trend correlated to the punching technique. Two values of bearing strength can be extracted from the load versus displacement curve. The first value represents the bearing stress/strength at the IPF, known as the bearing damage initiation load, where the sudden drop in load has occurred. The second value represents the ultimate bearing strength, which was obtained through an analysis of the maximum load and calculated using the standard equation (Eq. 2) recommended by ASTM.

A slight difference (i.e., 8% percentage difference) in the average bearing strength at IPF was observed between punching with $C = 30\%$ and with $C = 25\%$. This difference shows that the specimen that used punching technique with $C = 25\%$ failed at a slightly higher load compared to the one with $C = 30\%$. The results demonstrate a possible

Fig. 9 Load-displacement pattern for hole produced by punching with die clearance, $C = 25\%$



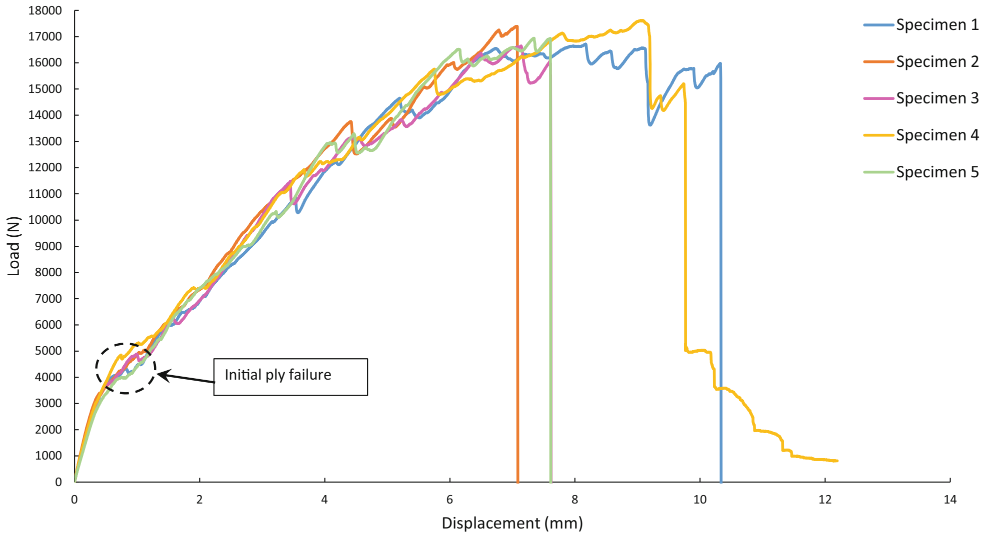


Fig. 10 Load-displacement pattern for hole produced by punching with die clearance, C = 30%

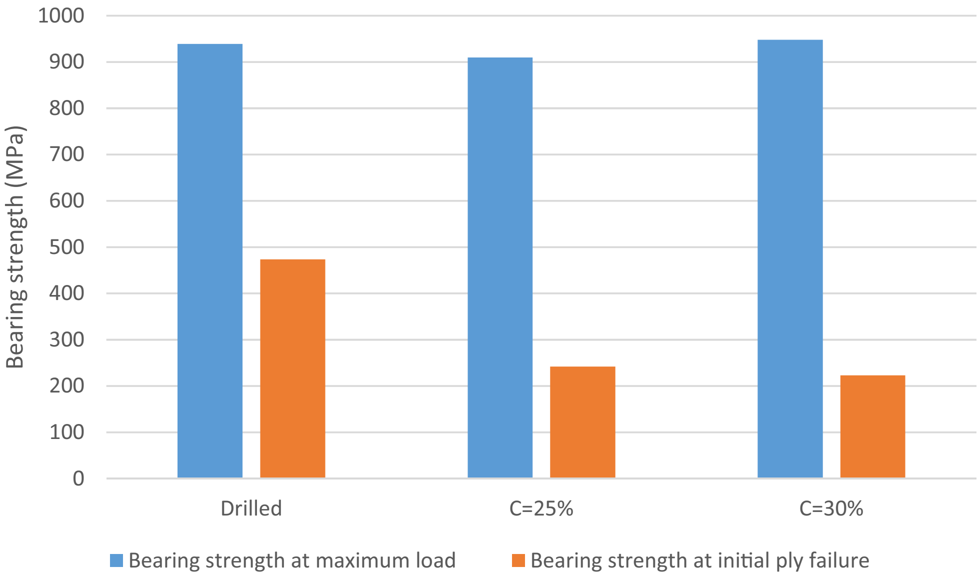
difference in surface integrity of the hole after the specimens were punched using different clearance sizes of the tool and the die. For specimens that used drilling, the average bearing stress/strength at IPF compared to the punching with C = 25% and C = 30% improved to 64% and 71%, respectively. This huge difference in bearing stress/strength between these two techniques can likely be explained by the initiation and growth of small cracks at the hole boundary of the specimen coupons. As expected, the damage induced by punching was greater compared to that by drilling during hole preparation. These results suggest that the drilling technique carries less stress to the hole, whereas the punching technique carries high stress because of the percentage difference (Table 3).

After the IPF, the specimens continued to sustain the maximum load under increasing displacements. Based on the bar chart in Fig. 11, for both techniques, the specimen reached the average ultimate bearing strength at around 910–950 Mpa in variation. The result shows that the drilled specimen can hold further loads up to 65.8% after the IPF before reaching the ultimate bearing strength at 939 MPa and dropping instantaneously to zero. This behavior of sudden drop to zero at the maximum load for drilled specimens is unique for Procedure-A double shear because no clamp or bolt, which could help the specimens suppress bearing damage, was used for support at the hole boundary during the test. However, the punching technique presented significantly different results. The bearing strength for punching with C = 30% shows the highest load that can be sustained until reaching the maximum load correlated to punching with C = 25% with a percentage difference, 123.8 and 115.9%, respectively. This finding implies that the damage that accumulated during hole preparation using punching with wide clearance (C = 30%) improves the bearing strength compared with punching with narrow clearance (C = 25%). Moreover, despite having reached the maximum failure load, the specimen continued to drop gradually until the final rupture. Unlike in drilling, this behavior presents that the specimen of punching had a longer fatigue life, which allowed for a considerable amount of stress before final failure. The results showed that punching with C = 30% attained the highest value of the ultimate bearing strength followed by drilling and then punching with C = 25%. This finding could be explained by considering the damage that accumulated at the IPF, which initiated large cracks to grow through the laminates matrix after the sudden drop in load of the drilled specimen. However, for the punching with C = 30%, the result can be attributed to the cracks that were induced during hole preparation. These cracks can be small or large, which gives space for the steady growth of progressive damage to the laminate matrix, and are sustained until a certain amount of load (i.e., maximum load) is reached before final rupture.

Table 3 Standard deviation (SD) at initial peak and ultimate bearing strength of different hole making technique

Hole making technique	SD at initial peak bearing strength (MPa)	SD at ultimate bearing strength (MPa)
Punching C = 30%	29.7	23.7
Punching C = 25%	16.9	34.9
Drill	14.9	41.1

Fig. 11 Bearing strength vs bearing strength at maximum load and bearing strength at initial ply failure



5 Conclusion

This paper presented the experimental work on the effect of hole preparation techniques, namely, drilling and punching, on CFRP with constant geometric parameters to the bearing strength and progressive failure analysis of the hole under tensile loading. The bearing strength of the drilled specimen at IPF was found to be the highest compared to that of the punching specimen. However, the results showed the opposite value for the ultimate bearing strength, where the punching with $C = 30\%$ achieved the highest value compared to the drilling. Further progressive failure analysis was carried out on the specimen hole by taking photographs before and after the experiment. The images showed that the progressive failure that took place on the bolt-hole specimen changed from bearing failure to net tension failure. Moreover, no difference was found in the failure mode for both punching and drilling techniques.

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