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Study on Mechanical Bearing Strength and Failure Modes of Composite Materials for Marine Structures

Dong-Uk Kim 1, Hyoung-Seock Seo 1,*, and Ho-Yun Jang 2

1 School of Naval Architecture & Ocean Engineering, University of Ulsan, Ulsan 44610, Korea; orrist@ulsan.ac.kr
2 Green Ship Research Division, Research Institute of Medium & Small Shipbuilding, Busan 46757, Korea; hyjang@rims.re.kr
* Correspondence: seohs@ulsan.ac.kr

Abstract: With the gradual application of composite materials to ships and offshore structures, the structural strength of composites that can replace steel should be explored. In this study, the mechanical bearing strength and failure modes of a composite-to-metal joining structure connected by mechanically fastened joints were experimentally analyzed. The effects of the fiber tensile strength and stress concentration on the static bearing strength and failure modes of the composite structures were investigated. For the experiment, quasi-isotropic \([45^\circ/0^\circ/-45^\circ/90^\circ]_2\) carbon fiber-reinforced plastic (CFRP) and glass fiber-reinforced plastic (GFRP) specimens were prepared with hole diameters of 5, 6, 8, and 10 mm. The experimental results showed that the average static bearing strength of the CFRP specimen was 30% or higher than that of the GFRP specimen. In terms of the failure mode of the mechanically fastened joint, a cleavage failure mode was observed in the GFRP specimen for hole diameters of 5 mm and 6 mm, whereas a net-tension failure mode was observed for hole diameters of 8 mm and 10 mm. Bearing failure occurred in the CFRP specimens.

Keywords: composite material; bearing strength; failure mode; \(W/D\) effect; stress concentration

1. Introduction

Recent global industrial and environmental changes have caused a paradigm shift in the application of parts and materials. For example, composite materials with advantages, such as low weight, high specific strength, good stiffness, and excellent corrosion resistance, are replacing metals in fields such as aviation, space science, defense, mobility, and sports. In shipbuilding and offshore fields, the use of composite materials as new candidates in the development of eco-friendly and smart ships is a major research topic. Although composite materials are being employed in special/small ships, conventional steel materials are still preferred in medium/large ships.

In recent years, because of the environmental regulations enacted by the International Maritime Organization (IMO), there is a need to reduce the weight of ships. This weight reduction can help improve the energy efficiency of the propulsion system, but requires the application of parts and materials with superior mechanical performance while being lighter than those used in existing ships. The application of composite materials is expected to facilitate the construction of large and commercial ships [1]. The International Convention for the Safety of Life at Sea (SOLAS) approved the use of lightweight composite materials for the first time; going forward, composite materials are expected to be actively used.

Because the current welding method used for metal materials cannot be applied to connect composites to metal structures, mechanical fastening is a good candidate [2]. However, when hole processing for mechanical fastening is performed on a composite material, discontinuous parts are formed, which reduces the structure intensity. These parts also act as notches, causing a decrease in the structural strength [3].
In a mechanically fastened joint of a composite material, stress concentration, large strain, and delamination failure occur because of the contact between the fastener and the material [4]. Godwin and Matthews studied the factors that determine the mechanical bearing strength of composite materials and summarized the factors affecting the bearing strength as follows:

- Material parameters: Fiber type and form (unidirectional, woven fabric, etc.), resin type, fiber orientation, laminate stacking sequence, fiber volume fraction, and fiber surface treatment.
- Fastener parameters: Fastener type (screw, bolt, rivet, etc.), fastener size, clamping force, washer size, hole size, and tolerance.
- Design parameters: Joint type (single lap, single cover butt, etc.), laminate thickness and tolerance, geometry (pitch, edge distance, hole pattern, etc.), load direction, loading rate, static or dynamic load, and failure criteria [5].

Ozaslan et al., experimentally and numerically analyzed the stress concentration and predicted the strength of a quasi-isotropic carbon/epoxy composite open-hole specimen based on the width-to-diameter ($W/D$) ratio. The stress concentration factor was found to be 3 when the $W/D$ ratio was 6. When the $W/D$ ratio was decreased from 6 to 3, the stress concentration factor increased by 15%. When the $W/D$ ratio was increased by four times, the tensile strength of the specimen increased by 62% [6]. Caprino et al., investigated the $W/D$ effect on mechanically fastened joints of fiberglass/aluminum composite specimens. The $W/D$ ratio at which net-tension failure transitions to bearing failure was found to be 2, and the mechanical bearing strength was proportional to the $W/D$ and $e/D$ (edge distance-to-diameter) ratios [7]. Sen et al., studied the effects of stacking sequence, bolt torque, $W/D$, and $e/D$ on the mechanical bearing strength of glass fiber-reinforced plastic (GFRP) specimens. When $e/D$ was 2 or greater, the failure mode of the specimen was found to be a mixed mode or a bearing mode [8]. Yoon et al., examined the mechanical bearing strength of carbon/epoxy composite specimens by conducting an energy-based progressive failure analysis (PFA). Open-hole tensile/compression tests, double-lap bolted joint tests, and single-lap bolted joint tests were performed and analyzed through a finite element analysis. Transverse damage was the major form of damage on the fracture surface due to fiber buckling and breaking around the hole. In addition, the bearing strength increased with the increasing $e/D$ ratio, and the failure mode of the joint changed from shear-out failure to bearing failure [9]. Calabrese et al., conducted a static bearing strength test on GFRP and metallic mechanical fixtures and suggested a 3D failure mode map based on the geometric shape [10]. Cooper et al., performed a tensile test on mechanically fastened joints of GFRP, along with metallic materials and investigated the bearing strength and failure mode based on the $e/D$ and $W/D$ ratios. When $e/D$ was <3, a shear-out failure appeared, and when $e/D$ was >3, a bearing failure was observed. Net-tension and bearing failures were observed when the $W/D$ ratios were <4 and >4, respectively [11]. Pakdil studied the ply-orientation, geometry, and effect of lateral pressure due to the bolt torque on glass fiber-reinforced epoxy laminated composites. The results showed that when a 45° lamination was included, the bearing strength was optimal [12]. Xiao et al., investigated the effects of bolt pressure and matrix on the mechanical bearing strength of carbon fiber-reinforced plastic (CFRP) specimens. Bearing failure developed due to damage accumulation, and the pressure of the bolt affected the shear crack propagation from the face lamina to the core lamina [13]. Kretsis and Matthews studied the effects of lateral pressure, thickness, width, edge distance, and lay-up on the bearing strength/failure modes of GFRP and CFRP specimens manufactured using different resin systems. The lay-up had the greatest effect on the failure mode, and the static clamping strength of the CFRP specimen was approximately 20% higher than that of the GFRP specimen [14].

Although many researchers have studied the bearing strength of composite-to-metal joining structures, information on the bearing strength is insufficient to consider the diversity of composite materials, stress concentration, and geometric parameters ($W/D$, $e/D$, and $t/D$). Therefore, in this study, the bearing strength and failure modes were analyzed...
by determining the effects of stress concentration and material properties based on the $W/D$ ratio through a bearing tensile test on the mechanically fastened joints of stainless steel fixtures between GFRP and CFRP specimens.

2. Theoretical Analysis

2.1. Failure Modes of a Mechanically Fastened Joint Composite

Figure 1 shows the failure modes of a mechanically fastened composite specimen specified in ASTM D5961. Each failure mode has the following characteristics:

- Net-tension failure: This occurs when the width excluding the hole diameter is insufficient or when the tensile strength of the fiber is insufficient.
- Shear-out failure: This occurs in a structure with a short free edge distance.
- Bearing failure: There is a high probability of bearing failure with a sufficient free edge distance or width, which occurs when a local pressure is applied to the bolt and contact portion of the structure.
- Cleavage failure: This type of failure can be characterized by shear-out and net-tension, resulting from the moment due to the bearing pressure applied by the fastener and the stress concentration at the tip and free edge of the hole.

![Figure 1. Failure modes of a mechanically fastened joint composite.](image)

In the case of composite materials, bearing failure can be easily detected, and such materials do not arrive at critical failure unexpectedly. In terms of repair, because the final failure may delay bearing failure, a composite material has good long-term stability against fractures. However, net-tension, shear-out, and cleavage failures can cause an abrupt failure of the composite material structure [15,16].

2.2. Relationship between Bearing Stress and Stress Concentration

Figure 2 shows the stress distribution under the bearing pressure on the composite material at the fastened part. There are two types of stress concentrations at the hole notch, where the bearing pressure is applied. First, the stress concentration around the notch hole occurs because of the bearing load applied by the fastener to the specimen. It acts in the load direction at the tip of the hole notch and decreases when the width ($W$) is constant and the hole diameter ($D$) increases. For a restricted width, the reduction in the hole diameter generates a high bearing stress with an increase in the stress concentration owing to the high bearing load acting on the local area.
According to Kwon et al., the tensile stress $\sigma_t$ applied to a nominal section can be determined from the stress concentration factor $K_{tc}$ corresponding to the maximum tensile strength of the joint and the geometry factor, as expressed in Equation (1). In Equation (2), $K_{tc}$ is typically induced by the stress concentration factor $K_{te}$ due to the bearing load and the correlation factor of $C$ in the $0^\circ$ fiber orientation. In Equation (3), $K_{te}$ is derived as the ratio of the width to the edge distance and the constant value $\Theta$ obtained by the ratio of the width to the edge distance in Equation (4). In this study, because $e/W > 1$, $K_{te}$ is simply expressed as the ratio of the width to the edge distance, as in Equation (3) [17].

$$\sigma_t = K_{tc} \frac{P}{(W - d) t}$$

$$K_{tc} = 1 + C (K_{te} - 1)$$

where $C$ is the correlation factor (related to the fiber content in $0^\circ$ fiber orientation).

$$K_{te} = \frac{W}{D} + \frac{D}{W} + 0.5 \left(1 - \frac{D}{W}\right) \Theta \approx \frac{W}{D} + \frac{D}{W}$$

$$\Theta = \left(\frac{W}{e} - 1\right) if \frac{e}{W} \leq 1, \quad \Theta = 0 if \frac{e}{W} \geq 1$$

2.3. Bearing Stress

Figure 3 shows the geometric factors related to the bearing stress. The bearing stress and strain of the mechanically fastened part of the composite material were calculated using Equations (5) and (6), as specified in ASTM D5961, respectively [18]. In Equation (5), the bearing stress $\sigma_{br}$ is defined as the ratio of the maximum recorded $P_{ult}$ to the hole diameter $D$ and the specimen thickness $t$.

$$\sigma_{br} = \frac{P_{ult}}{D t}$$

where $\sigma_{br}$ is the bearing stress (MPa), $P_{ult}$ is the ultimate load (N), $D$ is the hole diameter (mm), and $t$ is the specimen thickness (mm).
Figure 3. Front view of composite specimen.

The bearing strain is calculated by dividing the displacement of the specimen by the hole diameter, as expressed in Equation (6).

\[ \varepsilon_{br} = \frac{\delta}{KD} \]  

where \( \varepsilon_{br} \) is the bearing strain, \( \delta \) is the displacement (mm), \( K \) is the constant value 1: double shear test, 2: single shear test), and \( D \) is the hole diameter (mm).

However, if the bearing strain is calculated using Equation (6), it is difficult to calculate the bearing strain induced specifically by the \( W/D \) effect because the bearing strain value is affected by the increase in the hole diameter. Therefore, as shown in Figure 3, the distance (\( e \)) from the center of the hole to the free edge of the specimen was defined as the gauge length (\( L \)). The modified bearing strain was calculated using Equation (7), and the influence of the hole diameter on the bearing strain was excluded.

\[ \varepsilon_d = \frac{\delta_d}{L} \]  

where \( \varepsilon_d \) is the damage strain, \( L \) is the gauge length (mm), \( \delta_d \) is the failure distance of the specimen from the initial position of the bolt to the point where it is moved (mm).

3. Experiments
3.1. Specimen Preparation

The GFRP specimen was fabricated using Glass UD200 Prepreg (Owen Corning ®, Toledo, OH, USA), and the CFRP specimen was manufactured using Carbon UD200 Prepreg (SK Chemical ®, Seongnam City, Gyoenggi-do, South Korea). Specimens with a quasi-isotropic fiber orientation, \([45^\circ/0^\circ/-45^\circ/90^\circ]_{2S}\), were prepared using an autoclave process. As shown in Figure 4a,b, the total length, tab length, and width of the specimen were 120, 50, and 20 mm, respectively. The average thicknesses of the GFRP and CFRP specimens were 2.6 mm and 3.0 mm, respectively. As listed in Table 1, to consider the effect of the hole size, the specimen width was fixed at 20 mm, and the hole diameters were changed to 5, 6, 8, and 10 mm. In particular, for a hole diameter of 10 mm, the damage was artificially made around the hole of the specimen to investigate how the pre-damage affects the bearing strength.
Figure 4. Dimensions of composite specimens: (a) GFRP specimen; (b) CFRP specimen.

Table 1. Specifications of the tested specimens.

| D (mm) | W (mm) | e (mm) | W/D  | e/D  |
|-------|--------|--------|------|------|
| 5     | 20     | 30     | 4.0  | 6.0  |
| 6     | 20     | 30     | 3.3  | 5.0  |
| 8     | 20     | 30     | 2.5  | 3.8  |
| 10    | 20     | 30     | 2.0  | 3.0  |

D: Hole diameter; W: Width of specimen; e: Free edge distance.

Figure 5 shows the C-scan images to examine the inner damage in each specimen. The damage was monitored using FMS 10-Axis Dual Squirter Ultrasonic System equipment (MARIETTA NDT®, Marietta, GA, USA). For hole diameters of 5, 6, and 8 mm, there are no damages, such as void and delamination, as shown in Figure 5. However, when the hole diameter is 10 mm, an inner damage can be clearly detected in both the GFRP and CFRP specimens. The degree of inner damage in the CFRP specimen is more severe than that in the GFRP specimen.

3.2. Experimental Setup

As shown in Figure 6, static bearing tests were conducted using AG-50kNX (SHI-MADZHU, Kyoto, Japan) with a load cell capacity of 50 kN in accordance with ASTM D5961 [18]. The loading rate was set to 2 mm/min, and the fracture sensitivity was set to 70% of the maximum load.
Figure 6. Tensile test equipment.

Figure 7 shows the status of the GFRP and CFRP specimens fastened to the fixture. In the case of single-lap fastening, because of the effect of eccentric loading, an STS (stainless steel) double-lap fixture was applied to prevent this effect and to maintain a rigid fastening during the static bearing test. In addition, STS bolts were used to withstand high shear strength and maintain a sufficient bearing strength. A tightening torque of 15 N·m was applied to all the specimens to maintain solid tightening during the test. The lateral pressure due to the bolt torque increases the mechanical bearing strength, which may affect the failure mode. The tightening torque was measured thrice using a digital torque wrench and was applied equally to all the specimens.

Figure 7. Mechanically fastened specimen.

4. Results and Discussion

4.1. Bearing Strength Analysis

Figure 8 shows the bearing load–displacement curves of the GFRP and CFRP specimens with different $W/D$ values. As shown in Figure 8a,b, the bearing failure load is maximum for the largest hole diameter of 10 mm in both the GFRP and CFRP specimens. Typically, when the hole diameter decreases, the maximum bearing failure load decreases. As $W/D$ decreases, the maximum bearing failure load increases. This indicates that a large hole diameter can result in a high bearing failure resistance. In terms of the strength, the load applied to the unit area decreases with the increasing hole diameter. Therefore, the localized failure of the material is delayed, and the specimen fractures at the maximum bearing failure load. Figure 9 shows a comparison of the two groups of specimens in terms of the bearing strength. Irrespective of the diameter, the bearing strength of the CFRP
specimen is more than 30% greater than that of the GFRP specimen. Overall, the material properties of carbon fibers for tension, compression, and shear are better than those of glass fibers [19–21].

Figure 8. Bearing load vs. displacement curves: (a) GFRP specimen; (b) CFRP specimen.

Figure 9. Comparison between GFRP and CFRP specimens under bearing strengths: (a) $W/D = 4.0$; (b) $W/D = 3.3$; (c) $W/D = 2.5$; (d) $W/D = 2.0$.

In terms of the bearing stiffness, the CFRP specimen exhibited a higher stiffness than the GFRP specimen. In particular, after passing the friction-overcome region, the CFRP specimen curve exhibited a relatively steeper slope than the GFRP specimen curve for $W/D$ values of 4, 3.3, and 2.5, as shown in Figure 9a–c. On the other hand, when $W/D = 2.0$, as shown in Figure 9d, the stiffness curve of the CFRP is in good agreement with that of the GFRP specimen in the linear and nonlinear regions. This shows that the geometry, i.e., a specific large diameter, may have a greater effect on the stiffness slope under a bearing behavior than the type of material used.
Figure 10 shows the relationship between the engineering bearing stress and the engineering strain of the GFRP and CFRP specimens. The engineering bearing stress in the contact area between the bolt and the specimen was calculated using Equation (5). As the diameter increases, the contact area widens, thereby decreasing the bearing stress. In contrast, in terms of the strength, this means that the bearing strength increases as $W/D$ decreases, as shown in Figure 8.

Figure 11 shows a comparison between the GFRP and CFRP specimens in terms of their maximum bearing stress. As shown in Figure 11, there is a specific difference in the bearing stress in that it significantly decreases to more than 30% when $W/D \leq 2.5$. Therefore, the GFRP specimen seems to be affected more critically by the $W/D$ than the CFRP specimen. Through the coefficient of variation (COV) results shown in Figure 12, it is confirmed that the pre-damage effect for a 10 mm diameter can critically affect the mechanical bearing stress. The bearing test results for hole diameters of 5, 6, 8, and 10 mm are reasonable because the COV value is within 10%. However, in the case of a 10 mm hole diameter, the COV value of the GFRP specimen was 7.29% and that of the CFRP specimen was 5.23%. This means that the test results for a hole diameter of 10 mm were more scattered than those for the other hole diameters. From the C-scan image, although the inner damage in the CFRP specimen was significantly higher than that in the GFRP specimen, the latter showed a significant difference in the experimental results. Thus, the GFRP specimen may have a more critical pre-damage effect than the CFRP specimen. This type of pre-damage effect increases the uncertainty in the static bearing strength and structure integrity.

Figure 11. Comparison between GFRP and CFRP specimens in terms of their maximum bearing stress.
4.2. Failure Mode Analysis

As seen in Table 2, the diverse failure modes were investigated for the GFRP and CFRP specimens in the experiment. According to Caprino et al., and Turvey [22,23], the failure phenomena can be distinguished after the bearing load reaches its maximum value. As shown in Figure 13, in the case of the GFRP specimen, two different failures can be experimentally observed: cleavage and net-tension. For hole diameters of 5 mm and 6 mm ($W/D \geq 3.3$), cleavage failure was investigated and the net-tension failure was observed for hole diameters of 8 mm and 10 mm ($W/D \leq 2.5$). As seen in Figure 8a, in the case of cleavage failure, after the load reaches the maximum, the curve arrives at the final failure and temporarily maintains a constant value. In the case of net-tension failure, the load curve immediately decreases to fracture after reaching the maximum load. When checking the $W/D$ effect on the GFRP specimen, the range of $2.5 \leq W/D \leq 3.3$ is considered the failure mode conversion section. In particular, the back-split crack defined in this study was observed in all the specimens where cleavage failure occurred.

Table 2. Diverse failure modes of composite specimens.

| GFRP  | 5 mm ($W/D = 4.0$) | 6 mm ($W/D = 3.3$) | 8 mm ($W/D = 2.5$) | 10 mm ($W/D = 2.0$) |
|-------|--------------------|--------------------|--------------------|--------------------|
| #1    | B + C + BS         | B + C + BS         | B + N              | B + N              |
| #2    | B + C + BS         | B + C + BS         | B + N              | B + N              |
| #3    | -                  | B + C + BS         | B + N              | B + N              |

| CFRP  | 5 mm ($W/D = 4.0$) | 6 mm ($W/D = 3.3$) | 8 mm ($W/D = 2.5$) | 10 mm ($W/D = 2.0$) |
|-------|--------------------|--------------------|--------------------|--------------------|
| #1    | B + D              | B + D              | B                  | B + D              |
| #2    | B                  | B + D              | B + D              | B + D              |
| #3    | B + D              | B                  | B + D              | B + D              |

B: Bearing failure; C: Cleavage failure; BS: Back-split crack; N: Net-tension failure; D: Delamination failure.

However, for the CFRP specimen, only bearing failure is observed irrespective of the hole diameter, as shown in Figure 14. The failure mode of the CFRP specimen was independent of the $W/D$ effect, unlike the GFRP specimen, and delamination on the free
edge surface just appeared based on the damage distance from the bolt. As shown in Figure 8b, although the load reaches its maximum value, it is retained until failure at a specific strain. If the stress is concentrated around the hole, the failure is accelerated in the fracture region owing to the contact between the bolt and the specimen. Consequently, the bearing load width will be considerable.

Figure 14. Bearing failure mode of CFRP specimen ($L_B$: Bearing length).

4.2.1. Bearing Failure and Delamination Failure Mode

As mentioned earlier, bearing failure occurred in the CFRP specimen and not in the GFRP specimen. When the $W/D$ was high, the stress concentration increased; however, the failure of the CFRP specimen with sufficient tensile strength was unaffected by the $W/D$ ratio. Table 3 summarizes the measured bearing length, which is a characteristic of the bearing failure mode of CFRP specimens. Here, $L_B$ is defined as the length at which the specimen was destroyed by the movement of the bolt and then calculated (length after failed-hole diameter). This shows the proper influence on the stress concentration. Wisnom et al., reported that the smaller the hole notch, the higher the degree of stress concentration. In addition, delamination due to bolt movement occurs more easily when the hole diameter is small [24]. Therefore, it is thought that the decrease in $W/D$ induces a reduction in the stress concentration factor and a decline in $L_B$.

Table 3. Measured bearing length of CFRP specimens.

|       | 5 mm | 6 mm | 8 mm | 10 mm |
|-------|------|------|------|-------|
| #1    | 15 mm| 14 mm| 2 mm | 9 mm  |
| #2    | 10 mm| 12 mm| 10 mm| 12 mm |
| #3    | 17 mm| 9 mm | 10 mm| 8 mm  |

The correlation between the bearing length and the presence or absence of delamination on the free edge surface was considered in the CFRP specimen. This can be seen by comparing Tables 2 and 3. Delamination was observed when the bearing length was greater than 15, 12, 10, and 8 mm for hole diameters of 5, 6, 8, and 10 mm, respectively. As listed in Tables 2 and 3, for the specimen with a low $W/D$ value, delamination occurred even though the specimen had a shorter bearing length than the specimen with a high $W/D$ value. From this result, it can be confirmed that the occurrence of delamination depends on the stress concentration when $W/D$ is high and on the bearing pressure when $W/D$ is low. Figure 15 shows the association between the bearing length and the delamination magnitude at the free edge surface of the specimens with the same hole diameter. An increase in the bearing length leads to significant delamination. Delamination is generated when a shear crack is propagated by the bearing pressure from the bolt and reaches the free edge surface. According to Wang et al., the development of shear cracks inside a laminate is due to delamination, which in this study showed similar results [25]. Therefore, to evaluate mechanically fastened joint design and safety, it is necessary to consider failure around the hole and along the thickness.
The analysis of the bearing failure mode was numerically investigated using Equations (1)–(4) between the bearing stress and the stress concentration. For the GFRP specimen, lateral failure was commonly observed at the nominal section of all the specimens in which cleavage and net-tension failure modes appeared.

This means that the calculated tensile stress in consideration of the maximum load and the stress concentration factor from the experimental results is equal to the tensile strength of the GFRP specimen. Table 4 lists the tensile strength values calculated using the theoretical formula. The tensile strength of the GFRP specimen and the tensile stress of the CFRP specimen were calculated using Equation (1) based on the experimental values. Therefore, to compare the tensile strength at the nominal section, the tensile strength of the CFRP was calculated by multiplying the ratio of the tensile strength in the $0^\circ$ fiber direction of the CFRP and GFRP specimens based on the tensile strength of the GFRP specimen in which lateral failure occurred. Generally, the difference in the tensile strengths between CFRP and GFRP in the $0^\circ$ fiber direction is at least 1.8 times, which is significant [19–21]. When the experimental value was compared with the theoretical value, the tensile stresses for all hole diameters were lower than the calculated values. Therefore, in the CFRP specimen, bearing failure is considered to occur dominantly instead of lateral failure because the tensile stress at the net section does not reach the tensile strength of the specimen.

Table 4. Comparison of tensile strength.

| $D$ (mm) | CFRP Tensile Strength (MPa) | CFRP Tensile Stress (MPa) | GFRP Tensile Stress (MPa) |
|----------|----------------------------|---------------------------|---------------------------|
|          | Calculated Data            | Experimental Data         | Experimental Data         |
| 5        | 773.30                     | 516.64                    | 429.61                    |
| 6        | 835.67                     | 589.71                    | 464.26                    |
| 8        | 930.69                     | 718.78                    | 617.05                    |
| 10       | 959.17                     | 880.73                    | 532.87                    |
4.2.2. Cleavage Failure and Back-Split Crack

The GFRP specimens with hole diameters of 5 mm and 6 mm exhibited cleavage failure, which is a combined mode of longitudinal and lateral failures. As shown in Figure 2, longitudinal failure occurs owing to the stress concentration at the hole notch tip. Because of the stress concentration, the cracks start propagating from the hole notch tip, causing an asymmetric load distribution at the nominal section. Therefore, the tensile stress increases at the nominal section in the direction opposite to that of the longitudinal cracks, leading to failure at the nominal section. The crack propagation in the lateral direction acts as a compression in the 90° fiber direction. However, because the fiber laid in the 90° direction has a high compressive strength, the crack propagates along the 45° fiber direction with a relatively low compressive strength. In all the specimens where cleavage failure occurred, back-split cracks were investigated, particularly in the direction in which there was no bearing load by the bolt. Figure 16 shows the cause of the back-split cracks. A load equal to the bearing load \( P \) was applied to the nominal section. A relatively large strain occurred in the nominal section owing to the tensile load. However, the load distribution was rather narrow at Section A. As a result, the generation of the back-split crack is attributed to the induced shear due to the strain difference at the interface section between the nominal section and Section A with a large strain.

![Figure 16. Back-split crack in the GFRP specimen: (a) Schematic view; (b) Back-split crack in the GFRP specimen.](image)

4.2.3. Net-Tension Failure Mode

The GFRP specimen with hole diameters of 8 mm and 10 mm exhibited a net-tension failure mode. This occurs when \( \frac{W}{D} \) is low or when the tensile strength of the fiber is insufficient [15]. When \( \frac{W}{D} \) was decreased, the stress concentration factor was lower, and the distribution of the tensile stress at the net section was wider. In the case of the GFRP specimen, the stress concentration was relieved as the \( \frac{W}{D} \) value decreased. In addition, the increased bearing load at the nominal section caused a mode 1 crack in the 90° direction fiber and a mode 3 crack in the 45° direction fiber, as shown in Figure 17. Consequently, crack opening and fracture occurred in the 90° and 45° directions. This confirmed the occurrence of net-tension failure.

![Figure 17. Fracture modes [26].](image)

5. Conclusions

The mechanical bearing strength and failure modes of the mechanical fastened joint for GFRP and CFRP specimens were studied experimentally. The average static bearing stress of the CFRP specimen was more than 15% higher than that of the CFRP specimen,
and when \( W/D \leq 2.5 \), there was a significant difference of more than 30%. This means that the stress concentration has a more critical effect on the bearing stress of the GFRP specimen than the CFRP specimen when \( W/D \leq 2.5 \).

In the case of the \( W/D \) effect, as the diameter increases, since the contact area increases the bearing stress decreases. In contrast, in terms of the strength, the bearing strength increases as \( W/D \) decreases. The stress concentration decreases as \( W/D \) decreases, and the tensile stress increases with a decreasing bearing stress. In particular, in the case of the GFRP specimen, lateral failure could be observed owing to the increase in the tensile strength. \( W/D \) affects the failure mode transition section of the GFRP specimen. That was confirmed to be \( 2.5 \leq W/D \leq 3.3 \); however, the failure mode transition section of the CFRP specimen could not be identified. Especially, for GFRP specimen, back-split cracks were identified without exception in the cleavage failure mode. It is necessary to prevent additional structural damage due to such cracks when designing a mechanically fastened GFRP structure.

Finally, an analysis of the bearing strength and failure modes of the GFRP and CFRP specimens showed that CFRP with a bearing failure mode exhibited a higher static bearing strength than GFRP with cleavage and net-tension failure modes. This indicates that CFRP is an effective material for mechanically fastened joint marine structures.

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