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Effect of ON and OFF Axis Open Hole Tensile Testing of GFRP/Epoxy Composites

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ABSTRACT

Composites are widely used for different applications in engineering mainly due to their tailored benefits, durability, reduced maintenance, and enhanced performance. GFRP is a synthetic material that has revolutionized the aerospace industry, offering a high strength-to-weight ratio, fuel efficiency, and enhanced performance for advanced applications. In structures like aircraft components, holes or notches are often present due to design requirements or secondary joining processes through rivets or bolted connections, which leads to wear and tear. Further, how these materials behave under tensile loads near these openings is critical for ensuring the safety and reliability of such structures. In the present study, GFRP/Epoxy composite laminates are subjected to open hole tensile test under ON and OFF axis orientations. The effect of loading under different sequences was studied. The nature of failure near the hole region was reviewed and presented. It is noted that the dominant failure was LGM type under the ON-axis and different under the OFF-axis which is not limited to shear failure, interlaminar delamination, and mixed mode failures. These trends are noted for different hole dia, namely 6,9,12 and 18mm. The study also presents the nature of the stress-strain curve for both configurations. The OFF-axis specimens displayed a non-linear behavior to failure as compared to the On-axis type. While, the on-axis specimens showed a marked reduction in peak load and tensile strength as hole dia increased with reductions up to 65.23% and 63.57%, respectively relative to hole-less specimens. The inclined failure in off-axis specimens varied between 50^0 - 55^0. Further, the damage tolerance in OFF-axis samples was higher as compared to ON-axis specimens.

1. Introduction

In the realm of modern engineering, composites have played a pivotal role since their emergence in the 1960s. They are particularly crucial in the creation of lightweight yet robust structures, a key factor across sectors such as aerospace, automotive, and renewable energy. In the aerospace industry, for instance, the use of composites has led to a significant transformation in the efficiency and performance of aircraft. These materials provide high strength-to-weight ratios, fuel efficiency, and enhanced durability for aircraft structures and

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components [1-3]. The construction of composite structures, inherently complex due to their inability to be fabricated as single units, necessitates innovative joining methods. Techniques such as adhesive bonding and mechanical fastening are not just conventional methods but are essential in ensuring the structural integrity and strength of composite assemblies. These methods adeptly address the challenges in load transfer, stress distribution, and durability, all while capitalizing on the inherent benefits of composites like their lightweight nature and resistance to corrosion. This, in turn, has significantly contributed to the advancement of structural engineering and design.

In practical applications, particularly where composites function as load-bearing elements, the requirement to create holes for assembly and connections often arises. This need for geometric modifications, while practical, leads to stress concentrations around these holes. This phenomenon can potentially reduce the overall structural strength and adversely affect the service lifespan of the composite structure. This issue presents substantial challenges in maintaining the integrity and functionality of composite-based structures under rigorous operational conditions [4]. Due to these challenges, there has been considerable research on the effects of notches or open holes in composite laminates. Recognized for their cost-effectiveness, such studies are critical in assessing failure mechanisms, particularly due to interactions between the matrix and fibers [5]. Extensive research has also been conducted on various other aspects, including the impact on ply thickness [6], the influence of different hole diameters and shapes [7-11], the behavior of multiple holes [12], and the structural integrity of 3D printed holes and their fracture behavior [13]. Studies on fatigue behavior [14,15] and in-plane scaling [16] further augment our understanding of these materials. These comprehensive investigations assist engineers in making well-informed decisions regarding the design and determination of the ultimate allowable strength of composites that inherently contain features like cut-outs and defects [17].

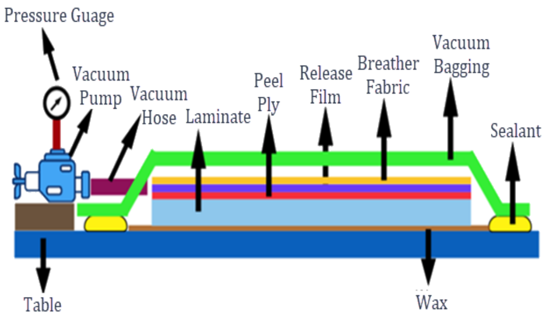
Notable studies in this field include the work of Zhang et al., who conducted open-hole tensile tests under longitudinal loads. Their findings revealed that initial damage in these composites typically manifests as matrix tensile damage, which progresses to fiber damage near the outer edges. This sequence of damage eventually leads to a failure state when the composite can no longer effectively bear the load [18]. Belgacem et al. delved into the impact of varying notch diameters and ply counts on the mechanical properties of interplay hybrid carbon/glass/epoxy laminates. Their results indicated a direct correlation between the decrease in the ultimate strength of the specimens and the increase in the geometric ratio (D/w) [2]. In more recent years, several authors have conducted in-depth analyses on the failure of unidirectional and multidirectional laminates with different stacking sequences [20, 21]. These studies, which included both on-axis and off-axis loading conditions, were aimed at understanding the deformation and damage evolution in composite materials [22]. It was discovered that off-axis loading resulted in a significant decrease in ultimate tensile strength, with the nature of the failure differing substantially from that observed in on-axis performance [23,24]. To this day, fully understanding the tensile mechanical responses of plain-woven composites with open holes, particularly under off-axis loading scenarios, remains a challenging endeavor. This is primarily due to their complex damage mechanisms and failure modes, which result in an increased failure strain compared to on-axis conditions. It has also been reported that the orientation of fibers plays a significant role in influencing external loading conditions, especially in off-axis situations [25]. Yang et al. [26] conducted studies on how off-axis angles affect the mesoscale deformation response and failure in orthotropic textile carbon-epoxy composites. They reported that these composites exhibit distinct load-bearing mechanisms when compared to on-axis scenarios. Similarly, Gang Liu et al. [27] reported that 3D woven composites, particularly at a 45° off-axis angle, exhibited considerable nonlinear behavior before complete failure. Among the tested angles (15°, 30°, 45°, 60°, and 75°), the composites at 45° showed the least strength but the highest failure strain. Despite extensive research in the field, including on-axis and off-axis testing processes with varying fiber orientations, there has been limited research focusing on the impact of varying hole diameters under such scenarios.

In the current work, Glass fiber-reinforced polymer (GFRP) laminates of a bi-woven nature were fabricated. These laminates were then subjected to on-axis and off-axis (45°) open-hole tensile tests with varying hole diameters of 6, 9, 12, and 18 mm. This investigation is aimed at understanding the influence of on-axis and off-axis conditions, coupled with different hole diameters, on the mechanical behavior of these composite materials.

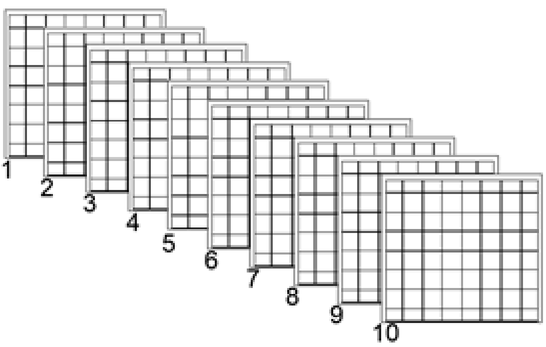
2. Materials and Methods

The fabrication of the glass fiber reinforced epoxy laminate commenced with procuring a 200gsm, 0.2mm thick, bi-woven glass fiber cloth from Marktech Composites Pvt Ltd, Bengaluru. Concurrently, an epoxy resin from Huntsman (Araldite and Epibond) was sourced from Heranba, Chennai, and prepared by mixing in a ratio of 10:1, resin to hardener (LY556+HY951) as per our previous studies [29]. The process began with the preparation of a clean granite table, which served as the working surface. Before laying down the glass fiber cloth, the table was treated with Waxpol to prevent sticking and facilitate the easy removal of the finished laminate.

A total of 10 layers with two different orientations as shown in Figures 1(b) & 1(c) of 500 mm x 500 mm cloth were placed one over the other, each receiving an even application of the epoxy resin mixture. During this stage, a special bubble buster tool (RL52-12150) from tools4frp, with a diameter of 12.7mm and a length of 150mm, was employed. This tool played a crucial role in eliminating excess bubbles, thereby ensuring that the laminate was void-free. After each layer was applied, the process was repeated until the final, tenth layer was reached. A peel ply was placed on top; this peel ply is crucial as it assists in removing excess resin and other impurities or volatiles during the hardening phase. Then, a release film was laid over the peel ply, followed by covering the entire assembly with a vacuum bagging film. This film was securely sealed with sealant tape to create a perfect vacuum. A high-performance vacuum pump, with a capacity of 11.8 CFM, was used for the vacuum bagging process, which lasted for 4 hours as shown in Figure 1(a).



(a)



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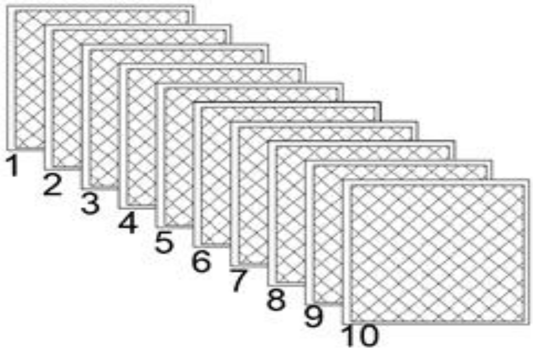

(C)

Fig. 1. (a) Vacuum Bagging Process, (b) Layer Diagram of the Composite Laminate for ON Axis, (c) OFF Axis Orientation

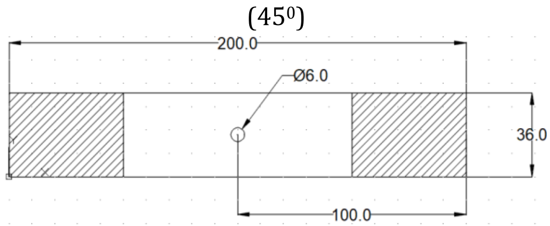

Fig. 2. Open-hole tensile test specimen geometry in mm [19]

After the vacuum bagging, the laminate was left to cure for 24 hours. Post-curing, the laminate was carefully removed from the setup using a snap-off blade. Attention was given to maintaining the thickness of the laminate at 2.1±0.1mm. The final stage involved cutting the laminate to specific dimensions as per ASTM D5766, as shown in Figure 2 using a waterjet cutting machine from OM-Waterjet, Peenya, Bengaluru. A total of 3 sets of samples for each configuration were cut to ensure repeatability of the test results as shown in Figures 3(a) & 3(b).

The specimens for the on-axis were cut normally as per the above dimensions, however for the off-axis, the cutting direction was at 45^0 as shown in Figure 3(a). The laminate after being cut was drilled at the center as per the w/D ratio 6 mentioned in the ASTM standards [18]. In the present study, the effect of this ratio is studied which was varied from 2 to 6 resulting in different diameters namely (6, 9, 12, and 18 mm) using a cemented carbide twist drill with different diameters and a spindle speed of 4500 rpm and a feed rate of 110mm/min to carry out the drilling using a VMC Drilling Machine [30]. The machining parameters were chosen according to the standard drill size suitable for joining the laminates. The speed was maintained at 4500 rpm to reduce the delamination effect. Sufficient care was taken to ensure the specimens were sandwiched between two GFRP laminates, mainly to reduce the drilling-induced damages in and around the hole region. The specimen notation is shown in Table 1 and drilled specimens are shown in Figure 3(b).

(a)

(b)

Fig. 3. (a) Waterjet cutting off-axis (45^0) Orientation, (b) Specimen with drilled holes

Table 1. On-axis and off-axis specimen code

Specimen Coding Sequence	Orientation	Dia of the hole (mm)	Thickness (mm)
AN		No Hole	
A6		6	
A9	On Axis	9	
A12		12	
A18		18	2.15
FN		No Hole	
F6	Off Axis	6	
F9		9	
F12		12	
F18		18	

3. Experimental Method

The open-hole tensile tests were conducted on a Wance UTM, as shown in Figure 4, a universal testing machine with a 50 kN capacity, at a constant loading rate of 2 mm/min, adhering to ASTM D5766 standards. These tests, performed at room temperature, aimed to assess the tensile strength of GFRP composite laminates with different hole diameters for both on-axis and off-axis conditions. Each GFRP laminate type was represented by three repeat specimens, ensuring comprehensive and reliable test data. Testing until final failure provided crucial insights into the materials' ultimate strength and failure modes. This rigorous methodology ensures accuracy and consistency in results, crucial for material evaluation and application in environments where structural integrity is critical.

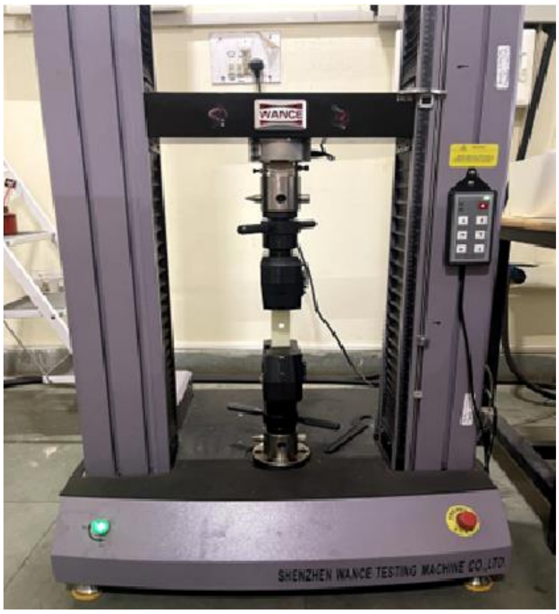

Fig 4. Open-Hole Tensile Testing

4. Results and Discussion

In this research study, experiments were conducted to investigate the influence of hole diameter on the strength of plain-woven composites related to on-axis and off-axis orientations when subjected to uniaxial tensile loads in a wance UTM with a 50 kN capacity. The test was carried out for four specimens to ensure the repeatability of results for both on-axis and off-axis conditions, as per ASTM standards.

4.1. On-Axis Peak Load and Tensile Strength

All the samples underwent linear deformation at lower stress levels and started to behave non-linearly at higher stress levels, as shown in Figure 5, leading to failure around the hole region. The mechanical behavior of various specimens under stress was analyzed, focusing on deformation and failure patterns. Figure 5 illustrates that all samples initially underwent linear deformation at lower stress levels before transitioning to non-linear behavior, leading predominantly to failure around the hole region. This aligns with findings in previous studies [8,9]. Peak load values are pivotal in understanding the impact of structural modifications, such as hole introduction, on material integrity. The hole-less specimen AN, with the highest peak load of 16.082 kN, serves as a reference. In contrast, specimens A6, A9, A12, and A18 with holes show significant peak load reductions of 40.42%, 51.46%, 59.74%, and 65.23%, respectively. In a study done by O'Higgins et al. [28], it was found that the percentage reduction between unholed and holed specimens was almost 50%. This indicates a clear correlation between increasing hole size and decreased peak load capacity, which is essential in load-bearing applications, highlighting the trade-off between design elements and mechanical strength.

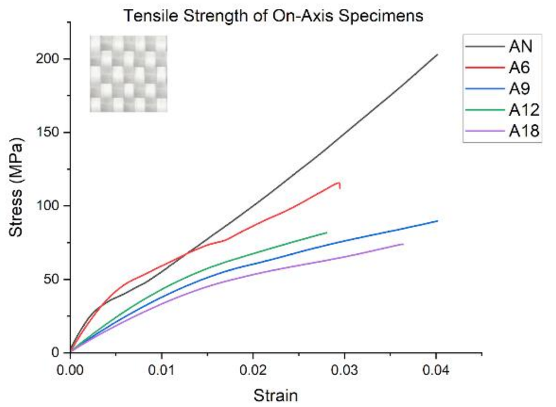

Fig. 5. On-axis tensile test results

Tensile strength analysis, though complicated by different metrics (σUH for AN and σH for others), reveals a consistent pattern. Compared to AN's σUH of 203.063 Mpa, there's a marked decrease in tensile strength in specimens with holes: 43.01% for A6, 53.58% for A9, 59.73% for A12, and 63.57% for A18. This trend suggests that larger holes significantly compromise material strength, with holes acting as stress concentrators, causing damage and reduced tensile resistance.

4.2. Off-Axis Peak Load and Tensile Strength

The investigation of mechanical behaviors under off-axis loading conditions, as defined by ASTM D5766 standards, reveals significant deviations in stress-strain characteristics when compared to on-axis loading scenarios. This study primarily attributes these variations to the angular displacement of fibers, specifically set at a 45-degree orientation relative to the loading axis. This orientation intensifies the nonlinearities observed in the stress-strain curves, which are indicative of the complex mechanical interactions within the composite material.

The initiation of failure in these tests typically begins at the microstructural level, where fiber-matrix interfaces are compromised due to the severance of adjacent fibers. This disruption significantly weakens the structural integrity, precipitating the rapid propagation of failure. This is visually documented in Figure 6, which highlights a marked reduction in stress levels for off-axis specimens in comparison to their on-axis counterparts, explaining the critical influence of fiber orientation on the overall mechanical response of the material.

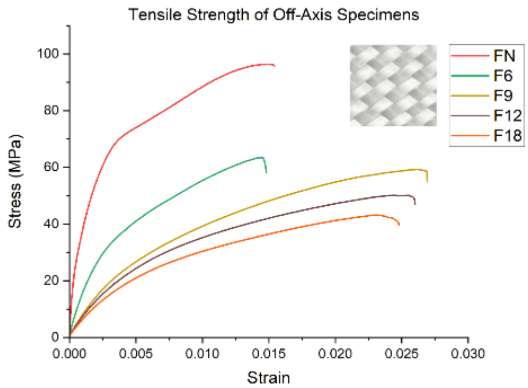

Fig. 6. Off-axis tensile test results

Detailed quantitative examination of various specimens—namely FN, F6, F9, F12, and F18—demonstrates diverse mechanical performances. Specimen FN, without any structural perforations, registered the highest tensile strength of 96.369 MPa. This value serves as a reference point against which other specimens are evaluated. For instance, specimen F18, exhibiting the lowest tensile strength in the series, recorded a strength of 43.187 MPa. The differential in performance across the specimens can be expressed as proportions of FN's tensile strength, with F6, F9, F12, and F18 achieving 65.82%, 61.51%, 52.05%, and 44.85% of FN's strength, respectively. This was due to the stress concentration factor, reduced effective cross-sectional area, initiation and propagation of cracks from the hole region, and most of all, the influence of fiber orientation and matrix interaction.

The assessment of peak load capacities further emphasizes the variability in mechanical robustness among the specimens. Specimen FN, demonstrating optimal structural resilience, achieved the highest peak load of 7.632 kN. In contrast, specimen F18 displayed the least robustness with a peak load of 3.575 kN. This stark contrast not only highlights the mechanical implications of off-axis loading but also quantifies the relative performance of each specimen, with F6 and F18 exhibiting peak loads at approximately 62.79% and 46.84% of FN's capacity, respectively.

When compared to the on-axis, the off-axis performed relatively low in terms of both tensile strength and peak load. This was due to the placement of the fibers at an angle of 45^0 as compared to on-axis loading. Further, studies have also claimed that the 45^0 orientations developed the least ultimate tensile strength [27]. Additionally, the plastic deformation increased as compared to the on-axis condition since the fibers were rotated.

4.3. Damage Mechanism

Both on-axis and off-axis specimens were subjected to uniform loading of 2 mm/min, and the damage mechanisms identified were different in both cases. In the case of the on-axis, the type of failure was LGM (linear Gauge Middle), a predominant type of failure as identified in Figure 7. Furthermore, this type of failure is an acceptable failure as suggested in the standard [19]. However, in the case of the off-axis specimens, the type of failure was inclined and about 50^0 – 55^0 with respect to the hole's horizontal axis as shown in Figure 8. A similar trend was observed by [27]. However, as the hole dia increased, the angle was reduced to between 45^0 – 50^0. The majority of failure noted on the on-axis was fiber pullout and matrix debonding, and in the case of the off-axis, it was yarn pull out, yarn cracking, and yarn kinking. Furthermore, in the on-axis specimens, the failure tends to be more catastrophic and localized due to the alignment of the fibers with the loading direction. Any disruption caused by holes directly impacts the primary load-carrying paths, leading to the rapid propagation of failure once the fiber capacity is exceeded.

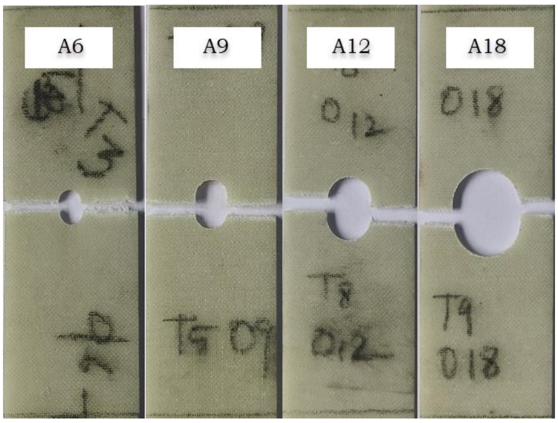

Fig. 7. Failure in specimens due to on-axis tensile loading for diameter (6,9,12,18mm)

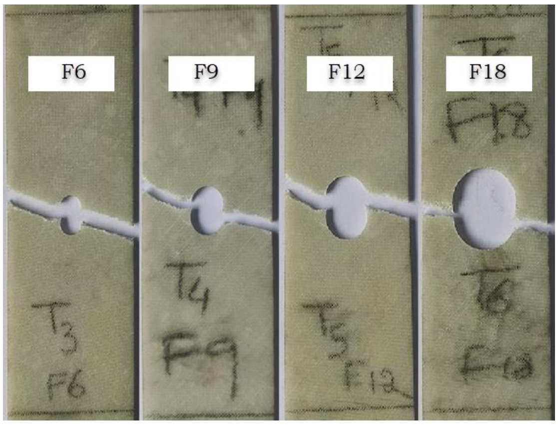

Fig. 8. Failure in specimens due to off-axis tensile loading for diameter (6,9,12,18mm)

Table 2. On-axis and off-axis specimen code

Specimen Code	Hole Dia (mm)	w/D Ratio	Peak Load (kN)	Deflection (mm)	Tensile Strength (σ_{UH}) MPa	Tensile Strength (σ_H) MPa	Damage Tolerance %
AN	-	-	16.082	4.016	203.063	-	-
A6	6	6	9.581	2.950	-	115.72	56.98
A9	9	4	7.806	1.745	-	94.27	46.42
A12	12	3	6.475	2.039	-	81.77	40.26
A18	18	2	5.592	1.454	-	73.97	36.42
FN	-	-	7.632	15.463	96.369	-	-
F6	6	6	4.794	3.705	-	63.42	65.81
F9	9	4	4.478	2.691	-	59.245	61.47
F12	12	3	3.611	2.599	-	50.160	52.05
F18	18	2	3.575	2.478	-	43.187	44.81

In off-axis conditions, the misalignment of fibers relative to the load path can lead to more diffuse damage patterns, such as delamination or matrix cracking, which can absorb more energy before catastrophic failure. This type of failure mechanism allows the material to maintain some load-carrying capacity even after initial damage onset, thus enhancing damage tolerance. The angled fibers in OFF-axis specimens can also alter the path and rate of crack propagation. Cracks may be redirected or slowed as they encounter fibers at an angle, which can increase the energy required to propagate the crack further. The calculated damage tolerance for the A6 specimen was found to be 56.98%, as per equation 1.

$$\text{Damage Tolerance} = 1 - \frac{(\sigma UH - \sigma H)}{\sigma H} \quad (1)$$

5. Conclusions

The detailed analysis of GFRP/Epoxy composite laminates subjected to open-hole tensile tests across different orientations and hole diameters offers substantial insights into the influence of these variables on the mechanical properties and failure mechanisms of the materials. The study distinctly underscores the relationship between structural modifications and their impacts on composite durability and integrity.

- Influence of Hole Diameter:

  The experiments indicate that the presence of holes significantly compromises the structural strength of the composites. As the hole diameter increases from 6mm to 18mm in ON-axis specimens, there is a marked decrement in peak load and tensile strength, with reductions reaching up to 65.23% and 63.57%, respectively. This phenomenon is due to the increased stress concentration around the holes, which effectively weakens the composite's load-bearing capacity. The findings necessitate careful consideration in the structural design of composites, particularly in applications where mechanical integrity is critical.

- Orientation Impact:

  Comparing on-axis and off-axis orientations, the study reveals that off-axis specimens consistently show lower mechanical performance than their on-axis counterparts. For instance, the off-axis specimens exhibit a decrease in peak load capacity by up to 46.84% compared to the highest-performing on-axis specimen. This difference is largely attributed to the fiber orientation relative to the loading direction, which significantly affects how stress is distributed and managed within the composite structure. The angular fiber orientation exacerbates the impact of external loads, leading to quicker and more severe failure modes.

- Damage Tolerance and Failure Modes:

  The study presents a distinct variation in damage tolerance and failure modes between the ON and OFF axis tests. ON-axis specimens primarily exhibited a Linear Gauge Middle (LGM) type failure, indicating a somewhat predictable and uniform stress distribution until failure. In contrast, OFF-axis specimens showed inclined failure patterns, with failure angles ranging between 50° and 55°. These inclined failures highlight the complex interaction between the matrix and fibers under stress, exacerbated by off-axis loading. Furthermore, as the hole diameter increased, the angle of failure slightly decreased, suggesting a modification in the stress trajectory across the composite material. Further, it was evident that there was an increase in damage tolerance for the off-axis specimens as compared to the on-axis.

Nomenclature

σ_{UH}	Tensile strength of no-hole specimens
σ_H	Tensile strength of specimen with holes
AN	Specimen with On-Axis fiber orientation without hole
FN	Specimen with OFF-Axis fiber orientation without hole

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Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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