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Fatigue Strength of Drilled Glass Fiber/epoxy Laminates for Bone Fracture Fixation

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Highlights

- This paper focuses on drilling of epoxy-reinforced glass fiber laminates.
- Various drill bits were used.
- Effects of drilling parameters on thrust force and torque were analyzed.

ArticleInfo

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Abstract

The metallic bone fracture fixation plates are progressively being replaced by epoxy-reinforced glass fiber laminates (ERGFL) due to a higher strength-to-weight ratio and near neat shape manufacturing. Bone fracture fixation laminates are required to sustain the cyclic load due to the physical movement of the body. Therefore, the characterizations of glass fiber/epoxy laminates with drilled holes are important to study. Despite extensive research on the mechanical characterization of composite laminates, several unique circumstances remain unexplored, such as the characterization of glass fiber/epoxy laminates with drilled holes. The drilling laminates weakened the laminates' mechanical strength and damaged the area around the drilled hole. With Jo drill point designs, the greatest thrust forces (0.56 kN) were observed at 2800 rpm of cutting speed and 0.19 mm/rev of feed rate. Among the various drill points used, the drilled ERGFL laminates with Jo drill had the maximum fatigue life cycle of 87×10^3.

1. INTRODUCTION

Polymer matrix composites are found in many everyday products. Nowadays, fiber-reinforced polymer matrix composites are widely used in several applications as a result of their excellent properties like lightness and higher strength and hardness. The superior corrosion resistance and high strength compared to weight ratio of composites make them useful in a variety of industries, including automotive, aerospace, marine, civil, and biomedical ones [1-4]. The reinforcement mixed into the epoxy matrix improves tribological and mechanical properties compared to the original matrix. In polymer-reinforced composites, synthetic and natural fibers are mixed into polymer-based matrix materials for the fabrication of composite [5-7]. Studies and research on the usage of natural fibres have been prompted by the high cost of synthetic fibres for aerospace and military applications. In comparison to conventional fibres, natural fibres provide several benefits such as biodegradability, renewable, non-toxicity, flammability, and high specific characteristics [8-10]. Hybrid composites are made with a single matrix material and a variety of fibres. Hybrid composites are superior to traditional composites because of their special features. It has been reported that fibrous substrates such as cotton, bamboo, and curauá have mechanical, electromagnetic, and antistatic properties [11-13]. Polyaniline (PANI) has recently become more popular in the manufacture of electronic composites and has gained popularity due to its electrical properties. Advanced development also

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*Corresponding author: e-mail: gupta_291@rediffmail.com includes transition metal additives because they act as redox-active catalysts, helping to increase capacity and speed. The NiO_2, MnO_2, and σ-Fe_2O_3 were used as metal oxide additives in composites for PANI-based electrodes [14]. The development of special carbons has been increasing in many areas for several decades. Carbon is also considered one of the potential materials because of its conductivity and it became a suitable material for combined electrical and mechanical equipment. Stainless steel and other aerospace materials have recently been substituted by carbon fibre reinforced plastics (CFRP) because of their superior strength-to-weight and stiffness-to-weight ratios, good damping, and low heat dissipation [15-17].

Epoxy-reinforced glass fiber laminates (ERGFL) are widely used in bone fracture fixation plates because they have outstanding properties, such as high ratio of strength to weight, design flexibility, and parts dimensional constancy [18-20]. As the demand for ERGFL increases, it is essential to study the damage induced during the hole-making process for these materials. As per the current manufacturing technology, the bone fracture fixation laminated product cannot be made directly by any means. Individually manufactured laminates by the primary manufacturing process are consequently joined to get the final parts. The joining of laminates by using mechanical means requires drilling operations to make holes in laminates [21]. Wang et al. reported that vibration drilling produces less thrust than traditional drilling when drilling carbon fiber-reinforced plastic composite, glass fiber-reinforced plastic composite, and printed circuit boards using carbide and HSS drill [22]. Xiong et al. discussed the impact and fatigue behavior of unstructured and structured CFRP laminates. It was found that the fatigue process occurs mainly in fatigue damage formation and expansion stages [23, 24]. Bourchak et al. investigated carbon fibre reinforced plastic laminates under static and fatigue stresses using sonic emission as a damage monitoring tool [25]. According to the study, the damage shown by ultrasonic C-scans and microscopy was connected with acoustic emission energy in terms of damage, position, and aggregation, demonstrating stages of effective disintegrate prior to catastrophic failure. A longitudinal assessment of acoustic energy revealed that significant intralaminar and interlaminar damage started to occur as early as twenty seven percent of the tensile strength. Acoustic energy, stress-strain curves, ultrasonic C-scans, and microscopic examination of static and fatigue test specimens all show a good correlation with it. Singh and Bhatnagar investigated how drilling parameters affected drilling-induced damage in composite materials made of fiber-reinforced plastic [26]. The outcome shows that drilling-induced damage is greatly influenced by the cutting speed-to-feed ratio. The strength of CFRP under monotonic and cyclic loading conditions was investigated by [27]. Weak fiber-matrix interfacial adhesion laminates were shown to have more residual strength (up to 32%) than laminates with good fiber-matrix adhesion under monotonous loading [27]. Non-uniform GFRP composites' bending fatigue behavior under static and fatigue circumstances was investigated by Khashaba et al. The ultimate flexural strength of GFRP specimens with notches was discovered to decline linearly with increasing diameter [28]. The static and fatigue strength of pin-loaded laminates is reduced by subpar performance. The impact on compressed laminates' strength is less noticeable. In their study, Lei et al. made predictions on the behaviour of short fibre doped composites in both cyclic and monotonic loading scenarios [29]. The authors discovered a correlation between the deterioration behaviour of the modulus and the fatigue life using a synergistic prediction approach. Najd et al. determined the fatigue threshold of polymeric composites by using self-heating techniques, namely electrical capacitance measurements and monitoring temperature changes [30]. A link was established between the fatigue limit and the measurement of damage in polymer matrix composites (PMCs). Koloor et al. conducted research on the fatigue damage of cyclic cohesive zone interfaces in polymeric composites [31]. They found that the damage caused by interlaminar shear follows a sigmoidal pattern in the evolution curve. Rakesh and his colleagues investigated the drilling characteristics of unidirectional composite laminates subjected to uniaxial stress conditions [32]. According to the paper, the damage that comes from drilling is affecting the remaining strength of composite laminates. In a separate investigation [33, 34], the author observed that the damage that comes from drilling also affects the remaining strength of the drilled composite laminates when subjected to bending and compression. However, according to the authors' knowledge, there are limited investigations done on the drilling behaviour of composite laminates under cyclic loading circumstances. Hence, the current investigation focused on examining the fatigue durability of epoxy laminates with drilled holes subjected to cyclic loading conditions.

2. MATERIAL METHOD

The hand-layup technique was used to manufacture GFREL laminates. The epoxy (Araldite LY556 with hardener HY951) and woven glass fibers mat were used as matrix and reinforcement materials for the fabrication of composites. The laminates were cured for 24 hours at room temperature. The GFREL laminates were drilled at various operating conditions, including rpm of spindle, feed rate, and drill point geometry with a 4 mm diameter. The feed rate was chosen as 0.12, 0.19, and 0.3 mm/rev, and the spindle speed was set at 1120, 1800, and 2800 RPM. The author's already reported study on the optimization of process parameters and drill point geometry [34]. Based on the authors opinion, the drilling parameters were chosen for study. The drill bits that were used as 4 mm diameter. Figure 1 shows the drill point geometries that were chosen for drilling. During the drilling of the GFREL, the thrust force and torque signals were recorded using a drill dynamometer (Kistler, model 9272) as illustrated in Figure 2. Figure 3 depicts the schematic illustration of the composite laminates used for testing as per ASTM standard E606 for low cycle fatigue, as well as the composite laminates that experienced failure following testing.

Figure 1. *Drill point geometry [34]*

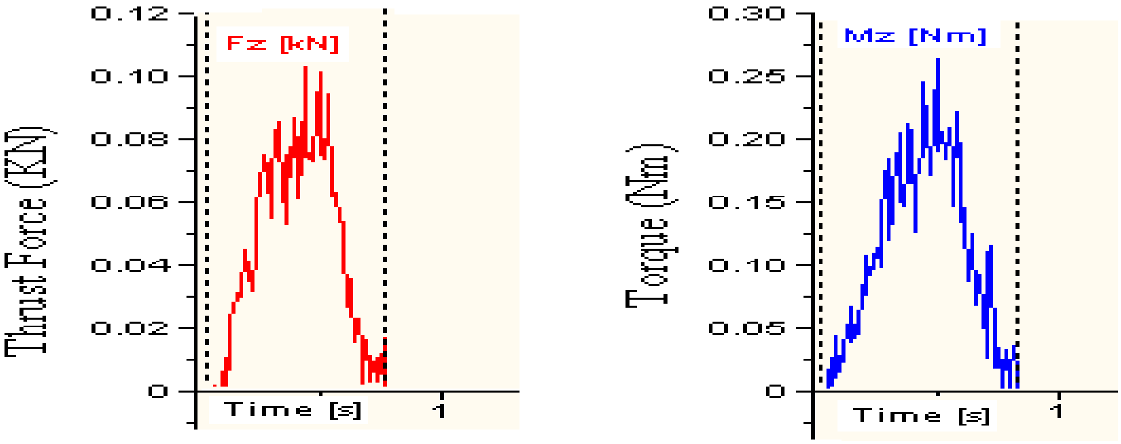

Figure 2. *Drilling forces with Jo drill (spindle speed: 1800 rpm, feed rate: 0.3mm/rev)*

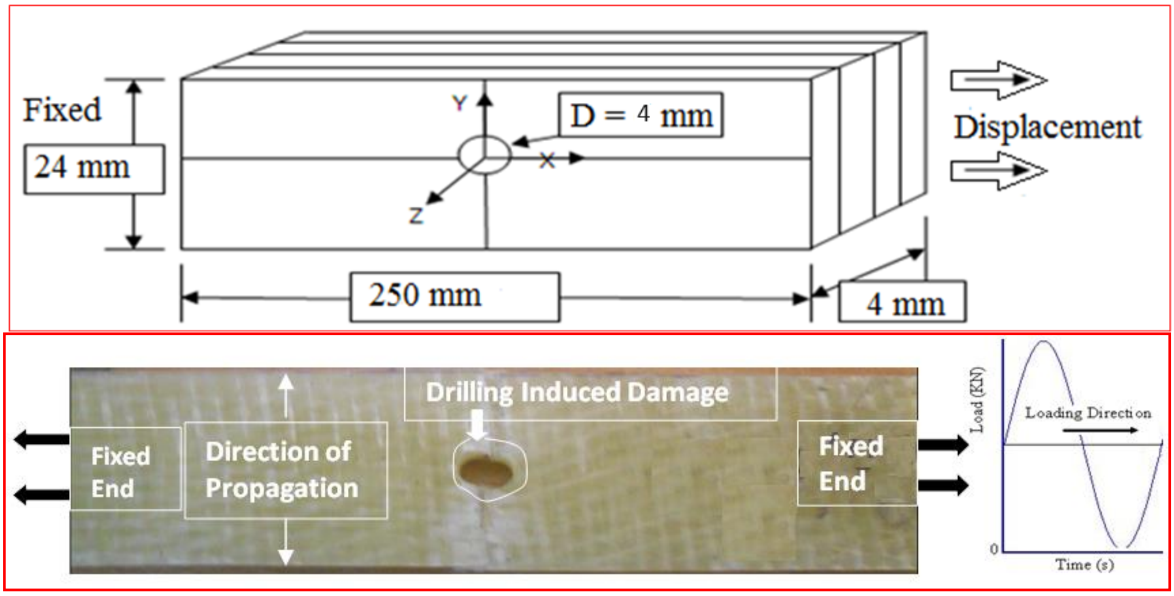

Figure 3. *Schematic representation of sample size and failed composite laminate*

3. RESULTS AND DISCUSSION

The response surface method's (RSM) suggested test design entails gathering the necessary information to ascertain which elements have the biggest influence on the product with the least number of tests. Analysis of variance (ANOVA) was used to evaluate experimental error and determine the relative impact of failure criteria. Table 1 shows the main results of the selection process on the fatigue failure. SEM micrograph of the wall pierced GFREL is shown in Figure 4. The results of GFREL's fatigue tests with a drilled hole are shown in Figure 5.

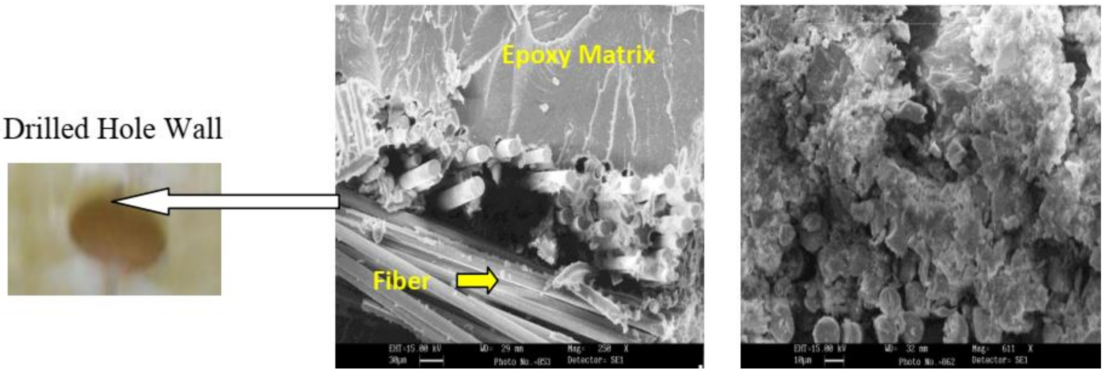

Figure 4. *SEM micrograph of drilled hole wall*

Table 1. *Drilling Process Parameters of GFREL*

Run	**Geometry**	**Feed Rate (mm/rev)**	**Speed (RPM)**	**Torque (Nm)**	**Thrust Force (KN)**	**Thousands of Cycles (10^3)**
1	Jodrill	0.12	1800	0.12	0.07	87
2	Parabolic	0.19	1800	0.25	0.12	62
3	Parabolic	0.12	2800	0.16	0.12	63
4	Twist drill	0.19	1120	0.20	0.11	75
5	Jodrill	0.19	1120	0.14	0.07	85
6	Parabolic	0.19	1800	0.25	0.12	61
7	Twist drill	0.12	1800	0.17	0.11	73
8	Jodrill	0.19	2800	0.15	0.56	79

9	Parabolic	0.19	1800	0.25	0.13	62
10	Twist drill	0.30	1800	0.20	0.12	63
11	Parabolic	0.30	2800	0.22	0.15	62
12	Jodrill	0.30	1800	0.26	0.10	80
13	Parabolic	0.12	1120	0.26	0.15	61
14	Parabolic	0.19	1800	0.25	0.14	62
15	Parabolic	0.30	1120	0.24	0.13	60
16	Twist drill	0.19	2800	0.19	0.11	61
17	Parabolic	0.19	1800	0.25	0.13	62

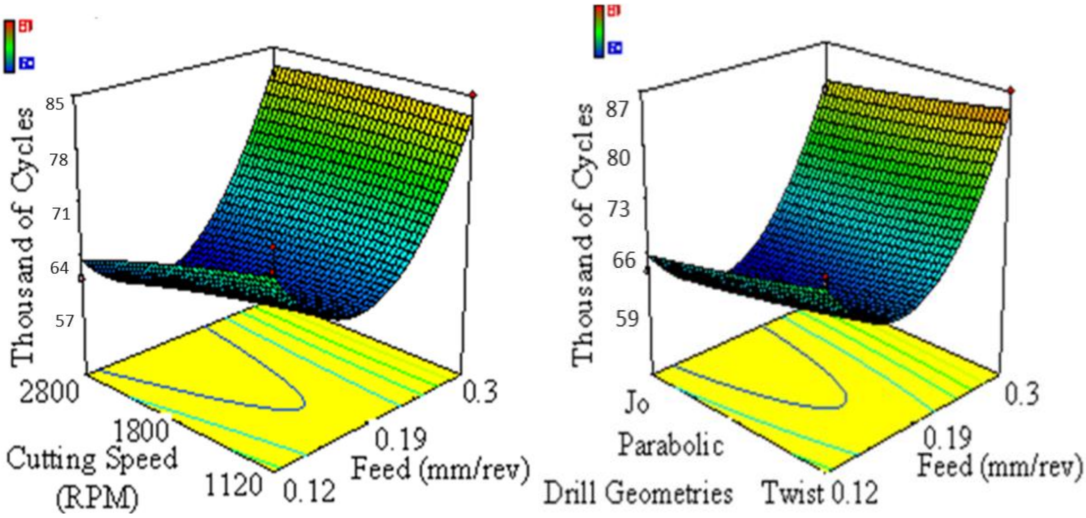

Figure 5. *Effect of drilling process parameters on the fatigue behavior*

Drilling holes in laminate is well recognized to result in harm to the immediate area around the hole. Jo drills inflict less damage when drilling compared to twist and parabolic drills. The Jo bit has a sleek cutting edge that effortlessly penetrates the laminate material. The drilling process has two parts: first, the drill tip creates a tiny hole, and subsequently, other actions are used to widen the hole. Rakesh et al. observed similar results [34]. Hence, it can be concluded that the Jo drill provides the most favorable circumstances when operated at a feed rate of 0.12 mm/rev at a spindle speed of 2800 RPM. This suggests that the combination of the highest spindle speed and the lowest feed rate results in the minimum thrust force. Among Jo and parabolic drills, the twist drill has the highest levels of thrust force and torque. Among the three geometries under consideration, Jo drill is deemed the most optimal given the perfect conditions. Figure 5 demonstrates that the Jo drill obtains the highest number of failure cycles (83×10^3) while drilling GFREL at a cutting speed of 1800 rpm and a feed rate of 0.12 mm/rev. At a cutting speed 1120 rpm and feed rate 0.3 mm/rev, the parabolic drill had the fewest failure cycles (60×10^3). The highest recorded thrust forces are obtained when drilling using Jo drill geometry at 2800 rpm and 0.19 feed rate. The drilling process with Jo drill geometry at a cutting speed of 1800 rpm and a feed rate of 0.12 results in the least amount of thrust forces. It can be inferred that the Jo drill produces holes in the GFREL laminates without causing damage. Consequently, drilling with the Jo drill geometry resulted in the maximum fatigue strength. The fatigue strength of FRP laminates has an inverse correlation with the damage caused by drilling. The findings underscore the need of optimizing drill geometry in order to minimize drilling damage. Recent research has shown that the drilling parameters have an impact on both the drilling force and the resulting damage [26, 29]. Hence, the fatigue strength of a drilled hole laminate is directly proportional to the reduction in drilling damage. Figure 6 displays scanning electron microscope (SEM) images of the fatigue failure of GFREL laminates.

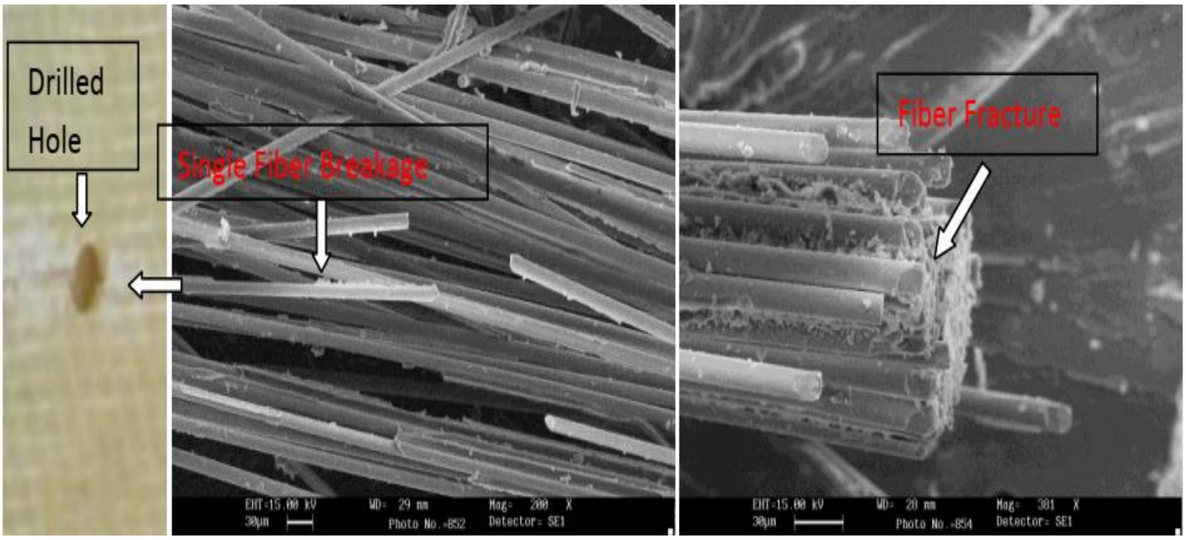

Figure 6. *SEMmicrographs of GFREL (fiber fracture due to fatigue loading)*

Figure 6 shows that drilling-induced damage is a major failure in fatigue loading.It is controlled by the properties of the matrix and the fiber.The cracking starts from the damagedregions,which comprise a matrix of micro-cracks and micro-voids. Hence, damage is initiated quicklyafter a minimum number of fatigue cycles, notably forlow and adequateintensities of the enforcedweight or dislocation.The propagation happensparticularly at the fiber/matrix interfaceregions.

4. CONCLUSIONS

The fatigue behavior of the drilled GFREL laminates has been investigated under several working settings, including spindle speed, feed rate, and drill point form. The extent of damage caused by drilling is affected by the operational conditions, which in turn affect the magnitude of the thrust forces. The drilling process has a substantial influence on the fatigue performance of laminates due to the resulting damage. The GFREL laminates with Jo drill had the greatest number of cycles till failure among other drill geometries. Through the process of removing the bond between the fibre and matrix, the failure propagates uniformly over the whole width of the drilled hole. Subsequently, the fibres begin to deteriorate. The Jo drill shape may be recommended for drilling epoxy-reinforced glass fibre laminates to repair bone fracture laminates.

CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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