

Bearing strength of carbon fiber reinforced polymer laminates with drilled dual-hole configurations

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ABSTRACT

Integrity of a hole is crucial in composite component assembly, which is typically prepared by drilling. In an assembly, practically multi-holes are prepared, and joint performance depends on many factors, including hole geometries and quality. In this study, the effects of hole configurations including, hole size, D , gap between holes, M and distance to edge, E to bearing strength of carbon fiber-reinforced polymer (CFRP) laminates with two serial holes is investigated. The holes were prepared using two types of drill bits, 4-flute solid carbide and conventional high-speed steel (HSS) for comparison. In terms of types of drill bit, the result showed that the specimen drilled with carbide tools delivered higher bearing strength at 1256 MPa, as opposed to 1092 MPa for the specimens prepared by a HSS drill bit. Furthermore, the measured hole diameter showed that the carbide-drill bit produced better holes compared to the HSS drill bit. The study concluded that for dual-holes case, selection of appropriate hole configuration and drill bit plays a crucial role in maintaining the structural integrity of CFRP, primarily for aerospace and automotive high-performance applications.

Keywords: bearing strength, drilling, carbon fiber, holes, laminate, drill bits.

INTRODUCTION

The aviation sector and automotive businesses, together with the building industry, extensively use carbon fiber reinforced polymer (CFRP) composites because they offer superior strength per unit weight along with great stiffness, alongside great fatigue strength and corrosion resistance capabilities [1,2]. CFRP stands out as the material of choice for the applications that require structural efficiency with weight reduction due to its exceptional performance characteristics [3]. The requirement for mechanical joining through bolting and riveting of CFRP structures demands drilling operations on the composite material. The anisotropic and layered structure of CFRP creates challenges during the drilling process [4]. Faulty drilling techniques result in the formation of delamination and fiber pull-out, together with

thermal degradation and matrix cracking events that weaken the joint region substantially [5]. Drill bit selection proves to be the most decisive element that affects drilling performance. Drilling operations with HSS tools remain popular because of their reasonable price and ready access, yet they generate increased drilling forces and produce high machining temperatures [6]. The composite material sustains additional damage because of the poor hole quality from these instances [7]. The optimized geometric properties of 4-flute reamers using solid carbide tools deliver superior cutting performance alongside decreased tool deflection, which results in better dimensional precision. Hence, optimizing the machining strategies by choosing correct parameters to minimize damage and enhance hole quality remains a key priority [8]. The edge distance-to-diameter (E/D) and hole spacing-to-diameter

(K/D) ratios substantially affect the failure modes and bearing strength under tensile loading. [9,10]. Some other studies explored fiber orientation optimization in open-hole composite laminates through experimental and numerical analysis, concluding that strategic fiber path alignment significantly enhances notched strength compared to conventional layups [11]. The impact of cutting parameters and tool geometries (e.g., drill diameter, cutting speed, feed rate) on the quality of drilled holes in CFRP was assessed, observing that inadequate configurations result in increased delamination and thermal damage [12].

For more than single hole, the local stress distribution is changed, and the interactions between adjacent holes become complicated, modifying the predominant failure modes. Some studies have found that the orientation and spacing of the holes significantly affect the stress concentration and strength, with the hole at an angle of 22.5° being the weakest due to its high interaction. Researchers have proposed a criterion for improving strength prediction under nonlinear conditions near two interacting holes, called the extended point stress criterion (EPSC)[13]. Properly distributing the holes in composite materials can increase the strength of the material. Some studies comparing single-hole samples of carbon fiber and glass fiber composites with those containing multiple holes found strength increases of up to 13% and 7%, respectively [14]. Some studies have shown that increasing the number of holes from 0 to 2 significantly reduces the tensile strength of carbon fiber composites, while increasing the number beyond that has little effect. They also indicated that the orientation and geometry of the holes play a prominent role in stress distribution and potential failure processes in the

samples [15]. In this study, it was shown that the difference between the stress of HSS and Carbide is about 13%.

This research emphasized the outcomes of drilling configurations and evaluates the choice of drilling tool affects the integrity of CFRP in multi-hole layouts. The objective of this research was to study the effect drilling geometries to bearing strength of dual holes drilled on composite laminates.

METHODOLOGY

This study experimentally investigated the influence of drilling on the bearing strength of CFRP laminates with dual serial holes. The specimens were fabricated using CFRP laminates of 3.6 mm thickness, comprising 26 layers. The stacking sequence used was [45/135/90²/0/90/0/90/0/135/45²/135]. The specimens were prepared and drilled using two different types of drill bits, i.e., 4-flute solid carbide drill and high-speed steel (HSS) drill. In addition to choosing different locations for the holes, as shown in Table 2.

Specimen preparation

The specimens used in this study were cut according to the hole configurations as shown in Figure 1 from CFRP laminates. The prepreg used was a carbon fiber twill fabric with a fiber areal weight of 300 g/m². Table 1 exhibited the mechanical properties of the CFRP laminate.

Drilling process

Drilling was conducted using a Fanuc Robodrill α-T21iFLb CNC machine (Figure 3), under

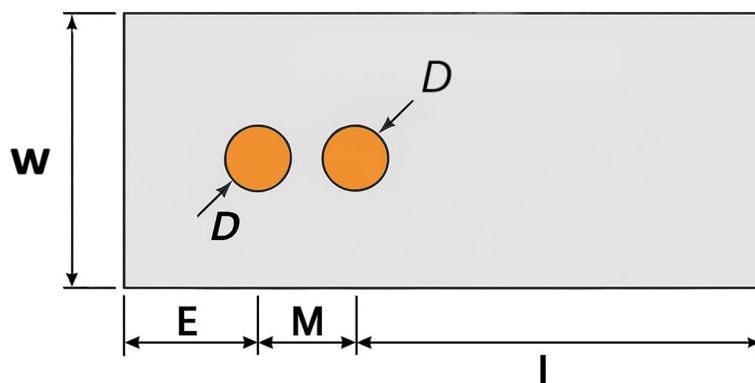


Figure 1. Schematic diagram of two-pin arrangement on CFRP specimen based on ASTM D5961

Table 1. Mechanical properties of the CFRP laminate [16,17].

Properties	Value	Unit
Tensile modulus	137	GPa
Tensile strength	1032	MPa
Elongation at break	1.7%	

precisely controlled parameters. Two types of drill bits were used, a HSS drill bit and a 4-flute solid carbide drill bit, as shown in Figure 2. The optimum drilling parameters are 2600 rpm and 0.05 mm/rev for spindle speed and feed rate, respectively, as recommended by [18].

Hole quality assessment and surface damage characterization

In order to test the quality of the drilled holes and elucidate the failure mechanisms. Moreover, the dimensional accuracy and roundness of the drilled holes were measured using a coordinate measuring machine (CMM), see Figure 4. The CMM measurements provided accurate measurement of hole diameter, ovality, and position deviation, which are critical parameters that influenced the distribution of the load and the bearing strength.

The specimen was mounted and subjected to tensile loading using a universal tensile machine (UTM) at a constant crosshead speed of 1 mm/min as shown in Figure 5. For each tool type, three specimens were tested. The data were collected in real time using a 16-bit resolution acquisition system connected through RC filters and low-drift converters, with a sampling rate of 1 Hz. Property data were rectified according to ASTM (D5961) standards and represented the average of three specimens per configuration

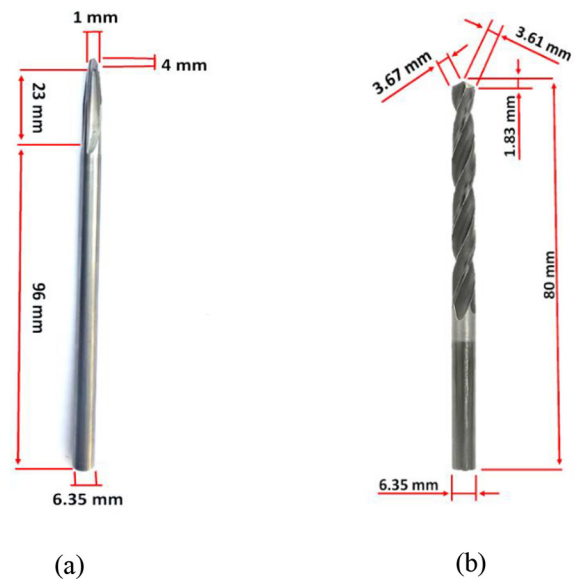


Figure 2. Schematic diagram of: (a) 4-flute solid carbide, (b) high-speed steel (HSS) drill bit

SEM examination

Scanning electron microscopy (SEM) was utilized to analyze the surface morphology and damage behavior of the CFRP laminates prior to and following the bearing strength tests. SEM observations were carried out around the drilled holes, but special focus is on the edges of holes and the area between the two holes which has the highest stress concentration where emphasis must be laid. The initial integrity of the laminate and the quality of the drilling process was determined using the pre-test SEM images, whereas the post-test images were to determine which mechanisms of micro-scale damage were the most dominant due to bearing loading. This strategy made it possible to establish a direct relationship between the characteristics of microstructural damage and the bearing behavior, which was experimentally observed.

Table 2. Hole position and edge distance parameters

Type	Drill tools	E/D	M/D	M(mm)	E(mm)	L(mm)	W(mm)
C-1	Carbide	2	2	12.7	12.7	110.4	36
C-2	Carbide	2	3	19	12.7	116.7	36
C-3	Carbide	2	4	25.4	12.7	123	36
T-1	HSS	2	2	12.7	12.7	110.4	36
T-2	HSS	2	3	19	12.7	116.7	36
T-3	HSS	2	4	25.4	12.7	123	36

Note: D – hole diameter, M – hole spacing between two holes center, E – edge distance, I – distance between second hole to edge, W – width of specimen.

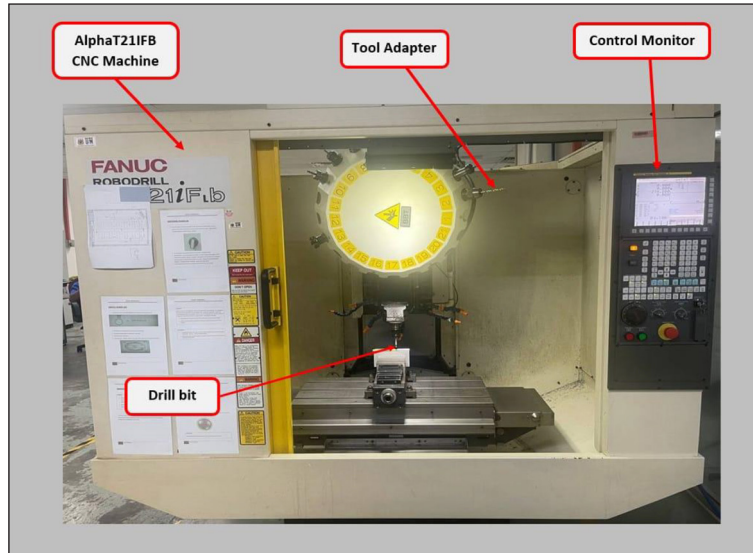


Figure 3. Robodrill machining setup

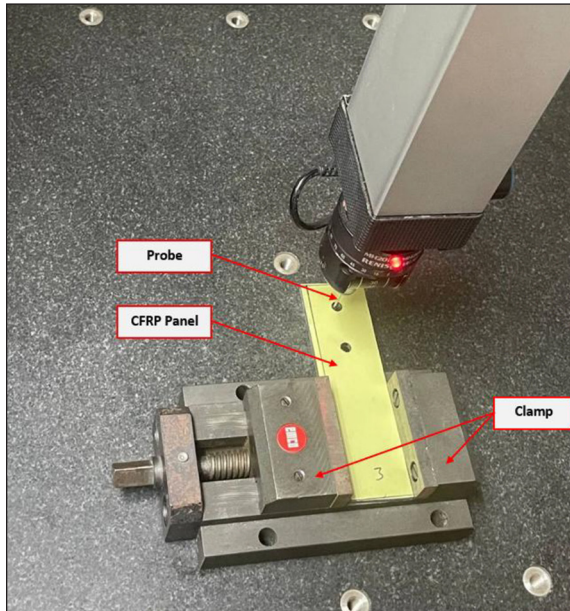


Figure 4. Measurement of hole diameter using CMM

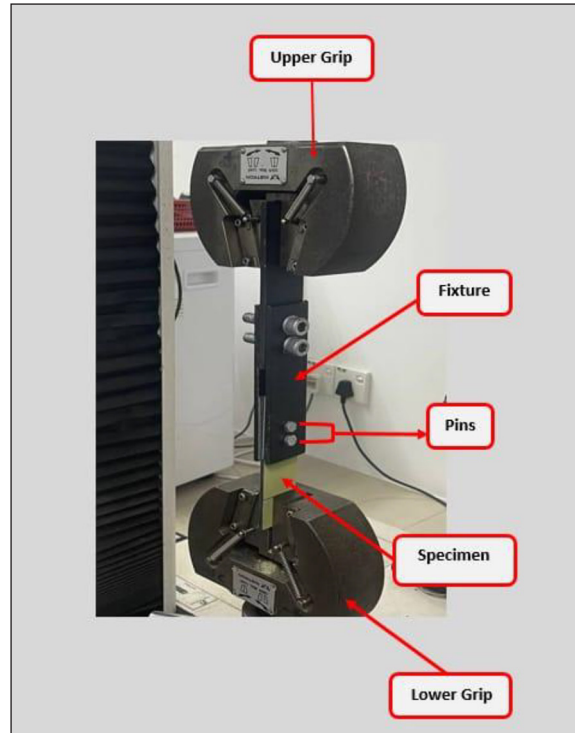


Figure 5. Clamping of the CFRP specimen on universal testing machine (UTM)

RESULTS AND DISCUSSION

In this part of the research, the results obtained from the experimental tests were discussed in two sections.

Hole measurement

The hole measurement data revealed a clear distinction in dimensional accuracy between the two tool types. The average hole diameter produced by the HSS tool was measured at (6.430 mm), see Figure 6a, while the holes

created by the 4-flute solid carbide tool measured (6.384 mm) on average, see Figure 6b. The range of diameter measurements for both drill bit types is shown in Table 3. This difference, though seemingly minor, represents a significant deviation in the context of composite structural applications. The holes made with HSS were regularly wider than the nominal diameter (6.35 mm) because of

more vibration, higher tool force, and heat. As a result of oversized holes, the fit between the bolt and laminate is affected, and there may be more local stress concentrations and weak spots around the drilled area. These holes that are larger than needed might reduce the reliability of the joints and cause early failure under repeated stress.

Alternatively, the carbide-drilled holes were only slightly larger than nearly matched the nominal or were exactly as designed, and this is good for fit and joint stability. The dimensional tolerance was improved by the rigidity and sharpness of the 4-flute carbide tool, and how stable the cutting edge remained during the drilling process. Equal to what was found by testing, the analysis of hole size and shape proves that high-quality holes correlate with stronger and more dependable support. Having precise holes leads to more supportive structures and greater reliability of performance.

Bearing strength

The experimental stress-strain curves provide valuable insights into the bearing behavior of the CFRP specimens with dual serial holes under tensile loading. These curves reflect both elastic and plastic deformation regions and demonstrate the

mechanical performance resulting from different drilling methods with ASTM D 5963.

The specimens which were drilled with the HSS drill bit in Figure 7 presented a dominant net-tension/cleavage failure mode. Observable tilted cracks emanated out of the lower hole towards the specimen edge, which revealed the presence of tensile and shear stress. The coarse and broken parts of the surroundings of the holes indicate that there was much damage caused by drilling like fiber breakage and delamination, leading to stress concentration and premature failure. This is an indication of poor quality of the holes and low bearing strength as opposed to holes drilled with the carbide tool. The choice of a drill bit is a very important parameter, which directly affects the failure of CFRP laminates. The differences in the material and geometry of the drill bit influence the magnitude of cutting forces and the level of machining caused damage around the hole [19]. The damage, such as delamination, matrix cracking, fiber pull-out, and bore-surface irregularities, can decisively affect the mode of predominant failure.

Figure 8 displays the stress-strain responses of the specimens drilled using the 4-flute solid carbide tool. Among these, the lowest bearing strength was observed in one of the specimens

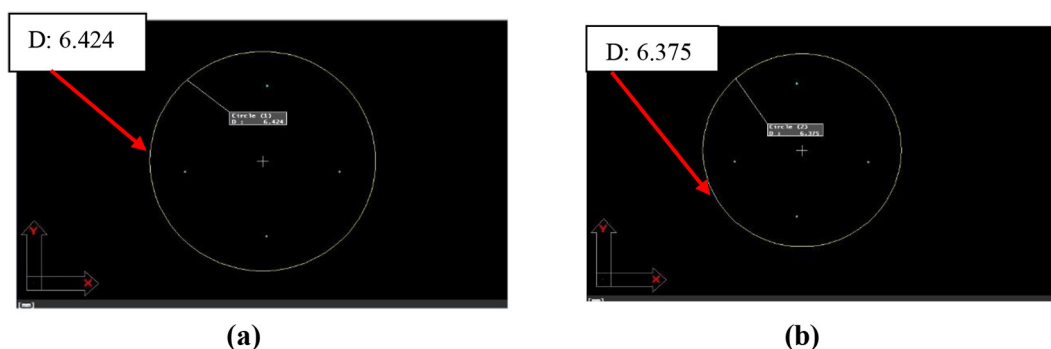


Figure 6. Hole diameter measurement: (a) for HSS, (b) for 4-flute solid carbide

Table 3. Measured diameter range for both HSS & 4-flute solid carbide

Drill bit type	Measured diameter range (mm)	Mean diameter(mm)	Average diameter (mm)
C-1	6.349–6.366	6.357	6.384
C-2	6.378–6.404	6.391	
C-3	6.390–6.417	6.403	
T-1	6.406–6.436	6.421	6.430
T-2	6.425–6.456	6.440	
T-3	6.415–6.443	6.429	

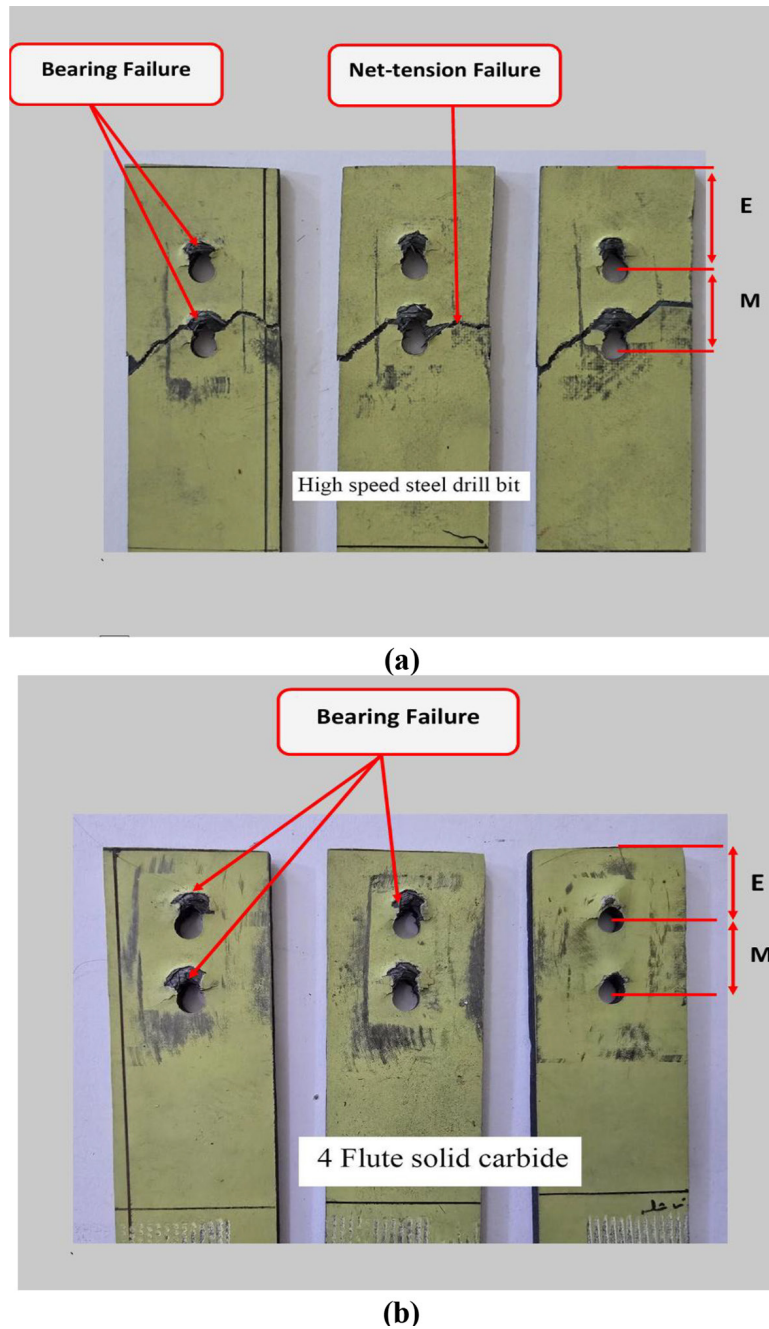


Figure 7. Post-failure appearance of CFRP: (a) for HSS, (b) for 4-flute solid carbide

with a value of 874 MPa. This lower strength was associated with fiber damage near 0° orientations, where the bonding between epoxy and fiber was weakened. In contrast, other specimens with the same drill bit achieved higher bearing strength values, reaching up to 1256 MPa. These specimens benefited from better fiber orientation and improved surface quality at the hole edges. Figure 9 represents the results from the specimens drilled using the HSS tool. Notably, increased delamination and fiber breakage were evident, leading to lower overall mechanical

performance. Although one specimen reached a relatively high bearing strength of 1092 MPa, the average value remained lower compared to those of the carbide group. The experimental results confirm that the strain values were generally less affected than stress values. The fiber-matrix separation due to poor drilling quality had a more pronounced impact on strength than on elongation. These findings underline the critical influence of drill type and hole integrity on the bearing performance of CFRP components under load. To provide a clear visual comparison,

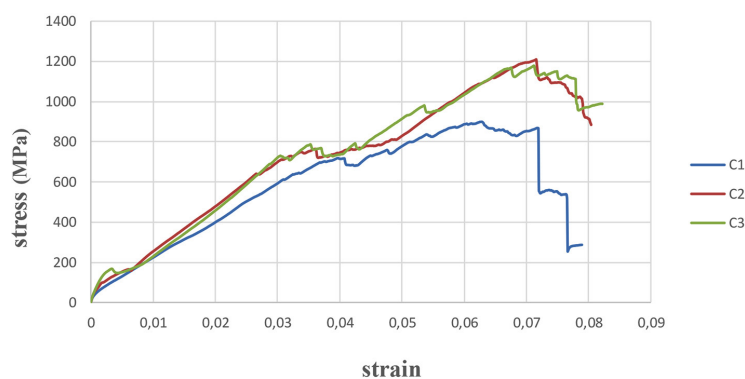


Figure 8. Stress-strain curve for specimens C-1, C-2, and C-3

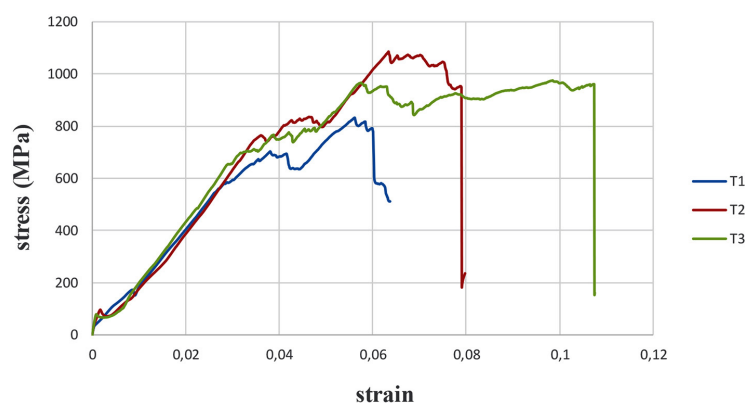


Figure 9. Stress-strain curve for specimens T-1, T-2, and T-3

the following Figure 10 combines the stress-strain curves of all three carbide-drilled specimens (C-1, C-2, and C-3) side-by-side with (T-1, T-2, and T-3).

The analysis of stress-strain curves of the CFRP specimens drilled using HSS and 4-flute solid carbide bits with varying inter-hole distances, M (2D, 3D, and 4D, where D is the diameter of the hole) was conducted experimentally and showed a great effect of the two parameters on the hole integrity. The specimens having larger distance between holes between (especially the ones with 4D, such as C-3 and T-3) always had higher values of maximum stress and higher ultimate strain to failure. This is explained by the decreased interaction and the decrease in the concentration of stress between the holes that are adjacent, and more energy is absorbed, and the catastrophic failure mechanisms, as shown in Figure 11a, including shear-out and net-tension rupture, are delayed. The comparison of the types of drill bits showed that the specimens that were prepared using carbide bits (C-series) had a sharper rise to peak stress and a steeper post-peak drop, which are characteristics of a brittle

bearing failure once their maximum load had been reached as indicated in Figure 11b. Such behavior is generally attributed to a better quality of holes, such as less surface roughness and less delamination as found by (Yaşar et al., 2017) [20], which is the result of better cutting properties of carbide tools. For example, C-3 clearly displayed the highest peak value of 1256 MPa owing to the fiber alignment and clean finish provided by carbide-drilling.

Conversely, the specimens drilled HSS (T-series) exhibited a slower post-peak decrease and in a few cases, retained higher ductility through extended deformation to ultimate disintegration. The reason for this behavior can be the local delamination or fiber pull-out, slightly increased hole damage, allowing much more redistribution of load and local plasticity as discovered by [4]. Consequently, even if some samples, such as T-2, reached high values of 1092 MPa, their stress curves fell fairly early, suggesting damage at the fiber level and failure spreading as indicated by [21].

In the case of the specimens where the hole spacing, M at 2D, there was a significantly lower

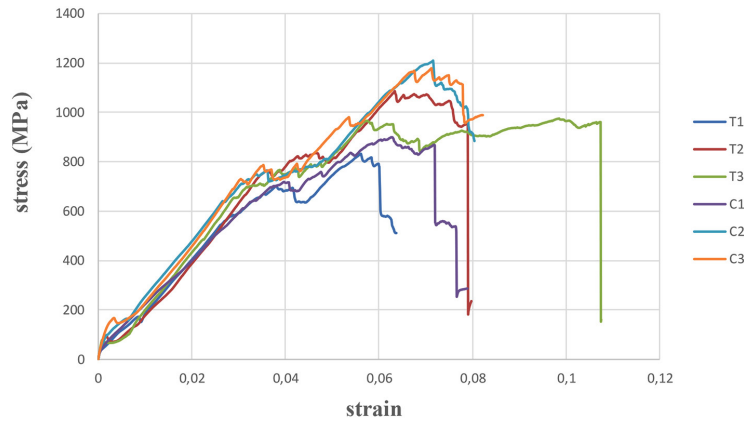


Figure 10. Comparison of stress-strain behavior between the carbide- and HSS-drilled CFRP

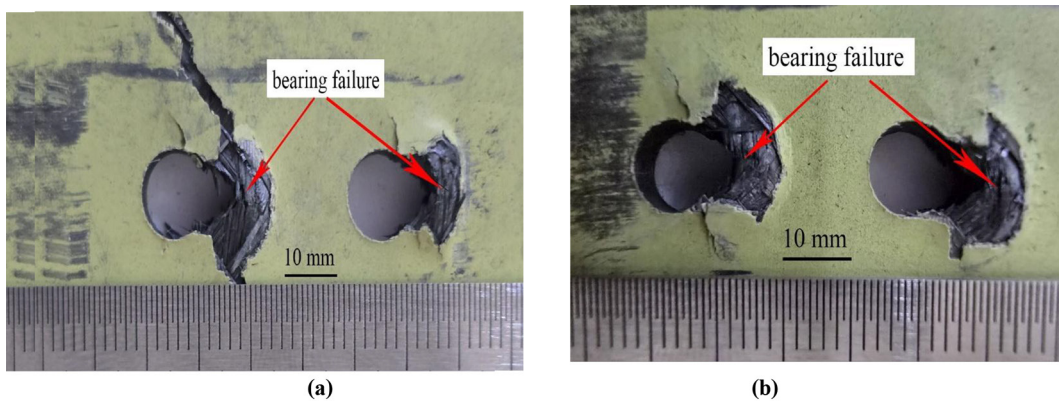


Figure 11. Bearing failure in CFRP: (a) for HSS, (b) for 4-flute solid carbide

maximum stress and early failure with both types of tools, proving the negative influence of closer hole spacing on the residual strength. This is caused by the overlapping stress field and enhanced shear-out propensity as indicated by [22]. Nevertheless, the carbide-drilled samples had higher stress capacity than their HSS counterparts in all the configurations considered, which supports the importance of high-quality hole edges in composite bearing.

It was found that the strain behavior of all specimens was similar to that of composites, yet the strain stability was higher among carbide-drilled samples. Therefore, the damage and deformation were more controlled by the use of carbide and not by unexpected faults or separations within the composite. These findings emphasize that tool choice makes a difference in obtaining both precision and strong CFRP joints. Precise joints and fitments are usual in the aerospace and automotive industries, and these distinctions may determine if their assembly remains safe or fails early.

Microstructural damage analysis

The image of the SEM before the testing of the bearing in Figure 12 reveals that the CFRP laminate was in good structural conditions, the fibers were oriented correctly and firmly fixed in the epoxy. There were low levels of surface damage and few matrix micro-cracks around the hole edge, and this indicates that the drilling process provided an acceptable hole quality that did not result in severe initial defects. Conversely, the SEM image obtained following the bearing strength test, as shown in Figure 12, indicates a large amount of damage around the region of drilled holes. There is evident pronounced matrix cracking, fiber-matrix debonding, as well as fiber breakage, especially along the direction of loading. It was also observed that there was localized delamination and fiber pull-out, which pointed to progressive bearing failure and not catastrophic fracture. The stress concentration in the area of the ligament was enhanced by the interaction of the dual-hole configuration,

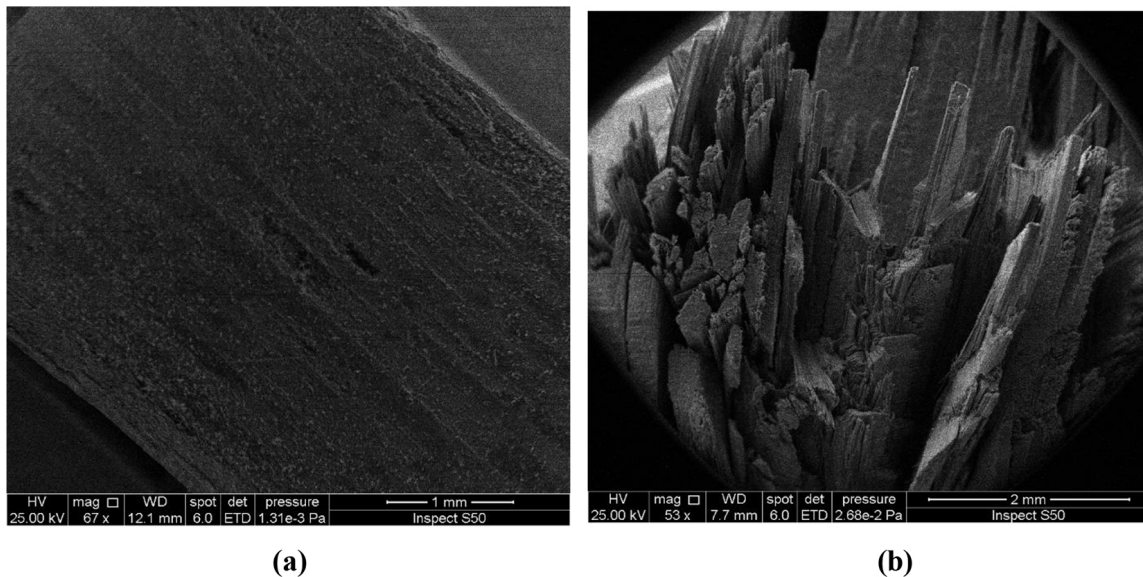


Figure 12. SEM images of the CFRP laminate (a) before bearing test (b) after bearing test

which promoted the rate of the spread of damage and lowered the load-carrying capacity of the laminate. These microstructure observations give strong clues on the mechanisms that govern the bearing strength degradation of the CFRP laminates with two-hole arrangements, and are well aligned with the bearing test result of the experiment. SEM images were conducted in Al-Nahrain University in Baghdad Inspect S50.

CONCLUSIONS

This research reveals that the hole geometries and configuration can significantly impact the mechanical behavior of the CFRP laminates containing dual holes. Carbide drill with a 4-flute reamer yielded samples with the highest bearing capacity (up to 1256 MPa) and improved load-carrying capacity. The holes were consistently average sized at 6.384 mm, ensuring precision and stability in structure. However, drilling with HSS resulted in a wider range of bearing strength, lower maximum stress and an average hole diameter of 6.430 mm. As a result, there was a significant decrease in overall mechanical integrity in terms of bearing strength of the composites. The future work should focus on investigating different hole configurations and different hole sizes. It is also important to study the effect of the distance of the holes from the edge of the specimen to study the effect of stresses and the failure mechanism.

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REFERENCES

1. Parveez B., Kittur M.I., Badruddin I.A., Kamangar S., Hussien M., Umarfarooq M.A. Scientific advancements in composite materials for aircraft applications: A review. *Polymers (Basel)*. 2022; 14(22): 5007. <https://doi.org/10.3390/polym14225007>
2. Khan F., et al. Advances of composite materials in automobile applications – A review. *Journal of Engineering Research*. 2024. <https://doi.org/10.1016/j.jer.2024.02.017>
3. Galinska A., Cezary G. Mechanical joining of fibre reinforced polymer. 2020.
4. Xu J., Geier N., Shen J., Krishnaraj V., Samsudeen-sadham S. A review on CFRP drilling: Fundamental mechanisms, damage issues, and approaches toward high-quality drilling. *Journal of Materials Research and Technology*. 2023; 24: 9677–9707. <https://doi.org/10.1016/j.jmrt.2023.05.023>
5. Thakur R.K., Singh K.K. Evaluation of hole quality to explore the influence of graphene nanoplatelets embedded in epoxy/carbon composite during abrasive water jet drilling. *Journal of Manufacturing Processes*. 2023; 85: 569–583. <https://doi.org/10.1016/j.jmapro.2022.11.054>
6. Aamir M., Tolouei-Rad M., Giasin K., Nosrati A. Recent advances in drilling of carbon fiber-reinforced polymers for aerospace applications: A

- review. *International Journal of Advanced Manufacturing Technology*. 2019. <https://doi.org/10.1007/s00170-019-04348-z>
7. Sur G., Erkan Ö. Surface quality optimization of CFRP plates drilled with standard and step drill bits using Taguchi, TOPSIS and AHP method. *Engineering Computations*. 2020; 38(5): 2163–2187. <https://doi.org/10.1108/EC-04-2020-0202>
 8. Caggiano A., Improta I., Nele L. Characterization of a new dry drill-milling process of carbon fibre reinforced polymer laminates. *Materials (Basel)*. 2018; 11(8): 1470. <https://doi.org/10.3390/ma11081470>
 9. Sayman O., Siyahkoc R., Sen F., Ozcan R. Experimental determination of bearing strength in fiber reinforced laminated composite bolted joints under pre-load. *Journal of Reinforced Plastics and Composites*. 2007. <https://doi.org/10.1177/0731684407079379>
 10. Öndürücü A., Esendemir Ü., Tunay R.F. Progressive failure analysis of glass-epoxy laminated composite pinned-joints. *Materials & Design*. 2012. <https://doi.org/10.1016/j.matdes.2011.11.031>
 11. Almeida J.H.S., Bittrich L., Spickenheuer A. Improving the open-hole tension characteristics with variable-axial composite laminates: Optimization, progressive damage modeling and experimental observations. *Composites Science and Technology*. 2020; 185: 107889. <https://doi.org/10.1016/j.compscitech.2019.107889>
 12. Ze G.K., Pramanik A., Basak A.K., Prakash C., Shankar S., Radhika N. Challenges associated with drilling of carbon fiber reinforced polymer (CFRP) composites: A review. *Journal of Composites Science*. 2023. <https://doi.org/10.1016/j.jcomsc.2023.100356>
 13. Özaslan E., Güler M.A., Yetgin A., Acar B. Stress analysis and strength prediction of composite laminates with two interacting holes. *Composite Structures*. 2019; 221: 110869. <https://doi.org/10.1016/j.compstruct.2019.04.041>
 14. Chowdary P., Kumar R.A., Jhanji K., Kumar R.N. Strength and failure analysis of different composite laminates with multiple holes in series. *International Journal of Scientific Engineering and Technology*. 2015; 10(91): 89–92.
 15. Okayasu M., Naito R., Fukuyama D. Effects of machined circular holes on the mechanical properties of unidirectional carbon fiber-reinforced plastics. *Journal of Composite Materials*. 2017: 1–10. <https://doi.org/10.1177/0021998317709331>
 16. Kamaruzaman M.F.S., Hassan M.H., Razali M.F. Hole quality assessment of drilled carbon fiber reinforced polymer (CFRP) panel using various custom twist drill geometries. *Pertanika Journal of Science & Technology*. 2022; 30(4): 2603–2612. <https://doi.org/10.47836/pjst.30.4.17>
 17. Ou Y., Zhu D., Zhang H., Yao Y., Mobasher B., Huang L. Mechanical properties and failure characteristics of CFRP under intermediate strain rates and varying temperatures. *Composites Part B: Engineering*. 2016; 95: 123–136. <https://doi.org/10.1016/j.compositesb.2016.03.085>
 18. Abdullah M.S., Abdullah A.B., Samad Z. Hole integrity of carbon fibre reinforced epoxy composites using combined punching and drilling techniques. *International Journal of Advanced Manufacturing Technology*. 2020; 110: 2517–2527. <https://doi.org/10.1007/s00170-020-06030-1>
 19. Cantero J.L., Miguélez M.H. Tool wear and induced damage in CFRP drilling with step and double point angle drill bits. *Procedia Manufacturing*. 2020. <https://doi.org/10.1016/j.promfg.2019.09.049>
 20. Yaşar N., Korkmaz M.E., Günay M. Investigation on hole quality of cutting conditions in drilling of CFRP composite. *MATEC Web of Conferences*. 2017; 112: 01013. <https://doi.org/10.1051/mateconf/201711201013>
 21. Karakuzu R., Taylak N., İçten B.M., Aktaş M. Effects of geometric parameters on failure behavior in laminated composite plates with two parallel pin-loaded holes. *Composite Structures*. 2008; 85(1): 1–9. <https://doi.org/10.1016/j.compstruct.2007.10.003>
 22. Li S., Li Y., Wang P., Han F., Ma Z. On experimental and numerical damage evolution of multi open-holes composite laminates with local to global method. *Composite Structures*. 2025; 371: 119397. <https://doi.org/10.1016/j.compstruct.2025.119397>