



Experimental Investigation of Drilling Parameters Affecting Hole Quality in Glass Fiber/Polyester Composites

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Glass fiber/polyester composite, GFRP, Drilled hole quality, Process parameters, Delamination factor.

Abstract: Glass fiber/polyester composites are increasingly used in naval, aerospace, and automotive industries due to their excellent strength-to-weight ratio and corrosion resistance. However, drilling-induced delamination remains a major concern that compromises hole quality and structural performance. In this study, the drilling behavior of randomly oriented chopped strand mat GFRP/polyester laminates (3 mm thickness, 5 layers, 450 g/m² areal density) was experimentally investigated under varying spindle speeds (1000–2000 RPM), feed rates (100–300 mm/min), and drill diameters (5, 8, and 10 mm). Hole quality was evaluated using AutoCAD-based measurement of the delamination factor. The results show that delamination factor increases with feed rate, while higher spindle speeds reduce it, in agreement with previous studies that attribute this behavior to reduced thrust forces. Among the tested conditions, the lowest delamination factor (≈ 1.09) was obtained at 1500 RPM and 100 mm/min feed rate, whereas the highest (≈ 1.54) occurred at 1000 RPM and 300 mm/min. The contribution of this work lies in focusing on the underexplored chopped strand mat GFRP/polyester composites and employing AutoCAD-based quantitative assessment, providing new insights and a practical baseline for improving drilling performance in these materials.

1. Introduction

Over the past few decades, utilization of polymers and composites has been rapidly increasing in a variety of fields, such as naval, aerospace, and automotive industries. Particularly, glass fiber reinforced plastics (GFRP) possess remarkable properties such as a great corrosion resistance, good

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impact resistance, and high strength-to-weight ratio [1,2]. These characteristics make them an alternative to conventional metals, which possess high stiffness mass and improved fatigue resistance. Hence, their application targets engineering structures of highly demanding performance versus weight requirements [3,4]

Even though fibers are incorporated to enhance properties, drilling of composite materials, drilling being the principal operation, is still faced with problems of non-homogeneity and anisotropy [5]. Challenges in drilling, including fiber pull-out, thermal deterioration, and matrix cracking, are commonly seen when fiber (reinforcement) is enclosed inside the matrix since it is quite hard and abrasive [6]. Delamination poses a critical problem whenever the drilling of composites is involved, which affects the end users as the drill seeks to remove the inner layers next to the center of the component where most structures are generated. This scenario is very worrying in industries such as aerospace, where nearly 60% of composite components are bent in one direction, and there is no direct point contact between the drill and the fibers; therefore, delamination is considered a primary reason for rejection of components in such applications [7]. Due to the significance of drilling in the assembly of composite parts, particularly for precision applications such as those in the aerospace and automotive industries, there is a need to comprehend and reduce the defects caused by this process [5]. Considerable research has already been done on the delamination occurring during the drilling process of fiber reinforced polymer (FRP) composites to seek optimal values of drilling parameters and, consequently, to enhance the quality of drilled holes in the advanced materials [2]. Current activities demonstrate that more work should be done in composites machining to make them more useful and perform better in harsh engineering applications [8].

Mohan et al. [9] studied the effects of drilling parameters on delamination in GFRP laminates. Key factors influencing delamination were specimen thickness, feed rate, and cutting speed. Optimal conditions for minimal peel-up delamination were a feed rate of 50 mm/min, cutting speed of 1200 rpm, drill diameter of 6 mm, and material thickness of 12 mm. Khashaba et al. [10] examined delamination during the drilling process of chopped composites. It has been noted that the size of delamination minimizes as the feed lowers, whereas there is no evident impact of the cutting speed on the size of delamination. Rajamurugan et al. [2] established empirical correlations between drilling parameters and delamination in GFR–polyester composites through response surface approach. Their results showed that increasing feed rate and drill diameter increases delamination size, while spindle speed has a minimal effect. Fiber orientation angle did not show a clear trend. The most influential parameter was tool feed rate, followed by drill diameter. Eisa et al. [11] optimized drilling process parameters for GFRP composites using the Taguchi technique to minimize the delamination factor. Their results showed that increasing drilling speed (2250-2750 RPM) and feed rate (100-125 mm/min)

increased delamination. However, high drilling speed and low feed rate reduced delamination. Feed rates were the most influential factor on delamination. Chadha et al. [8] studied the drilling parameters which affect delamination in GFRP composites. It was clearly observed from the results that with increased cutting speeds and feed rates, delamination increased, but an increase in the number of layers in the composite decreased it. Composites with four layers suffered lower levels of damage than those with two or three layers. Balaji et al. [12] studied the delamination effect of drilling Glass Fiber Mat Composite. The factors studied include feed rate and cutting speed. Their results supported that the delamination can not only be reduced but in fact, efficient targeting can be achieved at higher cutting speeds and lower feed rates. Therefore, it is essential to properly choose process parameters so that delamination can be limited when drilling. Bosco et al. [13] studied the delamination effect while drilling armour steel-GFRP sandwich composites. The factors studied include feed rate, cutting speed, and drill diameter. Higher feed rate of 0.12 mm/rev led to increased delamination while lower feed rate of 0.03 mm/rev led to less delamination. Increasing the drill diameter also contributed to the increased delamination because of the increased area of contact. Spindle speed was not of high significance, although faster speeds were preferable. Proper selection of these parameters is crucial to reduce delamination during drilling. Paundra et al. [14] studied the delamination phenomenon when drilling glass fiber reinforced polyester resin-based composites with different layers. Four types of specimens with different layers; 3, 4, 5, and 6 layers were used in their experiments. They found that the 3-layer specimen had the highest delamination value (1.6) while the 6-layer specimen had the lowest (1.2). A higher delamination value is believed to be associated with a lower composite tensile strength. However, in this study, even though the delamination values were lower than expected, no significant differences were evident during tensile testing and layer number appeared to be the most appropriate parameter regarding tensile strength. Mahrous et al. [15] carried out drilling tests on random glass-fiber reinforced polyester composites to improve the drilling conditions and reduce the delamination level. The study focused on the impact of spindle speed, feed rate and overhang ratio on peeling up delamination factor and push down delamination factor. It was observed that all parameters chosen in this study significantly affected the peel up delamination factor and pushed down delamination factor at 95% confidence level. Arhamnamazi et al. [16] conducted the drilling of carbon fiber reinforced polymer (CFRP) composites utilizing a central composite design, manipulating parameters like rotating speed, feed rate, and the angle between the sequences of composite layers. The objective was to reduce the delamination factors and thrust force. The combination of a low feed rate (1200 mm/min), elevated rotational speed (12000 rev/min), and a reduced layering angle of 15 degrees yielded a diminished thrust force and a smaller delamination factor, hence validating the efficacy of these models.

Despite these contributions, relatively little attention has been given to chopped strand mat GFRP laminates, particularly when considering the combined effect of process parameters using CAD-based delamination assessment. The present study investigated the hole-drilling operations of randomly chopped strand mat glass fiber composites. Samples with a thickness of 3 mm, composed of 5 layers of glass fiber with a mass per unit area of 450 g/m², were prepared using unsaturated polyester resin. Different drill bits with diameters of 10 mm, 8 mm, and 5 mm were employed to study the effect of varying rotation speed and feed rate on drilling quality. The assessment was further carried out using AutoCAD to determine the delamination factor, which enhanced the analysis of the response of different parameter combinations and drilling properties, in addition to investigating performance enhancement.

Although several studies have investigated the drilling of GFRP composites, the majority have focused on either (CFRP) or unidirectional GFRP laminates, with relatively limited attention given to randomly oriented chopped strand mat glass fiber/polyester composites. The novelty of this study lies in providing a systematic experimental analysis of the combined influence of drill bit diameter, spindle speed, and feed rate on hole quality, while employing AutoCAD-based delamination factor assessment as a quantitative tool. The focus is on establishing parameter ranges that minimize delamination, thereby providing a practical baseline for machining chopped strand mat GFRP composites.

2. Materials and method

This section outlines the experimental framework of the study, including the materials employed for fabricating the GFRP laminates and the detailed methodology followed for the drilling investigations.

2.1. Materials

The composite specimens were fabricated using unsaturated polyester resin as the matrix and E-glass fibers as the reinforcement. The selection of these materials was based on their wide use in structural applications and their relevance to assessing machinability in polymer-based composites.

2.1.1. Polyester resin: it is one of the types of thermosetting resins widely used in the manufacture of composite materials because of its cheap price. It also has a wide variety of uses and is easily able to handle different manufacturing processes [17]. Polyester is a liquid substance with a transparent color. The resin was mixed as a base material with the Catalyst-type methyl ethyl ketone peroxide (MEKP) at an amount of 1 to 3 grams per 100 grams [18].

2.1.2. E-glass fiber: It is a synthetic, inorganic fiber. It is characterized by high strength exceeding that of steel, low elongation, flexibility, and high specific density. It has high resistance to all types of chemicals and high electrical insulation resistance. Glass fibers are used to insulate electrical wires and

thermal insulation, and they are used to strengthen plastic to give it higher durability [17]. In this research, random chopped strand mat glass fibers with a density of 450 g/m² are used.

2.2. Preparation of glass fiber composite

The hand layup method was used to manufacture the composite material. SUPIC-710 PT unsaturated polyester resin (Ortho Resin) was used as the matrix, and methyl ethyl ketone peroxide (MEKP) catalyst was added at a fixed ratio of 1.5 g per 100 g of resin, which is a commonly recommended proportion to ensure complete curing without excessive exothermic reaction. The reinforcement consisted of E-glass randomly chopped strand mats (commercial name: E6CRMC450-1250-E20 (OET), emulsion binder type, JUSHI Group Co., Ltd.) with an areal density of 450 g/m². First, a mixture of polyester resin and catalyst was applied in a transparent bowl and stirred for a minute to ensure complete mixing. The fibers were cut into 25 x 25 cm pieces. The lower and upper molds, made from the required size wood, were prepared for the casting process. Prospan paper with a smooth texture was placed on the surface of the lower mold before casting and on the upper mold after casting, serving both as a release film to prevent adhesion and as a means of providing a smooth surface finish on both sides. A thin layer of polyester was placed on the Prospan paper in the bottom mold. Then, a layer of glass fiber was placed, fully filled with polyester resin, and the mixture was spread uniformly. A spiral-shaped iron roller resembling a screw with a square shape was then used to extract air bubbles after placing the polyester resin on the fibers. This process was repeated with layers of glass fiber until five layers were completed, ensuring a laminate thickness of 3 mm. After building the composite using the required layers, a layer of polyester was placed after the last layer. Two rectangular plates, each with a thickness of 3 mm, were placed on the right and left sides to ensure uniform thickness in the specimen. Then, the Prospan paper and the upper mold were placed. A load of 70 kg was applied on the mold. The laminates were cured at room temperature under standard laboratory conditions without special environmental control for a fixed duration of 24 hours. By cutting the damaged sides, the required size of the composite laminate can be achieved using this method [19].

2.3. Machining set-up

A Siemens CNC milling machine with a SINUMERIK 802D SL control was used for drilling the holes as shown in Figure 1. Figure 2 show the machining experimental set-up. Solid carbide twist drills with diameters of 5, 8, and 10 mm were employed. The drills were commercially available types purchased from the local market. Each drill had a standard two-flute geometry with a point angle of 118°, and the tools were uncoated to maintain consistent tool-material interaction without the added influence of coatings. The specimens were fixed on the machine table using standard fixtures. The hole-to-hole center spacing was set to three times the drill diameter, consistent with ASTM

D5961/D5961M-17 recommendations for edge distance ratios in composite laminates to avoid internal stress in the material during machining [20]. This practice has also been noted in previous drilling studies to avoid interaction of delamination zones between adjacent holes.

The drill bits were mounted in the CNC spindle using a collet chuck to ensure accurate alignment and firm holding during drilling. The GFRP specimens were secured on the CNC milling table using mechanical clamps, and a sacrificial wooden plate was placed beneath the laminates to minimize vibration and reduce push-out delamination. All drilling experiments were carried out under dry conditions (without lubrication or external cooling) and under standard laboratory conditions at room temperature and ambient humidity.



Fig. 1: CNC milling machine (Extron M320 with SINUMERIK 802D SL control) used for the drilling experiments on GFRP specimens.

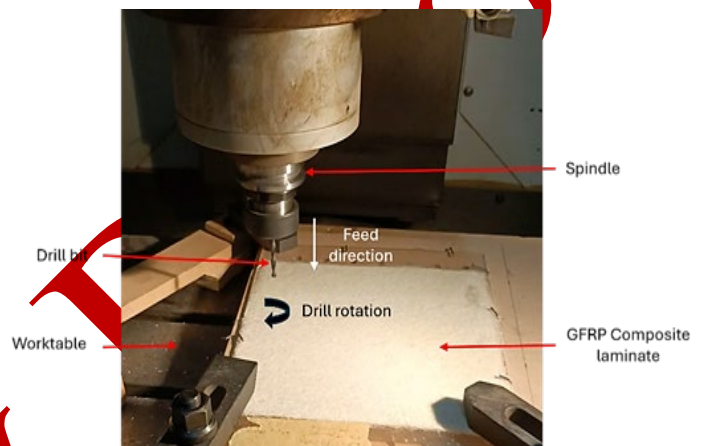


Fig. 2: Experimental drilling setup showing the positioning and clamping of the GFRP laminate specimen on the CNC milling platform. Arrows indicate the feed direction and drill rotation.

2.4. Experimental design and procedure

The experiments were conducted by varying three main factors: drill bit diameter, feed rate, and spindle speed, each at three different levels. Table 1 presents the design matrix of the experimental plan. A total of 27 tests were performed, with each test repeated three times to ensure accuracy. The average of the three results was then calculated for each test. The focus was on measuring delamination in the glass fiber material. Before the drilling operation, the CAD drawings were created using AutoCAD software as shown in Figure 3 (a). The drilling process was then carried out to produce the composite laminates with the desired drilled holes as shown in Figure 3 (b).

Table 1: Design matrix for drilling

Exp. No	Drill Diameter (mm)	Spindle Speed (RPM)	Feed Rate (mm/min)	Repetitions
1	10	1000	100	3
2	10	1000	200	3
3	10	1000	300	3
4	10	1500	100	3
5	10	1500	200	3
6	10	1500	300	3
7	10	2000	100	3
8	10	2000	200	3
9	10	2000	300	3
10	8	1000	100	3
11	8	1000	200	3
12	8	1000	300	3
13	8	1500	100	3
14	8	1500	200	3
15	8	1500	300	3
16	8	2000	100	3
17	8	2000	200	3
18	8	2000	300	3
19	5	1000	100	3
20	5	1000	200	3
21	5	1000	300	3
22	5	1500	100	3
23	5	1500	200	3
24	5	1500	300	3
25	5	2000	100	3
26	5	2000	200	3
27	5	2000	300	3



Fig. 3: Drilled GFRP laminate specimen illustrating the experimental drilling plan with multiple holes produced under different machining conditions.

The selection of drilling parameters and tools was based on both literature evidence and industrial practice. The ranges of spindle speed (1000–2000 RPM) and feed rate (100–300 mm/min) were chosen in accordance with values reported to significantly influence delamination and hole quality in GFRP composites [9,11]. Drill bit diameter was also identified as a critical factor affecting delamination in previous studies [2]. These ranges additionally fall within the practical operating limits of the CNC machine, representing realistic industrial drilling conditions for polymer-based composites. Drill bit diameters of 5 mm, 8 mm, and 10 mm were selected to cover typical small-to-medium hole sizes required in structural and assembly applications. The drilling depth was fixed at 6 mm, corresponding to the laminate thickness. Each drilling condition from the design matrix (Table 1) was repeated three times, and the average values were used for analysis. The experiments were executed in randomized order to minimize bias. To eliminate tool wear effects, new drills were used for each experimental set. The drill bits employed are shown in Figure 4. Delamination was subsequently analyzed using AutoCAD-based image measurements. The drilling parameters, including spindle speed, feed rate, and drill bit diameter, were programmed into the CNC drilling machine for consistent operation across all tests.



Fig. 4: Solid carbide twist drill bits employed in the study:(a) 10 mm, (b) 8 mm, and (c) 5 mm diameter, all with two-flute geometry and 118°-point angle.

2.5. Measurement of delamination factor

Delamination around the drilled holes was assessed using an OLYMPUS SZ61 stereomicroscope equipped with an OLYMPUS SC100 camera as shown in Figure 5. The stereomicroscope provides 45x magnification and has a resolution of 1.0 μm . An increasing delamination factor indicates greater delamination damage. The delamination factor was determined using the following equation:

$$F_d = \frac{D_{max}}{D_{nom}} \quad (1)$$

Where F_d is the delamination factor, D_{max} is the maximum delamination diameter, and D_{nom} is the nominal drill diameter.

Here, D_{max} was defined as the maximum projected diameter of the delamination zone measured around the hole boundary in the microscope images, with the delamination boundary identified visually as the outermost fiber-break/crack boundary surrounding the hole, as shown in Figure 6. Measurements were taken from images captured with the OLYMPUS SC100 camera, and the maximum and nominal diameters were analyzed using AutoCAD software for precise dimensioning. Each microscope image included a built-in scale bar, which was used as the reference for calibration in AutoCAD. For each drilled hole, three independent measurements were taken, and the average value was reported to minimize random error. This procedure ensured reliable and repeatable measurements, while reducing the effect of individual reading variations. The methodology is consistent with prior studies recommendations for composite damage assessment, particularly those using image-based measurement methods [21], as well as parametric investigations in drilling-induced delamination of GFRP [22-23].



Fig. 5: Stereomicroscope to identify delamination

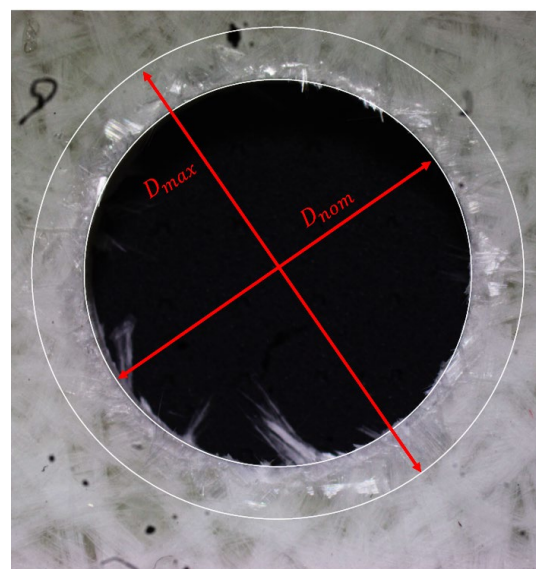


Fig. 6: Microscopic image showing surface damage in GFRP composite after drilling

3. Results and discussion

Figure 7 shows the variation of delamination factors with feed rate at different spindle speeds for a 10 mm drill diameter. From the results, it can be observed that the delamination factor increases with the feed rate. Specifically, at a speed of 1000 RPM and a feed rate of 100 mm/min, the delamination factor was 1.168. This ratio increased to 1.197 at a feed rate of 200 mm/min and further rose to 1.303 at a feed rate of 300 mm/min. This indicates that higher feed rates lead to greater delamination due to increased thrust force on the workpiece, resulting in more glass fiber pull-out. At a speed of 1500 RPM, the delamination factor was lower, at 1.095 with a feed rate of 100 mm/min, but increased to 1.179 at a feed rate of 200 mm/min and reached 1.200 at a feed rate of 300 mm/min. The trends that are observed at this speed are analogous to those at 1000 RPM, which leads to the conclusion that feed rate appears to be the dominant factor within the tested range, based on the observed trends. At 2000 RPM, the delaminating factor was moderate and ranged between 1.112 to 1.189 with a rise in feed rate. This means that to minimize and avoid the delamination effect during the process of drilling using the 10 mm drill bit, the drill speed should be about 1500 RPM at a feed of 100 mm/min, where both the thrust force and delamination factors are almost in equilibrium.

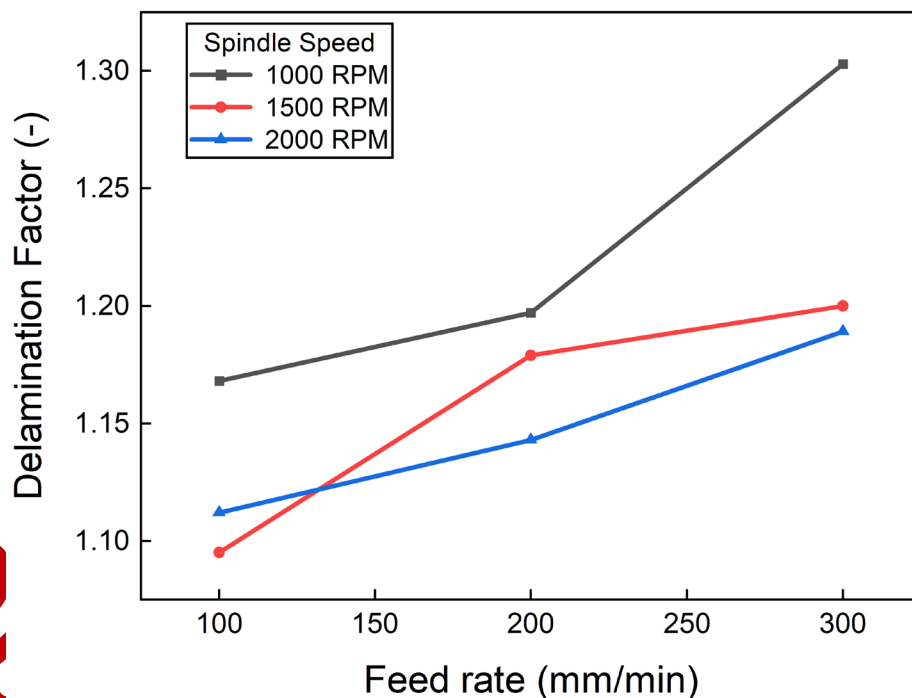


Fig. 7: Variation of delamination factor with feed rate at different spindle speeds for a drill diameter of 10 mm.

Figure 8 presents the variation of delamination factors with feed rate at different spindle speeds for an 8 mm drill diameter. Using an 8 mm drill bit, delamination factor was rather favorable at 1000 RPM and 100 mm/min feed rate at the level of 1.115 when using the 10 mm drill bit. On the other hand, this

ratio increased sharply at a feed rate of 200 mm/min where it recorded at 1.266 and then still rising to 1.536 at 300 mm/min, indicating a significant increase of delamination due to heavy thrust and aggressive glass fiber pull out. One of the lowest delamination factors was observed at 1500 RPM when drilling at a feed rate of 100 mm/min where it began at 1.203, 1.122 at 200 mm/min lower than increased again at 300 mm/min where ratio stood at 1.382 suggesting that there may be a feed rate limit beyond which delamination tends to become more pronounced. Same as feed increase, at 2000 RPM the delamination factor was much less than 1000 RPM which was 1.092 to 1.279, reflecting a better balance between thrust force and delamination.

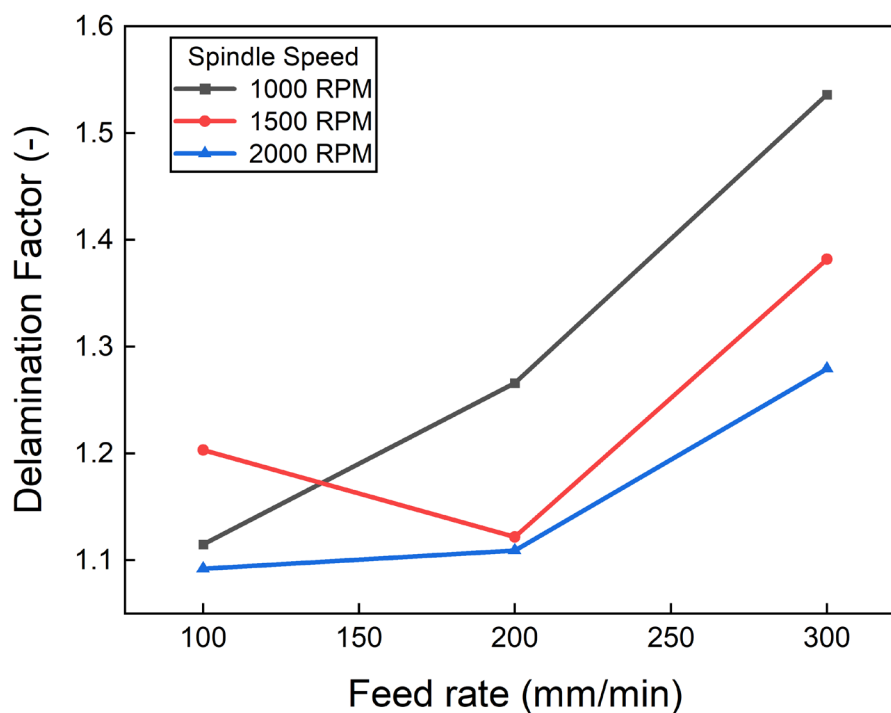


Fig. 8: Variation of delamination factor with feed rate at different spindle speeds for a drill diameter of 8 mm.

Figure 9 illustrates the variation of delamination factor with feed rate at different spindle speeds for a 5 mm drill diameter. For a 5 mm drill bit, the delamination factor began at 1.201 at 1000 RPM and a feed rate of 100 mm/min, increased to 1.268 at 200 mm/min, and reached 1.355 at 300 mm/min, indicating a notable increase in delamination with higher feed rates. At 1500 RPM, the ratio was lower at 1.125 with a feed rate of 100 mm/min, but increased significantly to 1.267 at 200 mm/min and further to 1.308 at 300 mm/min. At 2000 RPM, the delamination factor started relatively low at 1.114 with a feed rate of 100 mm/min, increased to 1.274 at 200 mm/min, and slightly decreased to 1.236 at 300 mm/min, suggesting that high speed might slightly reduce delamination at high feed rates. Overall, the more favorable conditions for minimizing delamination with a 5 mm drill bit are at 1500 RPM and a feed rate of 100 mm/min, providing a better balance between thrust force and delamination, which appears to improve drilling quality under the tested conditions.

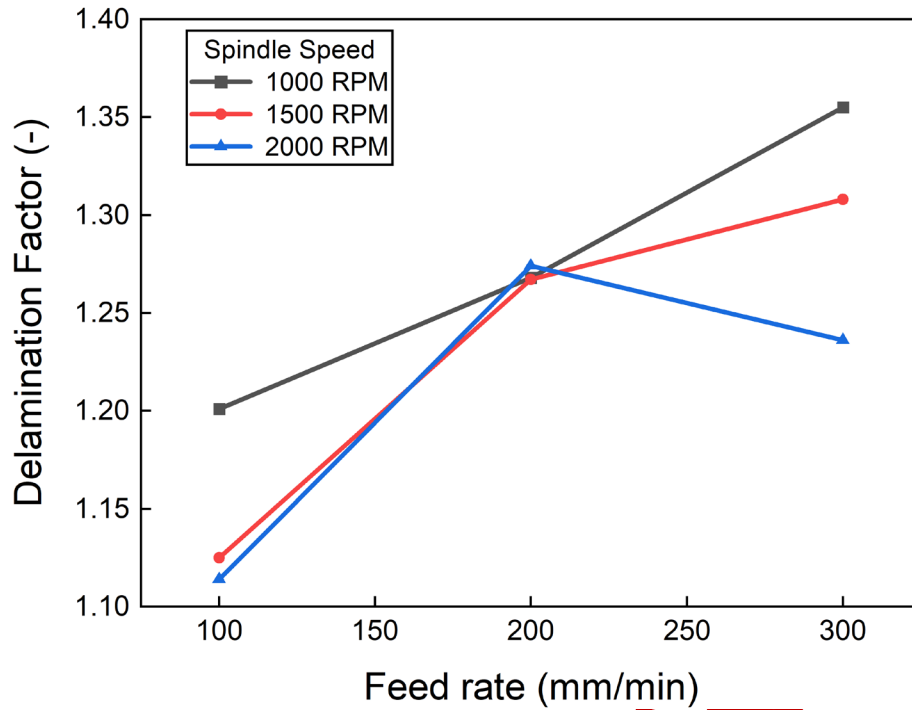


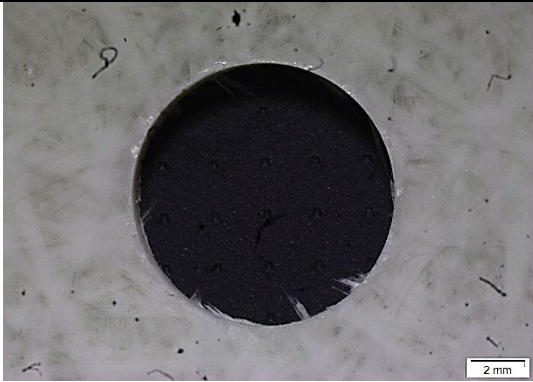
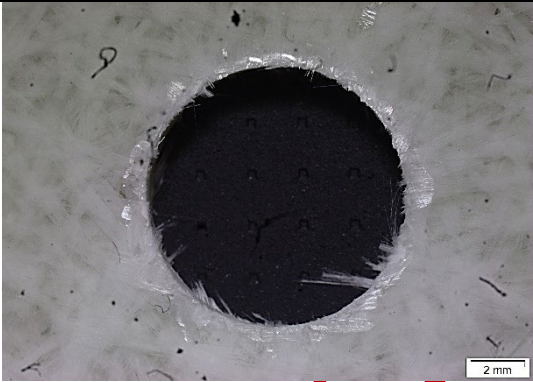
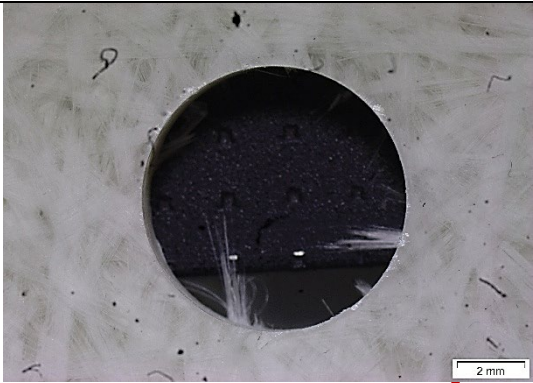
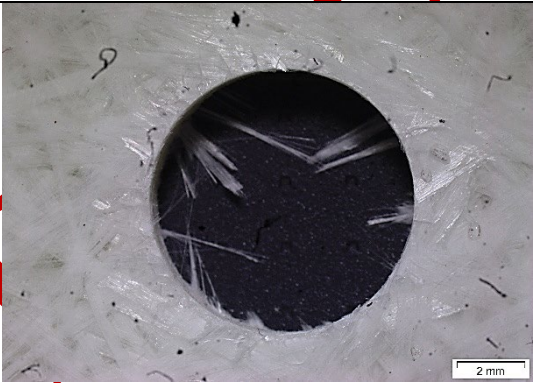
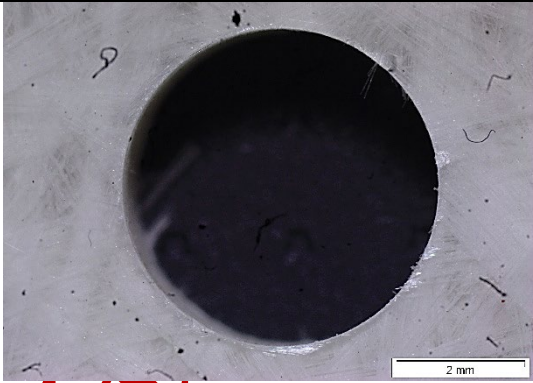
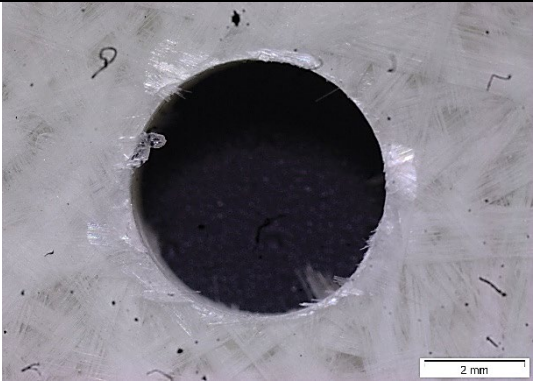
Fig. 9: Variation of delamination factor with feed rate at different spindle speeds for a drill diameter of 5 mm

Table 2 presents representative micrographs showing best and worst drilling conditions for each drill diameter. The best conditions (1500 RPM, 100 mm/min for 10 mm; 2000 RPM, 100 mm/min for 8 mm and 5 mm) show minimal delamination, while the worst conditions (1000 RPM, 300 mm/min) display severe fiber pull-out and matrix damage. These images provide visual confirmation of the quantitative results discussed above.

The analysis of delamination factors in GFRP composites indicates that cutting parameters such as spindle speed, feed rate, and drill diameter strongly influence hole quality. The results show that increasing spindle speed reduces the delamination factor, which can be explained by the lower drilling force. At higher rotational speeds, less friction exists between the drill and the material, thus reducing thrust force and limiting fiber pull-out and laminate delamination. Arhamnamazi et al. reported that increasing spindle speed in laminate machining helps reduce delamination [16], and Nassar et al. similarly observed that higher spindle speeds improve hole quality and reduce damage [24].

Conversely, an increase in feed rate was found to elevate the delamination factor. Higher feed rates demand greater thrust forces, which increases the risk of fiber pull-out from the hole periphery and causes more significant delamination. Chadha et al. demonstrated that lower feed rates result in reduced delamination in GFRP drilling [8], and Manickam et al. also confirmed that optimizing feed rate is essential to minimize delamination [25].

Table 2 Representative micrographs of drilled holes under best and worst conditions for drill diameters of 10 mm, 8 mm, and 5 mm.

Dia	The best	The worst
10 mm	 S1500 F100	 S1000 F300
8 mm	 S2000 F100	 S1000 F300
5 mm	 S2000 F100	 S1000 F300

The increase in delamination at higher feed rates can further be attributed to elevated thrust forces that accelerate interlaminar crack initiation and propagation, while lower spindle speeds may promote matrix softening due to thermal effects. These thermo-mechanical interactions have been highlighted in recent studies on GFRP drilling, which show strong sensitivity of delamination to tool geometry and cutting conditions [26]. Statistical modeling using response surface methodology and ANOVA confirms that feed rate and drill diameter are among the most influential parameters governing delamination [27]. More recent work employing ANFIS-based prediction and optimization also reinforces the dependence of delamination on spindle speed, feed rate, and drill geometry, providing

practical pathways to minimize damage [28]. These reports support the present findings, wherein higher feed rates and larger diameters are directly linked with increased delamination.

The observed delamination behavior can also be explained by machining mechanics and established failure mechanisms in fiber-reinforced polymers. At higher feed rates, thrust force promotes interlaminar crack propagation, fiber–matrix debonding, and fiber pull-out, which together contribute to higher delamination. In contrast, increasing spindle speed reduces the cutting force per unit area and induces partial matrix softening, facilitating smoother chip formation and reducing resistance at the tool–workpiece interface. These effects are consistent with reported peel-up and push-out delamination mechanisms in FRP composites, particularly at the entry and exit zones of the drill [26–28].

Drill diameter also plays an important role in delamination behavior. Smaller drill diameters (e.g., 5 mm) consistently resulted in higher delamination, which can be attributed to stress concentration effects at the hole boundary. Geometric discontinuities amplify local stresses, increasing the likelihood of fiber–matrix debonding and crack initiation. Fiber bridging a toughening mechanism where pulled fibers cross the delaminated zone and resist crack opening may further influence delamination propagation in layered composites [31–32]. Larger drill diameters, on the other hand, distribute cutting forces more evenly and reduce stress concentration, yet they generate higher overall thrust forces that can promote delamination under high feed rates. These mechanical effects are consistent with previous findings [27,29–31]. Behera et al. demonstrated that smaller diameter holes are prone to higher stress concentrations near the edges [29], and Vipani et al. also reported that stress concentration around smaller holes increases delamination due to localized forces [30].

Overall, a comparative analysis of different drilling conditions revealed that combinations of high spindle speed and low feed rate produced the lowest delamination factors across all diameters. These findings suggest that favorable conditions for minimizing delamination involve careful balancing of spindle speed and feed rate, together with appropriate drill geometry. In practice, this indicates that optimizing cutting parameters is essential to enhance hole quality and reduce delamination in GFRP composites.

4. Conclusion

This study experimentally investigated the effects of spindle speed, feed rate, and drill bit diameter on delamination during drilling of randomly oriented chopped strand mat glass fiber/polyester composites. The results confirmed that feed rate was the dominant factor influencing delamination, while drill diameter also had a strong effect and spindle speed exhibited a smaller but noticeable influence.

It was observed that delamination decreased with increasing spindle speed and with lower feed rates. The most favorable parameters for minimizing delamination were identified for each drill diameter under the tested experimental conditions. For the 10 mm drill bit, the optimum parameters were 1500 RPM and 100 mm/min. For the 8 mm drill bit, 2000 RPM and 100 mm/min gave the best results, while for the 5 mm drill bit, 2000 RPM and 100 mm/min minimized delamination.

Overall, employing higher spindle speeds combined with lower feed rates consistently resulted in reduced delamination across all drill diameters. These findings provide practical guidance for selecting suitable drilling conditions in GFRP composites to achieve improved hole quality and structural reliability.

In addition to these findings, the results have important practical implications for industries such as aerospace, automotive, and marine structures, where GFRP components are widely used. Minimizing delamination through optimized drilling parameters can improve hole quality, ensure structural integrity, and enhance the reliability of assembled parts. Future work will extend the present study by incorporating statistical design of experiments (DOE) and ANOVA to confirm the significance of the observed effects, as well as advanced imaging techniques such as SEM to further investigate microstructural damage mechanisms.

Conflict of Interest

The authors declare that they have no known conflicts of interest or personal relationships that could have appeared to influence the work reported in this paper. No financial or non-financial benefits have been received from any third party for the submission of this manuscript.

Data Availability Statement:

The data supporting the findings of this study are available from the authors upon request.

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