Experimental Study on the Effect of Two Equal-Sized Holes Lying at Different Angles in a CFRP Plate under Bending

Phacharaporn Bunyawanichakul1*, Paiboon Limpitipanich2, and Pongwit Siribodhi1

1Design Clinic Research Unit, Department of Aerospace Engineering, Faculty of Engineering, Kasetsart University, 50 Ngam Wong Wan Rd., Ladyaow, Chatuchak, Bangkok, 10900, Thailand.
2Department of Mechanical Engineering, Faculty of Engineering, Burapha University, 169 Longhard-bangsaen Rd., Saensook, Muang, Chonburi, 20131, Thailand.

*Corresponding author e-mail: phacharaporn.b@ku.ac.th

Abstract. A bending test method was designed to investigate the failure characteristics of drilling carbon-fiber reinforced composite (CFRP) plates. The CFRP plates were fabricated and drilled to join other parts for use in aircraft structures (riveting or bolting). Each sample had two equal-sized holes at 0, 0, or -0 degrees at a fixed distance of 36 mm in the longitudinal direction. The sample dimensions were identified following a study on tensile testing single-holed samples based on the ASTM D5961 standard. The tensile test focused on three cases of laminate: [0]14, [22.5]14, and [45]14. The maximum mean forces for [0]14, [22.5]14, and [45]14 laminate configurations were 6.32, 6.59, and 7.12 kN respectively. These results were implemented into a bending test which included two configurations of laminate: [0]14 and [45]14 and two equal-sized holes with a variable distance of 0 and 9 mm in the transverse direction of the plate. The bending test configuration is presented in this paper. The results revealed different load-bearing capabilities in each of the three types of specimen configuration. Samples with two holes lying at ±0 degree affected the overall strength in the [45]14 case, and as in [0]14 there was no difference between the eccentricity and the aligned holes. In [45]14, the eccentricity decreased the maximum allowable force by 15.7 percent in the normal eccentricity case and by 15.94 percent in the alternate eccentricity case compared to the aligned case.

Keywords: Carbon-fiber reinforced composites (CFRP), Composites, Two holes, Bending, Joining.

1. Introduction

For decades, composite materials have been widely used not only in the aircraft industry but also in various applications such as automobiles, boats, construction, and in some structural parts of machine components [5-6]. Composites continue to replace conventional materials like steel and aluminum yearly. Engineers have more design flexibility and can steadily improve some strength of their functional parts by using fiber-reinforced composites like fiberglass and carbon fiber. The strength-to-weight ratio is the greatest advantage of composite material usage. It is the key factor for its use in aircraft components because of the weight reduction.

However, the composite also has some disadvantages. First, composites are designed to have superior mechanical properties to those of the constituent material action independently. The properties are unique to each purpose with a specific design for the orientation and manufacturing processes, which provides big challenges to consistently form the structural components. Second, continuous fibers are required for applications at a high performance level. Complex structural sub-assemblies formed by continuous fiber composites must be either attached or assembled with other structural components. There are numerous bonding methods: adhesive, bolts, rivets, welding, etc. From an engineering point of view, adequate bonding strength is needed.
usually provided by mechanical fastenings using bolts or rivets. This requires the formation of bolt holes in the drilling process which can cause discontinuity in composite structures [1]. In addition, drill holes have influence stress concentration that locally affects failure initiation, failure mechanisms, failure propagation and the overall behavior of the structural components. This effect can reduce the load carrying capacity of the joint.

The connection concept of this study was used to construct a wing spar for an aerobatic airplane designed in Thailand as a kit plane. The plane manufacturer wanted to build an aircraft where the customer can be involved in the assembly process in creating their own flying machine. Focusing on the wing spar connection, a single hole is not appropriate for a design in terms of strength and reliability. Multiple holes are the only choice for the connection. From the manufacturer point of view, using two holes facilitates the assembly of the airplane. A series of investigative activities in this study was set up [2-4]. However, the research still needs the further experimental results to improve understanding under bending as it is the major load from wing through the connection.

Taking the main loading issues related to the joining pattern, an experimental program was designed to investigate the effects of three different patterns having two equal-sized holes lying at 0, \( \theta \), or -\( \theta \) degrees in a composite plate under bending (Fig.1). The patterns were assigned to be the framework as this is a type of joint that has been intended for use in the construction of the wing spar.

![Fig. 1: Hole pattern in two-holed samples](image)

2. Materials and methodology

The selection of materials was defined by the plane manufacturer. The wing spar components were made with carbon-fiber reinforced composites (CFRP). The materials used included a twill 2 x 2 Carbon fiber from Toray carbon fibers America, Inc and an Epotec YD535LV/TH7257 epoxy resin with low viscosity from Aditya Birla Chemicals Thailand Co., Ltd was used as the binding polymer matrix.

The chosen methods are in this section. At the beginning of the analysis, it is important to realize that the bending strength of two holes has several factors that must be taken into account, including the laminate stacking sequence, laminate thickness, sample size, hole size, hole location, and failure mechanism as well as damage from the fabrication process. It is noted that the failure mechanism is controllable by the laminate stacking sequence and the bearing strength can be more easily identified using a single hole [3]. Therefore, this study used the ASTM D5961 standard test methods to initially define work on the issues of laminate thickness, sample size, hole size, and the failure mechanism. After the bearing strength of a single hole is exhibited, the failure of a two-holed specimen under bending testing can be realized corresponding to the same specimen configurations. Consequently, the experimental procedure covers the following: choosing sample sizes, sample holes, type of testing, hole location, and design jigs and fixtures.

2.1. Description of tested materials

The CFRP plates (250 mm x 430 mm) were fabricated using the resin infusion technique at the laboratory scale. The epoxy has a 3 to 4 hour work life that guarantees fast and complete impregnation of reinforcing fibers and allows laminates to be produced by resin infusion. During the manufacturing processes, the molding was cured at room temperature for 24 hours before it was post cured in an oven at 80°C for 4 hours. Table 1 describes the samples used in this study. For single-holed specimens, the laminate layup configurations were [0]\(_{14}\), [22.5]\(_{14}\), and [45]\(_{14}\). For two-holed specimens, only two different lay-ups of [0]\(_{14}\) and [45]\(_{14}\) were prepared.

After post curing, the CFRP composite plates were cut to rectangular shapes of 36 mm x 210 mm for the single hole tensile test and 45 mm x 210 mm for double-hole bending test using CNC machine. The 3 mm hole was drilled using a CNC machine at the desired position before drilling 5.8 mm and reaming 6.1 mm in diameter. The dimensions of the tensile and bending samples are shown in Fig. 2 to Fig. 4.
Table 1: Test sample description

| Test     | Ply stacking sequence | No. of holes | No. of specimens | Remarks |
|----------|-----------------------|--------------|------------------|---------|
| Tensile  | [0]₁₄                 | 1            | 5                | -       |
|          | [22.5]₁₄              | 1            | 5                | -       |
|          | [45]₁₄                | 1            | 5                | -       |
| Bending  | [0]₁₄                 | 2            | 6                | Hole 0  |
|          | [0]₁₄                 | 2            | 3                | Hole 0  |
|          | [0]₁₄                 | 2            | 3                | Hole -0 |
|          | [45]₁₄                | 2            | 6                | Hole 0  |
|          | [45]₁₄                | 2            | 3                | Hole 0  |

The averaged volume fraction of the sample was 0.52, which was calculated using Eq. (1):

\[ V_f = \frac{\rho_f m_f}{\rho_f (1-m_f) + \rho_r m_r} \]  

(1)

where \( \rho \) is the density, \( m \) is the mass, and the subscripts \( r \) and \( f \) are the properties of epoxy and carbon fiber, respectively.

Fig. 2: Dimension of tensile samples

Fig. 3: Dimension of bending samples with two holes lying at 0 degrees

Fig. 4: Dimension of bending samples two holes lying at \( \pm \theta \) degrees

2.2. Experimental setup

2.2.1. Tensile test configuration of single-holed specimens

In this study, a double shear fixture was designed to apply a load to determine the bearing response of the specimens. One end of the fixture was a plate without a hole while the other end was composed of two rigid plates with a hole. The two rigid plates were set with a spacer slightly thicker than the thickness of the tested
specimen. The end of the two plates was drilled with an equal size to one end of the specimens. During the test, a pin was inserted in the three holes by placing the specimen between the two rigid plates of the fixture. The installation of the fixture and a specimen is demonstrated in Fig. 5.

![Test setup for tensile test](image1)

**Fig. 5:** Test setup for tensile test

Using an Instron 8802 universal testing machine with a maximum load capacity of 250 kN, the bearing force was created by tension loading through the pin. A 6 mm diameter pin was used for the connection. It was installed in the three holes drilled slightly larger than its diameter. One end of the specimen was secured to the bottom vice-grip and the other end of the fixture was held by the upper vice-grip to pull the specimens with a moving speed of 0.5 mm/min. The tensile load was applied until failure was observed.

2.2.2. Bending test configuration of two equal-hole-sized specimens

For the double-holed samples, three-point bending tests were performed on a composite plate specimen using a long arm to generate the bending load through the holes of the sample. The sample was connected with the arm using two 6 mm pins. The distance between the two supporting locations was 1,000 mm. The beam was compressed at mid-span using an MTS/2S universal testing machine with a maximum load capacity of 10 kN. Fig. 6 demonstrates the test set up of three-point bending test for aligning double holes. The moving anvil had a speed of 0.5 mm/min until the sample was broken.

![Test setup for bending test](image2)

**Fig. 6:** Test setup for bending test

3. Experimental results and discussion

3.1. Single-holed tensile test

The tensile tests of 15 single-holed samples were carried out for three lay-ups using the fixture in section 2.2.1. The results of each ply stacking sequence and their averages are summarized in Table 2. The averages of maximum force or mean force for the [0]_14, [22.5]_14, and [45]_14 samples were 6.32, 6.59, and 7.12 kN, respectively. The obtained data showed that the [45]_14 samples had the highest mean force and the [0]_14 samples had the lowest mean force. The maximum difference between the [45]_14 and [0]_14 samples was 11.24%.
Table 2: Single-holed tensile test results

| Ply stacking sequence | Maximum force of five samples (kN) | Mean force (kN) |
|-----------------------|-----------------------------------|-----------------|
| [0]_14               | 6.41, 6.60, 6.25, 6.32, 6.02       | 6.32            |
| [22.5]_14            | 6.38, 6.59, 6.53, 6.82, 6.73       | 6.59            |
| [45]_14              | 7.33, 6.53, 6.97, 7.45, 7.31       | 7.12            |

The relationships between the load and displacement of the three types of laminate were observed during the test. Between the same ply stacking sequence specimens, the bearing response behavior showed almost the same rigidity and there was a similar magnitude of maximum forces. The bearing response of a specimen representing each lay-up is characterized in Fig. 7. It should be noted that the stiffness of each orientation exhibited an opposite trend to the average maximum force. The [0]_14 samples presented the highest stiffness with the lowest displacement, followed by the [22.5]_14 samples, and the [45]_14 samples had the lowest stiffness with the highest displacement. Observing the specimens after the test, it was found that failure would prematurely occur around the hole and propagate along the fiber direction.

![Fig. 7: Load-displacement curve of single-holed specimens](image)

3.2. Result for two equal-sized holes

3.2.1. [0]_14 cases with hole 0, +θ and -θ degree

The relationship of the mid-span force and deflection for the [0]_14 samples when the holes were drilled at an angle of 0 and ±θ degree are presented in Fig. 8 and Fig. 9, respectively. It can be seen in both graphs that the mid-span force linearly increased as the mid-span deflection rises until failure is observed. The maximum mean force for the [0]_14 laminate configuration was 2.79 kN, for the samples with 0 degree hole is 2.89 kN, and for the -θ degree hole was 2.62 kN. The eccentricity increased the maximum force by 3.51 percent in the +θ eccentricity case and by a 6.19 percent decrease in the -θ eccentricity case compared to the aligned case.
3.2.2. $[45]_{14}$ cases with hole 0, $\pm \theta$ and $-\theta$ degree

The relationship of the mid-span force and deflection for the $[45]_{14}$ samples when the holes were drilled at an angle of 0 and $\pm \theta$ degree are presented in Fig. 10 and Fig. 11, respectively. A nonlinear response was observed as the bearing responded to the tensile test. The maximum mean forces for 0, $+\theta$, and $-\theta$ degrees were 232, 273, and 226 kN, respectively. The eccentricity of the hole at $-\theta$ degree increased the maximum mean force by 17.45 percent, while the force was reduced by 2.78 percent in the $+\theta$ eccentricity case compared to the aligned case.

Fig. 8: Mid-span force and deflection relationship for $[0]_{14}$ sample with $0^\circ$ hole.

Fig. 9: Mid-span force and deflection relationship for $[0]_{14}$ sample with $\pm 0^\circ$ hole.

Fig. 10: Mid-span force and deflection relationship for $[45]_{14}$ sample with $0^\circ$ hole.
3.3. Effect of fiber orientation on the bending test

The tensile tests were carried out for [0]_14, [22.5]_14, and [45]_14 ply orientations. Fig. 12 presents the failure of the hole under the bearing force. The schematic of carbon-fiber orientation and bearing force are demonstrated. For the [0]_14 sample, the fiber was oriented in either the loading or transverse directions. Both longitudinal and transverse fibers resisted the bearing load, while the longitudinal one was compressed. For the [22.5]_14 sample, both the fibers lying along 22.5 and 67.5 degrees compared to the loading direction resisted the bearing load. Both 45 degree orientations of the fiber were advantageous in resisting the bearing force in the [45]_14 case. This was why the maximum bearing force was presented by the [45]_14 case and the minimum bearing force was exerted by the [0]_14 laminate configuration.

![Fig. 12: Failure direction of single-holed tensile test.](image)

Fig. 12: Failure direction of single-holed tensile test.

Fig. 13 demonstrates the schematic of forces from applying the bending moment to the two holes of the sample in the three-point bending test. It can be seen that there are two reaction forces (R_L and R_R) acting on the overall configuration as shown in Fig. 13(a). Schematics of the forces on the sample are shown in Fig. 13(b) when the load F and moment M are replaced with an equivalent force-couple system at the centroid of the two holes by considering the whole system as a rigid body. It can be found that the applied force on the outer hole, M/d - F/2 must be lower than the applied force on the inner hole, M/d + F/2. Therefore, the inner hole should initially fail due to bearing force before that occurs at the outer one. It should be noted that the mass of the samples is diminished in the schematic because it is too small when compared to the mass of the long arm.
The bending tests were carried out for $[0]_{14}$ and $[45]_{14}$ ply orientations. Three different patterns were tested having two equal-sized holes lying at $0^\circ$, $\theta^\circ$, or $-\theta^\circ$ degrees in a composite plate as shown in Fig.1. It was found that the failure occurred in the samples as the inner hole rotated about the outer hole in every case. Fig.14 presents the orientation of the force along the inner hole for the three degree cases by applying equilibrium analyses on the resulting free-bodies to determine the internal shear forces and bending couples. It can be seen that the bearing load was exerted on the inner hole with angles of $90^\circ$, $127^\circ$, and $127^\circ$ for the samples having the two holes lying at $0^\circ$, $\theta^\circ$, and $-\theta^\circ$, respectively. The inner hole must carry both the force and moment from the shear force and bending moment developed within the beam. The $-\theta^\circ$ degree samples had the lowest strength under bending in the tests. With the limitation on edge distance, there is a higher failure potential for the $-0^\circ$ degree samples than the other proposed patterns of the hole.

4. Conclusions
The present study investigated the bearing strength of single-holed specimens in accordance with the ASTM D5961 standard test. From the laboratory testing, it was possible to conclude that crack formation is likely due to the orientation of the fiber. For the $[0]_{14}$ samples, where the load was applied along the fiber direction, the failures occurred at the contact area and then propagated in the load direction because of the load carried by the fibers. For the $[22.5]_{14}$ and $[45]_{14}$ samples, the direction of the fibers was inclined to the load direction. The failure presented at the resin supporting the bearing load at the contact area which then propagated along the fiber direction which was inclined to the applying load. The test results indicated that the $[0]_{14}$ sample had the
highest maximum bearing force with the lowest displacement. This implied that CFRP is brittle in nature and thus prone to cracking along the fiber direction.

The above-mentioned investigations provide a general guideline for joints where a single hole is applied to the structure. The concept of the failure of the single-holed samples under tension is considered in the same manner as the two-holed sample under bending. A comparison of the failure initiation for the three different hole patterns with two lay-ups was observed. The force-deflection curve showed non-linear behavior for the [45]_{14} samples. The samples with two holes lying at -0 degrees had slightly more resistance under bending than the other hole patterns. The results revealed that failure corresponded to the orientation of the fiber.

Acknowledgement
This research was financially supported in part by the Kasetsart University Research and Development Institute (KURDI), Bangkok, Thailand (document number 20420186110223000). The authors would like to express their sincere gratitude to KURDI and to everyone who made a contribution to this study.

References
[1] Durao L, Tavares J, De Albuquerque V, Marques J & Andreade O. Drilling Damage in Composite Material. Materials (ISSN 1996-1944), Vol.7, No.5, 2014; pp.3802-3819. available online: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5453231/, last visit:08.02.2019.
[2] Krajangsawasdi N, & Bunyawanichakul P. Analysis on optimal location of double-bolted joint with parallel misalignment Subjected to eccentric load. Proceedings of 55th Kasetsart University Annual Conference: Science and Genetic Engineering, Architecture and Engineering, Agro-Industry, Natural Resources and Environment 2017; pp:432-442. ISBN: 978-616-278-368-5.
[3] Krajangsawasdi N, & Bunyawanichakul P. Experimental study on angle orientation to the failure of GFRP composite. The 2nd Southeast Asia Workshop on Aerospace Engineering SAWAE 2017.
[4] Krajangsawasdi N, & Bunyawanichakul P. Strength of composite plate with parallel offset misalignment double-bolted joint under bending moment. MATEC Web Conference issued on the 2nd International Conference on Composite Material, Polymer Science and Engineering CMPSE2018; Vol.264, No.01002. doi:10.1051/matecconf/201926401002.
[5] Nedelcu R, & Redon P. Composites materials for aviation industry. The 14th International Conference Scientific Research and Education in the Air Force-AFASES 2012; 917–922.
[6] Tsai S. Theory of composites design 3rd edition. 2008; pp_A1-7.