Finite element analysis of drilling-induced damage responses on FRP hybrid bio/composite laminates

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Abstract. Machining/drilling is crucial in the joining process of composites. However, drilling composite materials often leads to hole dimensional inaccuracy, surface roughness and delamination, among others. These drilling-induced damage (DID) responses are associated with torque and thrust (principal drilling forces), and rampant in fibre-reinforced polymeric (FRP) hybrid bio/composite laminates. Therefore, a three-dimensional (3D) numerical approach, using finite element method (FEM) was undertaken to analyse the DID responses of FRP hybrid bio/composite laminates. Drilling simulation was performed at spindle velocity and feed rate of 3000 rpm and 5 mm/s, respectively. Both thrust force and torque were produced, computed and interpreted. From the results obtained, it was evident that drilling of synthetic (glass, G and carbon, C) FRP hybrid composites demanded higher or substantial torque and thrust forces, due to their superior strengths, exemplified by the $(2G+2F)_{13}$ samples, when compared with the weaker natural/plant (flax, F; jute, J and hemp, H) FRP hybrid bio/composites, especially $(J+F)_{27}$ samples. In addition, the investigation established the advantages of dual layup methods over single arrangements. Carbon and glass FRP hybrid composites exhibited excellent hybridisation properties, but their brittleness necessitated careful management of torque and thrust forces to prevent high DID responses. Summarily, this investigation provided a guide for FRP hybrid bio/composites design and drilling, in addition to opportunities for additional research on other process parameters towards further study.

1 Introduction

The imperative role of drilling in modern manufacturing necessitates a better understanding of its mechanics, particularly in emerging field of composite materials. Finite element analysis (FEA) is indispensable for assessing drilling-induced damage (DID) responses. Therefore, this study aimed at leveraging FEA methodology to comprehensively and comparatively analyse the drilling behaviours of various fibre-reinforced polymeric (FRP) hybrid bio/composite laminates. This study addressed crucial DID responses, including delamination, surface roughness, stress and temperature distributions, as associated with the principal drilling forces (thrust force and torque). Besides, by incorporating both synthetic (carbon and glass) and natural (flax, hemp and jute) fibres into FRP hybrid bio/composites, significant enhancements in mechanical properties have been studied [1-3], underscoring the importance of studying their DID responses. The proposed finite element models facilitated predictive insights into DID responses, offering valuable data on delamination, stress, temperature profiles and thrust force and torque signals crucial for optimising drilling processes in composites manufacturing [4-6]. Proficiency in finite element modelling and simulation, using industry-standard software packages, such as ABAQUS, ANSYS and LS-DYNA was pivotal for the successful execution of this present study, ensuring robust analysis and accurate prediction of DID responses from various FRP hybrid bio/composite laminate samples with difference ply stacking sequences.

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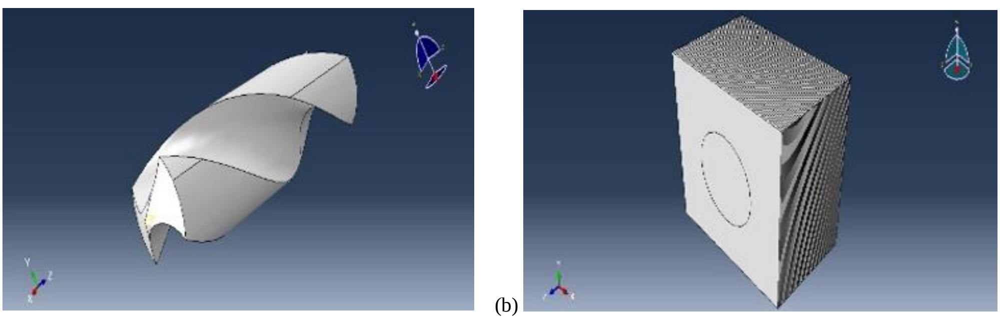
2 Computer-aided designs

2.1. Drill bit and FRP hybrid composite laminates

The intricately computer-aided design (CAD) of drill bit was carried out using CATIA (Fig. 1a), while the workpiece, a simple rectangular prism was modelled in ABAQUS (Fig. 1b), with a foundational 12 x 12 mm sketch extruded to a thickness of 7.58 mm. The workpiece comprises 54 layers, each has a thickness of 0.5 mm, alternating between jute and flax epoxy layers, organised using a datum plane set of 0.5 mm from the top and bottom, facilitating the layering technique within the solid. At the corners of each solid layer, a datum coordinate system was established, guiding the orientation of composite layers within the workpiece, and ensuring precise alignment and structural integrity. The CATIA-designed drill bit with a diameter of 10 mm was imported into ABAQUS without undergoing wear or stress analysis, treated as a rigid object. Discrete rigid option was used, due to its role solely in machining process. Employing the conversion shell element tool, the solid drill bit was transformed into a surface element, recognising its critical role of outer shape when cutting the workpiece, thus necessitating the conversion.

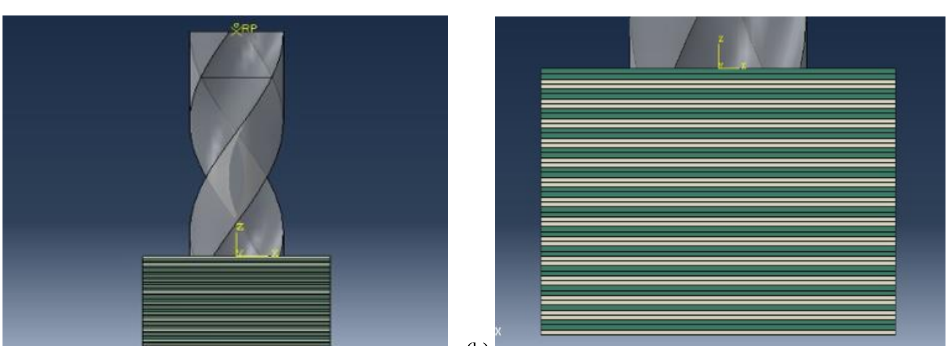


(a) (b)

Fig. 1. CAD of the (a) geometric drill bit (b) workpiece/composite used.

2.2. Ply stacking sequences

The ply stacking sequence of the various FRP hybrid bio/composite laminate samples was careful constructed, using a layup method. This was essential to figure out how composite layers were arranged and aligned (Fig. 2). Fibres of jute, flax, carbon and glass were designated as J, F, C and G, respectively. From Figs 2(a) and (b), combinations in (J-F)$_{27}$, (J-C)$_{27}$, (J-G)$_{27}$, (F-C)$_{27}$, (F-G)$_{27}$, (2F-2J)$_{13}$, (2F-2C)$_{13}$, (2F-2G)$_{13}$, (2J-2C)$_{13}$, (2J-2C)$_{13}$, (G-C)$_{27}$, (C-G)$_{27}$, (2G+2C)$_{13}$ and (2C+2G)$_{13}$ identified the 10 specified layup sequences. The hybridisation showed a sophisticated understanding of material properties and mechanical behaviours of the samples. The configuration of the flax and jute fibres in (J-F)$_{27}$, for example, was intended to optimise the torque and thrust requirements for drilling operations by balancing the flexibility of flax with inherent strength of jute.



(a) (b)

Fig. 2. Drilling setup of (a) (J-F)$_{27}$ and (b) (2F-2J)$_{13}$ FRP hybrid biocomposite laminate samples.

2.3. Boundary conditions, mesh sensitivity and simulation

The composite sample was immobilised at all four ends, using encase function of ABAQUS, which prevented the translation or rotation of the workpiece over the prescribed surfaces. At tip of the drill bit, a reference point (RP) was created to calculate the feed rate along with cutting speed. The drill bit could only move in the feed axis, because it was restricted from moving in both *x* and *y* directions. ABAQUS established these boundary limits, involving RP. Using the ABAQUS element library, C3D8R 3-D brick element was chosen. To ensure that the results of the FEM were without regard for the element mesh size, a mesh convergence study was carried out. First, a bigger mesh size was used, and it was gradually reduced after each iteration until smaller decrease was no longer significantly affected the results. A steady spindle velocity of 3000 rpm and a feed rate of approximately 5 mm/sec were used in this drilling simulation. A coarser mesh having a size of 1.25 mm was used outside the drilling zone, while a final mesh dimension of 0.2 mm was used close to the hole [4-6], as depicted on the mesh convergence study (Fig. 2a).

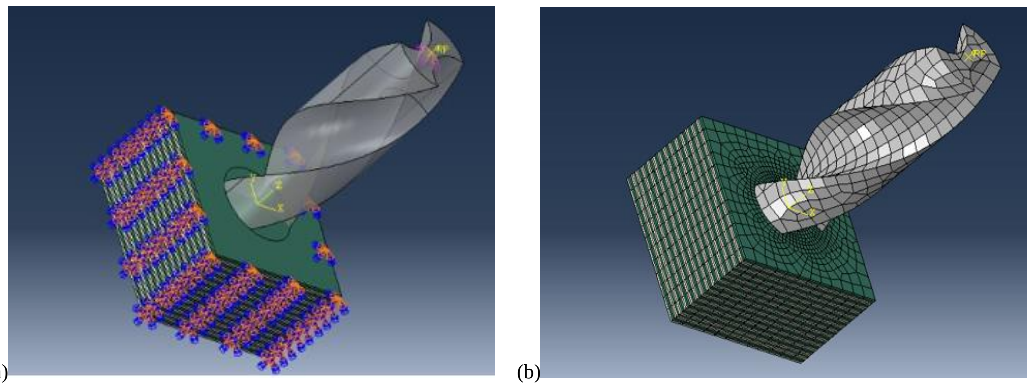

(a) (b)

Fig. 3. (a) Boundary conditions of composite laminate and (b) mesh view of drill bit used.

3 Results and discussion

The stress distribution over the FRP hybrid bio/composites is presented in Figs 4-6, as exactly at 1.5 seconds during drilling operation. At this time, majority of the stress was obtained on the $(F\text{-}J)_{27}$ layup sample (Fig. 4a). A maximum stress of 12.9 MPa was identified inside the workpiece, with the greater stress localised within the $(F\text{-}J)_{27}$ layup configuration. A large tension was built up in the immediate neighbourhood of the drilled hole. This observation highlighted the localised influence of drilling operation.

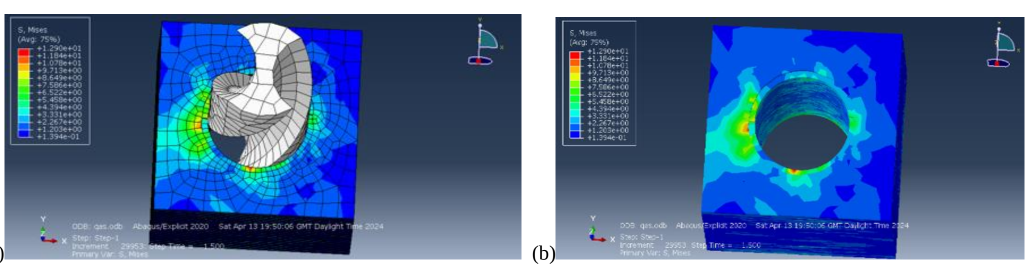

(a) (b)

Fig. 4. Stress on (J+F) hybrid biocomposite laminate sample (a) during and (b) after drilling simulation at 1.5 sec.

Comparatively, the synthetic single (G+C)27 sample recorded a higher maximum stress of 20.17 MPa when compared with its dual sequenced (2G+2C)13 counterpart with a maximum stress of 12.96 MPa (Fig. 5). These results were similar to (C+G)27 and (2C+2G)13 composite laminate samples with maximum stresses of 20.88 and 18.72 MPa, respectively (Fig. 6). The results obtained during drilling operation implied that stress distribution depended on types of reinforcements or fibres and stacking sequences of the bio/composite plies.

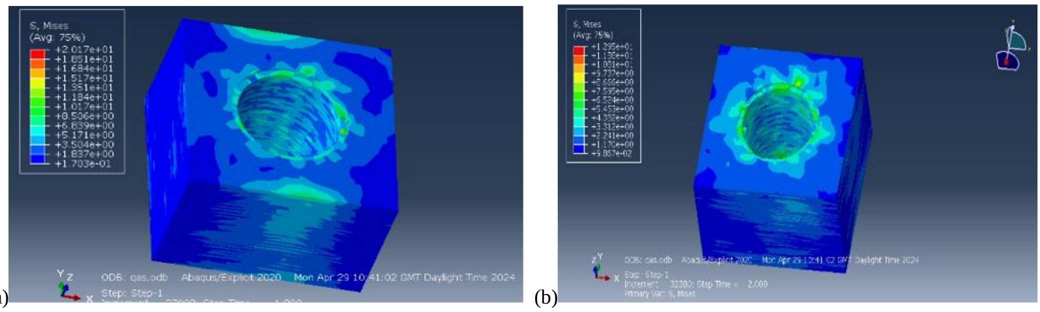


Fig. 5. Stress acting on (a) $(G+C)_{27}$ and (b) $(2G+2C)_{13}$ composite laminate samples.

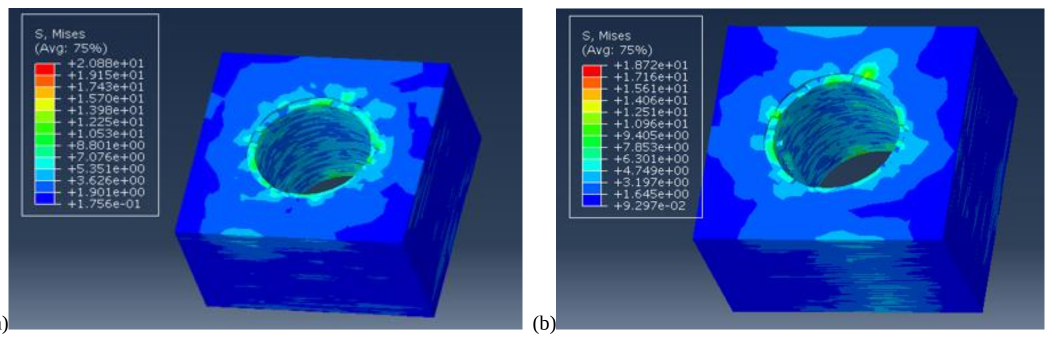


Fig. 6. (a) Stress acting on (a) $(C+G)_{27}$ and (b) $(2C+2G)_{13}$ composite laminate samples.

Besides, the thrust force required for different layup combinations in the hybrid composite materials showed significant differences between natural and synthetic FRP samples. Natural FRP hybrid biocomposites, being less strong, required less thrust force during drilling process, as exemplified by the 33 N needed for $(J+F)_{27}$ samples (Fig. 7). In contrast, drilling of synthetic/natural FRP counterparts, especially flax and glass fibres $(F+G)_{27}$ required higher thrust force of 48 N, due to their superior strengths. This illustrated how material composition directly impacted the drilling performance, with stronger materials require greater thrust force for drilling through the samples.

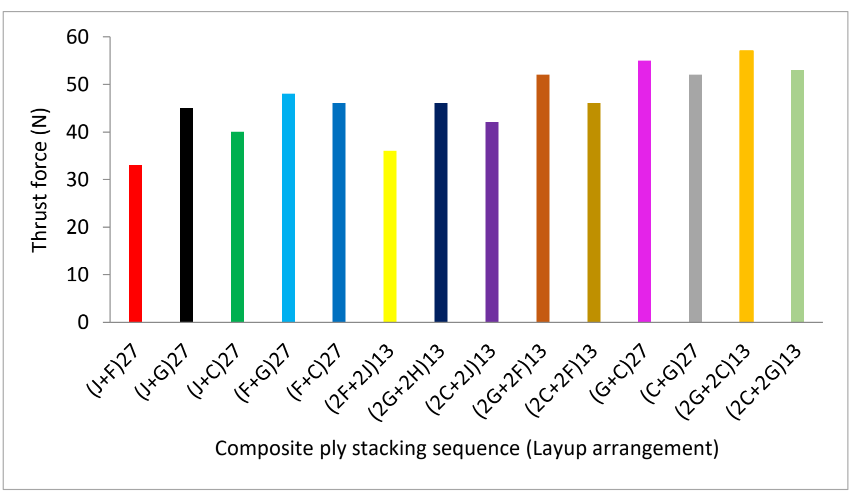


Fig. 7. Thrust forces of various FRP hybrid bio/composite samples with different ply stacking sequences.

Additionally, comparison of single and dual layup methods offered new insights into the dynamics of composite material strength. Dual layup $(2F+2J)_{13}$ and $(2F+2G)_{13}$ samples demonstrated an enhanced strength properties and required higher thrust forces of 36 and 52 N respectively, indicating their superior structural integrity when compared with the single sequenced $(F+J)_{27}$ and $(F+G)_{27}$ samples. More importantly, the maximum thrust forces of 55 and 57 N were recorded by the synthetic single $(G+C)_{27}$ and dual sequenced $(2G+2C)_{13}$ samples, respectively. The natural/plant single $(J+F)_{27}$ and $(J+F)_{27}$ and dual $(2F+2J)_{13}$ samples recorded 33 and 36 N, respectively. Summarily, these results showed differences in the principal forces required to drill single and double natural+natural, natural+synthetic and synthetic+synthetic FRP hybrid bio/composite laminate samples (Fig. 7). The aforementioned trends were comparable to their torques, as subsequently elucidated.

Similarly, the responses highlighted notable differences in the torque required for drilling different layup composite samples. For instance, the $(J+F)_{27}$ laminated composite sample, with lower strength, required torque of 12 N-m. In contrast, double and stronger layup configurations, such as $(2G+2F)_{13}$ produced significantly more (double) torque of 24 N-m during drilling operation (Fig. 8). This underscored the importance of layup arrangement and material choice against drilling performance. Moreover, the relative strength and durability of FRP hybrid composites were evident when comparing required torque across various layup combinations. Configurations with a higher percentage of stronger materials, such as glass fibres, showed an increased torque requirement, reflecting their improved ability to withstand drilling forces. Conversely, layup combinations with weaker materials, such as natural fibres required lower torque (Fig. 8), highlighting their relative inferior mechanical properties. It should be noted that high critical thrust force and torque, which were respectively produced from feed rate and cutting speed mainly responsible for the drilled hole dimensional inaccuracy, surface roughness and delamination of several FRP composites [1-3].

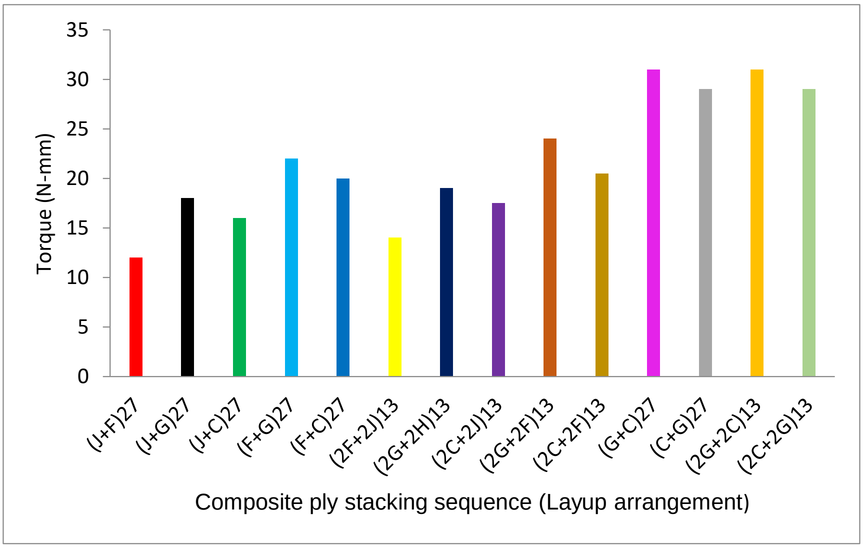


Fig. 8. Torques of various FRP hybrid bio/composite samples with different ply stacking sequences.

This study leveraged the ABAQUS software to maintain methodological rigour, employing precise geometry parameters, boundary conditions and meshing techniques to ensure robust simulation outcomes. Through a comprehensive investigation of various materials and layup procedures, drilling performance on FRP hybrid bio/composites was explored in-depth, offering clear insights into material dynamics. The critical data analysis involved meticulous recording and evaluation of torque and thrust force data, serving as pivotal indicators for assessing drilling stresses and composite performance. This facilitated informed decision-making and strategic design optimisation. Furthermore, by examining the thrust force and torque requirements across different layup techniques, this present study provided essential engineering insights that guide enhancements in composite performance. Clear graphical representations of the recorded data aided the concise presentation and understanding of complex findings. The iterative improvement process driven by these insights could lead to enhanced durability and efficiency in hybrid composite manufacturing.

In addition, this investigation contributed significantly to the advancement in composite material technology by deepening the understanding of drilling performance. This understanding informs future innovations, ultimately improving the overall quality and applicability of composite materials in various engineering fields. Through this rigorous and comprehensive approach, findings obtained through this study cannot only advance theoretical knowledge, but also have practical implications for the design and manufacturing/drilling of robust FRP hybrid composite structures. This research underscores the importance of methodological precision and data-driven analysis to enhance hybrid composite durability. By leveraging advanced simulation techniques and comprehensive experimentation, profitable way for innovation and improvement in composite material applications is paved.

4 Conclusion

This study has successfully employed numerical simulations, using ABAQUS to investigate into the drilling process of FRP hybrid bio/composite materials. Significant differences in thrust and torque requirements between synthetic and natural/plant FRP hybrid composites were established. Synthetic FRP hybrid composite laminate samples recorded higher thrust forces, due to their superior strengths, as exemplified by the $(2G+2F)_{13}$ lamination composite samples, which required substantial or higher thrust and torque when compared with the weaker $(J+F)_{27}$ layup counterparts.

More also, the research highlighted the advantages of dual layup methods over single layup arrangements, emphasising how combination of different materials enhanced strength characteristics and their drilling performances. Despite the strengths of both synthetic and natural FRP hybrid composites, considerations of cost and resource availability are crucial, with glass and flax identified as the most affordable and accessible materials.

Moreover, while carbon and glass FRP hybrid composites exhibited excellent hybrid properties, their brittleness necessitated careful management of thrust forces to prevent significant DID responses. The abundance of natural and synthetic materials presents vast opportunities for further research into composite materials. Advanced simulations can predict and optimise their mechanical properties, but these findings must be validated experimentally to ensure accuracy and reliability.

Finally, experimental validation is recommended to provide critical data to refine simulations, fostering the development of durable, reliable engineering solutions. The ply layup/stacking sequences of FRP hybrid composites significantly impacted their machining performances, which may be similar to variations in their fibre orientations. Therefore, detailed experimental planning and investigation into the effects of fibre orientations with/without ply layup/stacking sequences of FRP hybrid composites can be studied. These techniques will enable researchers to determine the optimal torque and thrust forces for effective machining/drilling, ultimately enhancing the understanding and drilling performance of FRP hybrid bio/composite structures.

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