Finite Element Analysis on Conventional Drilling of Natural Fibre-Reinforced Polymer Bio-composites

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Abstract. Finite element analysis (FEA) on conventional drilling of two bio-composite materials, consist of hybrid woven flax-basalt and woven basalt fibre with vinyl ester matrix, designated as composite materials A and B respectively, has been conducted. The simulation results using LS-DYNA and ANSYS software depict that different reinforcements (flax and basalt fibres) of the composite materials significantly influenced the degree of resistance, strength, deformation and elasticity exhibited during the machining process. It was observed that drilling-induced damage were experienced in different degrees by the materials. The quality of the holes produced was affected by the characteristics of these materials, when experimentally validated. Also, significant differences in tensile strength and impact of the drilling operation on the plies of the two materials were observed. Material A experienced higher stress and lower tensile strength, resulting into a higher level of push-out delamination, uncut-fibre and fibre pull-out, among other rampant drilling-induced damage, than material B. Both materials possessed high stress and deformation, which were more at the edges (entry and exit) of the drilled holes rather than the centre point where the drill impacted the hole. The equivalent elastic strain further shows a high level of impact at the surface of material A, unlike material B. Comparatively, the composite material B (woven basalt fibre reinforced polymer) has a better machinability when compared with hybrid material A (woven flax-basalt). Hence, it implies that the FRP composite materials responded to damage differently under same machining (drilling) process and condition.

Keywords. Bio-composite materials, finite element analysis, woven flax and basalt fibres, drilling-induced damage; tensile strength, quality of hole.

1. Introduction

The growing application of bio-composite materials has further increased the focus of manufacturing research on machinability of these heterogeneous and biodegradable materials. Drilling is an inevitable, a most frequently used and final principal machining operation during manufacturing processes in several industries [1]. The drilling process of bio-composite materials highly determines the quality of their holes. The recent advancement in the field of composites manufacturing technology has necessitated the application of the finite element analysis (FEA). The FEA has been well used in various engineering sectors to analysis the drilling and materials property behaviours of several solid structural components, usually under a well-defined stresses or forces, heat and vibration, essentially in aerospace industries. The use of finite element analysis or model has become prominent in composite technology, based on its capability of defining the quality impact of machining process on composite materials. The application of FEA on drilling of natural fibre-reinforced polymer (FRP) composites has several benefits, prominently, in manufacturing (drilling) industries.

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Drilling process is performed under the action of drilling (or cutting) forces: thrust force and torque, mainly. The drilling phenomena of some metals and alloys [2], metal matrix composites [3] and synthetic types of FRP composite materials: glass and carbon have been deeply studied using FEA, statistical and experimental methods [4-6]. In addition, the magnitude of thrust force and torque (drilling forces) as well as their signals generated during the synthetic composites drilling [4], the discrete damage modes of delamination or damage area [1, 7, 8], surface roughness [8], stress and temperature distributions [9] have been investigated.

Recently, the natural FRP composites have been gaining acceptance as an alternative materials to the synthetic FRP composites, especially for non-structural applications. This is due to their inherent desirable properties such as sustainability, renewability, cost effectiveness, biodegradability and ease of production, to mention but a few. These properties in addition to the aforementioned benefits of FEA have prompted further analysis of the natural composites using FEA method. Based on the published literature available till date, research on the FEA on drilling of natural FRP composite materials has not been reported or very scarce. Hence, this study presents FEA on convectional drilling of a hybrid woven flax-basalt and woven basalt-fibre with vinyl ester matrix bio-composite materials.

2. Finite element modelling

The FEA model was implemented to reflect the complexity of the drilling process including the chip geometry. The pre-processing phase involved the consideration of the various parameters including element selection, material properties and boundary conditions, followed by selection of a suitable LS-DYNA solver and MSC Patran pre-processor tool. LS-POST was used for the visualisation and display of the final simulation results.

2.1 Drill bit modelling

The tungsten-carbide drill bit was modelled (Figures 1) and simulated, having the cutting speed of 1700 rpm. The model of the bit includes a diameter of 10 mm, point angle of 118^{o}, web thickness of 0.9 mm and at helix angle of 30^{o}. The drill bit was discretised with 1237 nodes of the 4367, 4-noded tetrahedral elements.

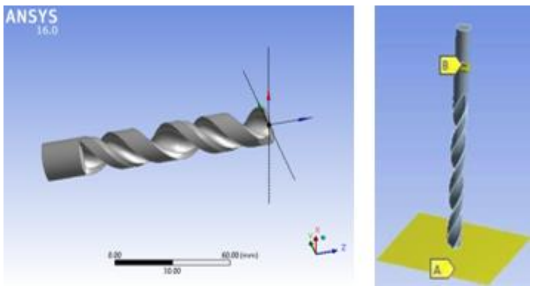


Figure 1. Drill bit model.

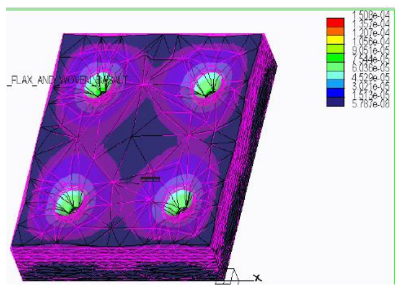


Figure 2. Modelling of the meshed material.

2.2 Material modelling

The two different materials were constructed in three phases. The individual layer was built. Two units of equal dimensions were stacked together to build the total material (Figure 2). This was done with the specification of the materials and the matrix. This enabled the formation using the layer thickness for the individual specimen. The materials were simulated by making the composites set at the rectangular cross-section, uniform along the length and breadth, and parallel distributed. The matrix phase was set as a perfect adhesion, continuous and isotropic, and homogeneous between the constitutive phases were set.

3. Experimentation (materials and method)

Materials A and B were used for the experiment, for the purpose of validating the simulation results. The mechanical properties of the materials are depicted in Table 1. Each material has 11 layers, as shown in Figure 3.

Table 1. Mechanical properties of the composite materials.

Property	Material A	Material B	Vinyl ester matrix
Layers orientations	Longitudinal	Longitudinal	Longitudinal
Young's Modulus (GPa)	50 - 70	89	3.6
Ultimate tensile strength (GPa)	1.440	4.84	0.085
Density (g cm^{-3})	1.4-1.5	2.6 – 2.8	1.17

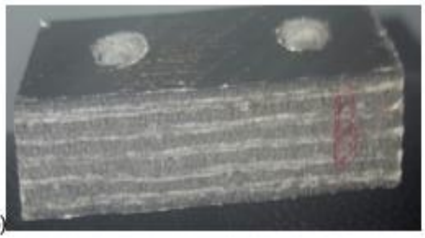
(a)  (b) 

Figure 3. (a) Material A and (b) material B, after drilling operation showing their ply layers.

The basalt fibres were fabricated in a continuous process. Basalt fabric yarns are woven from the continuous filament of basalt. The yarns are manufactured to a different level of weight, thickness and weave pattern. The basalt materials were placed inside a furnace with the use of gravity feeding using a bushing, before placed inside a single continuous filament basalt fibre strand.

Each of the material samples A and B has a dimension of 66.0 x 65.7 x 12.6 mm. The drilling operation was conducted on a HURCO VM 10 CNC machine centre, using a tungsten-carbide HSS drill bit diameter of 10 mm, cutting speed of 53.4 m/min, feed rate of 0.1 mm/rev and spindle revolution of 1700 rpm, without coolant. These parameters were equally used for the FEA/simulation, when drilling all the four holes.

4. Results and discussions (simulation)

4.1 Deformation and equivalent stress

The simulation results obtained from the FEA show a significant impact of drilling operation on the materials A and B. Material A has a minimum and maximum directional deformations of -5.199×10^{-7} mm and 0.19225 mm respectively, while material B has a minimum and maximum directional deformations of -35.000 mm and 1.2317 x 10^{-7} mm respectively. The total deformation of materials A and B are 35 and 30.13 mm respectively. This is attributed to the higher modulus of 89 GPa of Material B compared with material A of 60 GPa. Therefore, it shows that material B has a higher resistance to deformation. The equivalent stress results obtained show that a significant stress was developed after the drilling has been performed for over 80 seconds. This is similar to both materials. . A steady rise in equivalent stress was observed immediately after 120 seconds. This shows that consistent application of drilling forces on both materials increased the stress on them. Material A has a minimum and maximum values of 2.8388 x 10^{-11} and 2.469 x 10^{-2} MPa respectively, while material B has a minimum and maximum values of 2.64 x 10^{-12} and 3.44 x 10^{-2} MPa respectively.

4.2 Displacement and deformation

Figure 4 shows that at a hole depth around the centre of the materials, the drill exerted higher stress and strain, consequently caused more deformation. In addition, the surface roughness at surface around the drilled holes demonstrated the high possibility of stress at the beginning of the drilling operation. This could cause a peel-up delamination, burr formation, fibre pull-out and uncut (Figure 4a), among others. This is indicated by highest values of displacement and deformation occurred in material A, when compared with materials B. More also, it depicts that both materials have a highest stress concentration near their hole centres, as depicted in Figures 4(a) and (b).

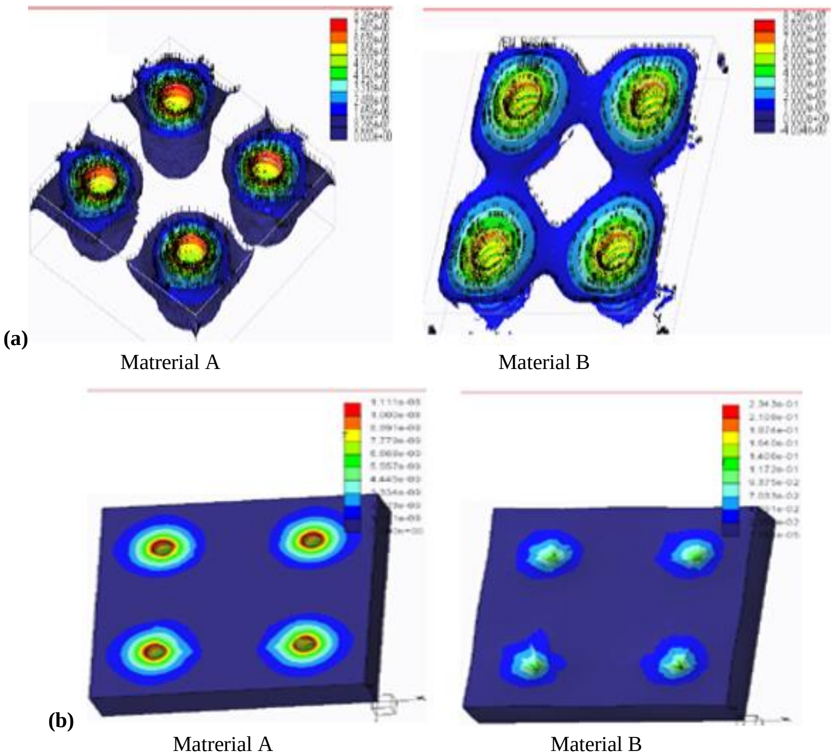


Figure 4. The simulation results of a conventional drilled holes of both materialsshowing (a) displacement and (b) deformation.

4.3 Equivalent elastic strain

The equivalent elastic strain helps to determine the variation in the stress impact of the drilling process on the materials. From the simulation results, the effects of the forces impacted by drilling on the materials show that the extreme strain was induced at the edges of both materials, but greater in material A. In addition, it is evident that the minimum elastic strain occurred at a region around the drilled hole, with values of 6.1372 x 10^{-22} and 4.8339 x 10^{-23} in materials A and B respectively. It is imperative top know that the area around the drilling exhibited a limited elastic strain across the layers. Materials A and B have maximum equivalent elastic strain of 2.7782 x 10^{-7} mm/mm and 7.2082 x 10^{-7} mm/mm, as shown in Figures 5(a) and (b) respectively.

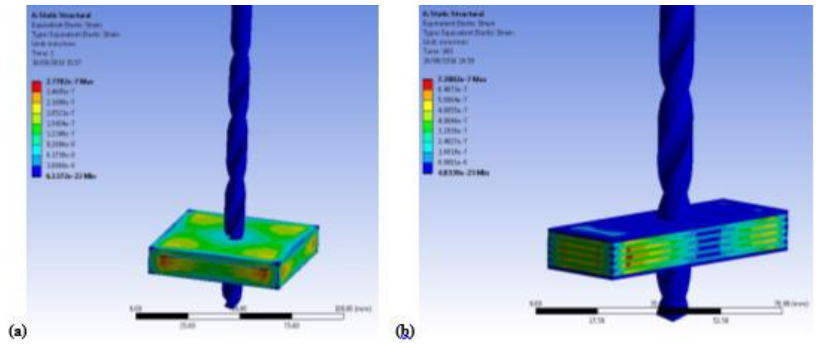


Figure 5. The FEA of a conventional drilling of (a) material A and (b) materials B, showing their equivalent elastic strains.

The equivalent elastic strain was low, showing a little impact at the initial stage of the drilling operation. However, there was a steady increase in the elastic strain immediately after the time was over 120 seconds. Importantly, the strain was more pronounced around the entire material A (Figure 5a). Conversely, the strain was not felt at surface of material B (Figure 5b), it was significantly felt at edges of each layer of both materials. The centre of the layers experienced the lowest strain.

4.4 Experimental validation

Figure 6 shows the experimental results of the drilled materials. It is observed that there was no much deformation or damage visually appeared on the holes of material B. It implies that the drilling forces have little or no significant impact on the integrity and total quality of the drilled hole of material B, as depicted in Figure 6. However, all the four holes of material A have a greater visible drilling-induced damage. The higher degree of damage on composite material A compared to material B can be attributed to the presence of hybridisation in material A, in addition to woven pattern of the flax/basalt fibre orientation within the laminates. Furthermore, hybridisation of material properties in a single sample affected the machinability of material A, as the two fibres responded differently under the same shearing or drilling conditions. Comparatively, flax fibres possess a lower mechanical properties when compared with basalt fibres. These properties include, but are not limited to, density, flexural and tensile strength, specific and Young's moduli, load bearing capacity and elongation to break, which tend to affect the overall performance of material A under drilling forces.

Matrerial A Material B

Figure 6. The experimental results of a conventional drilling of both materials.

5. Conclusions

The FEA results of this study, validated experimentally, have established that hybrid woven flax-basalt (material A) and woven basalt fibre (material B) with vinyl ester matrix bio-composite materials exhibited characteristics that depict the properties of their constituent fibre elements. The FEA modelling provided an opportunity to compare the effect of drilling on the two different materials A and B, showing a significant difference in tensile strength and impact of the drilling on the layers of the materials. Material B exhibited higher tensile strength than material A. In addition, the finite element model showed a high level of directional deformation in material A, while this impact was minute in material B. The equivalent elastic strain further revealed a higher level of impact at the surface of material A, when compared with material B. It was evident that delamination and its resultant poor quality of holes were much in material A than material B. This is attributed to the presence of hybridisation and flax fibre in material A as well as higher mechanical properties (ultimate tensile strength, density and Young's Modulus) of material B.

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