Proceeding Paper

Finite Element Study on Coconut Inflorescence Stem Fiber Composite Panels Subjected to Static Loading †

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Abstract: Natural fiber-reinforced composites (NFCs) are alternatives to synthetic fiber-reinforced composites, since they are abundant in nature, inexpensive, lightweight, and have a high strength-to-weight ratio. Natural fibers encompass a diverse composition, including lignin, hemicellulose, wax, and cellulose. Natural fibers are environmentally friendly, biodegradable, renewable, reusable, and sustainable. In bio-composites, natural fibers such as jute, banana, hemp, coir, areca nut, and coconut inflorescence stem fibers, are blended with resin. Natural fiber-reinforced bio-composites have various applications in the construction industry, automobile industry, aerospace industry, sports equipment and gadgets, textile industry, and hotel industry. Fibers from natural sources are also used as reinforcements in composites, such as roofing sheets, bricks, door panels, furniture panels, and panels for interior decoration. The mechanical properties of natural fiber-reinforced composites are profoundly influenced by the bonding between the fibers and the matrix. This study involves the testing of compact tension (CT) specimens under mode I fracture conditions and employs three-dimensional finite element analysis (FEA) using ANSYS software to enhance our understanding of the material’s fracture behavior. Finite element analysis was performed on coconut inflorescence stem fiber-reinforced composite (CIFRC) panels with preformed cracks. Numerical simulation was carried out using ANSYS software. Properties such as crack growth initiation, stress-intensity factor, and stresses along the length of a CIFRC panel were examined using finite element analysis (FEA). ASTM D-5045 standards were followed for the specimen size and the ASTM E399 standard was followed for the finite element pre-cracking. The simulation results were found to be in good agreement with the analytical results.

Keywords: natural fibers; composite; coconut inflorescence stem fiber; crack growth initiation; stress-intensity factor; finite element analysis

1. Introduction

The pursuit of high-performance materials in modern research extends beyond mechanical properties to encompass environmental and economic considerations. As part of this endeavor, extensive research is being conducted on renewable and eco-friendly materials, with a particular focus on natural fiber-reinforced composites. These composites,
comprising natural fibers and matrix materials, hold great promise due to their sustainable origins. Natural fibers are abundantly sourced from various parts of plants, including leaves, stems, flowers, and fruits. Notable examples include flax, jute, and hemp (stem-derived fibers), and banana sisal, kenaf, and henequen (leaf-derived fibers). Among these, coir fibers, extracted from coconut fruit, play a significant role. Natural fibers encompass a diverse composition, including lignin, hemicellulose, wax, and cellulose. Their use in structural and non-structural applications is gaining traction for several compelling reasons. Natural fibers offer cost-effectiveness, almost comparable strength to synthetic fibers, and reduced health hazards [1–4].

The mechanical properties of natural fiber-reinforced composites are profoundly influenced by the bonding between the fibers and the matrix. One effective strategy for enhancing this bonding is through chemical treatment of the fibers. Such treatment involves the removal of impurities and contaminants from the fibers, leading to improvements in their quality. Researchers [5–8] have demonstrated that alkali treatment, typically employing a 5–10% NaOH solution, is highly effective for fibers like sisal, banana, areca nut husk, and coconut. A. Widnyana et al. conducted a study on coconut fibers treated with a 6% NaOH solution, revealing a tensile strength of 130.9 MPa in single-fiber tensile tests, while composite panels made from coconut fibers achieved 24.5 MPa. Similarly, R. Subramanya et al. explored the tensile, impact, and fatigue behavior of treated and untreated banana fibers soaked in a 10% NaOH solution for approximately 6 h. The results showed significant improvements in tensile and impact properties for treated fibers, with tensile strength reaching 18.25 MPa compared to 15.74 MPa for untreated fibers. Impact strength also improved, with values of 0.14 J/m and 0.11 J/m observed for treated and untreated banana fiber composites, respectively. Notably, the fracture toughness of treated fiber composites exceeded that of the untreated counterparts, indicating the positive impact of fiber treatment on mechanical properties.

Mohammed et al. conducted compact tension tests on composite structures and simulated using finite element methods. The authors intended to study the initiation and propagation of cracks as sequential stages of fracture. FE modeling was used to determine the critical energy release rate, and then experimental data was used to validate. A finite element method was found to be a good technique for predicting crack propagation during the failure of composite laminates. Previous authors concluded that by using this FEM approach, not only were initiation and propagation energy release rates correctly predicted, but the fracture history of laminates was shown by FEM contours with 97% accuracy [9]. M. Arfan et al. conducted a study where they applied finite element analysis to investigate the behavior of woven bamboo and kenaf fibers under quasi-static loading conditions, specifically focusing on notch opening angles and mode I stress intensity factors (SIFs). In their simulation, they explored three different woven orientations: $0^\circ/90^\circ$, $30^\circ/-60^\circ$, and $45^\circ/-45^\circ$. The research revealed that kenaf fibers with a $0^\circ/90^\circ$ orientation exhibited notably strong characteristics when compared to bamboo fibers. Moreover, among the three weave orientations studied, both bamboo and kenaf fibers with a $0^\circ/90^\circ$ orientation demonstrated the highest stress intensity factors, followed by those with $30^\circ/-60^\circ$ and $45^\circ/-45^\circ$ orientations [10].

In summary, composite materials, especially those reinforced with natural fibers, can significantly reduce the weight of aircraft and spacecraft components. Natural fiber-reinforced composites could be used in structural elements, reducing the overall weight of buildings, and potentially making construction processes more eco-friendly. These materials can help reduce the weight of vessels, contributing to better fuel efficiency and lower environmental impact. Natural fiber composites align with sustainability goals as they are biodegradable and can be disposed of more responsibly at the end of their life cycle and can be used in the development of new composite materials or the exploration of novel applications in industries like renewable energy or sports equipment manufacturing.

This research aims to further explore these improvements by investigating the crack growth and stress intensity factor of a composite material comprising short coconut
inflorescence stem fibers and cashew nutshell resin. The study involves the testing of compact tension (CT) specimens under mode I fracture conditions \[11,12\] and employs three-dimensional finite element analysis (FEA) using ANSYS software to enhance our understanding of the material’s fracture behavior \[13,14\].

2. Materials

Composite materials were prepared using coconut inflorescence stem fibers as reinforcement and cashew nutshell liquid resin (CNSL) as a matrix. Cashew nutshell liquid resin is a natural polymer obtained from the pressing of cashew nut shells. It is a renewable resource and has excellent mechanical properties. It is also highly resistant to water and has a low thermal conductivity \[15–18\]. Coconut inflorescence stem fibers are an abundantly available natural fiber with excellent mechanical properties. They are lightweight and possess a high tensile strength, making them an ideal material for use as a reinforcement in composite materials. The fibers also have excellent thermal insulation properties, making them useful for insulation applications.

Composite specimens reinforced with natural fibers were prepared as per the American Society for Testing and Materials standards (ASTM D5045) \[19\]. The dimensions of the specimen considered for study are shown in Figure 1. This composite specimen was used for the analysis of crack growth and stress intensity factors.

3. Finite Element Modeling

Modeling

Geometry creation, import, and assumptions: The three-dimensional compact tension (CT) composite model was created using AutoCAD software, as presented in Figure 1. The model was created as per ASTM D5045 standards. The specimen’s width (W) and breadth (B) were 50 mm and 12.7 mm, respectively, for the present study. The ASTM standards define all other parameters based on the ‘W’, such as total specimen width of 62.5 mm, total specimen height of 60 mm, fixture hole diameter of 12.5 mm, and pre-crack length ‘a’ of 13.7 mm.

In this work, straight-through notch specimens were used as per ASTM E399 standards \[20\]. The simulation was performed with ANSYS Workbench. Figure 2 illustrates that the three-dimensional model file was imported into the workbench. This study assumes that the materials in the composite panels behaved in a linearly elastic manner, either of
the isotropic material properties for the composite and perfect interfacial bonding between
the layers of the composite.

![Figure 2. Three-dimensional model of CT specimen.](image)

Mesh generation: A tetrahedron mesh was generated by inserting an automatic
method with elements of 1mm size demonstrated in Figure 3. Edges at the crack tip
were selected and sphere influence-type meshing was performed with an element size of
0.5 mm. After meshing, the three-dimensional compact tension (CT) model consisted of
1,914,334 nodes and 1,404,228 elements.

![Figure 3. Meshed geometry in ANSYS Workbench.](image)

Crack initialization and smart crack growth simulation: A fracture tool was used to
provide pre-meshed crack coordinates for the compact tension composite model, and a
smart crack growth simulation was used to run a static simulation. A static simulation
was performed to analyze the behavior of the compact tension composite specimen un-
der the applied load. The simulation calculates stress distributions, displacements, and
other relevant mechanical responses. A smart crack growth simulation was utilized to
monitor the propagation of the pre-defined crack during the analysis. The simulation
tracks how the crack grows and its influence on the stress distribution within the speci-
men. Table 1 summarizes the material properties of the three-dimensional compact tension composite model.

**Table 1.** Mechanical properties of coconut inflorescence stem fiber-reinforced composite panel.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \rho ) (kg/m(^3))</td>
<td>1934.8</td>
</tr>
<tr>
<td>( E ) (MPa)</td>
<td>2337.7</td>
</tr>
<tr>
<td>( \nu )</td>
<td>0.31</td>
</tr>
<tr>
<td>( \sigma_T ) (MPa)</td>
<td>18.25</td>
</tr>
<tr>
<td>Critical stress intensity factor (KIC)</td>
<td>318.22 MPa mm(^{0.5})</td>
</tr>
</tbody>
</table>

Boundary conditions: The present work proposes a three-dimensional compact tension model that was subjected to static load. Load (\( P \)) was applied at the upper fixture hole in the positive y-axis direction and a fixed-end support was applied at the lower fixture hole to represent a clamped boundary condition as demonstrated in Figure 4.

![Figure 4](image)

**Figure 4.** A schematic representation of boundary conditions.

Load application: A point load with a magnitude of 400 MPa was applied at the upper fixture hole to simulate external loading. This load represents the force applied to the specimen.

### 4. Results and Discussion

**Finite Element Analysis**

A static structural module was used to study the fracture toughness, stress intensity factor, and crack extension of composite panels. The crack growth and stress variation along the length of composite panels are shown graphically in Figures 5–8. The deformed shape, stress contour, and stress intensity factor shapes are shown in Figures 6 and 9.

In Figure 5, the natural fiber-reinforced composite panel shows a linear change in crack extension after 0.6s, and the maximum crack extension for the coconut inflorescence stem fiber-reinforced composite (CIFRCs) panel was 1.66 mm at 1 s where a load of 2.22 kN was applied.
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**Figure 5.** Crack growth (mm) comparison with respect to time (s).

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From Figure 6, it can be observed that the stress intensity factor varies nonlinearly along the crack tip width in the CIFRC panel. Stress intensity factor values vary to a length of 14 mm. At the start, the stress intensity factor values increase up to a length of 1.5 mm, and after a 1.5 mm length, the stress intensity factor values decrease drastically up to a length of 3.5 mm. After 3.5 mm length, stress intensity factor values peak and keep oscillating up to a length of 9 mm; this was the region where fatigue cracks initiated due to static load. After a 9 mm length of crack width, the stress intensity factor continues to decrease up to 10.9 mm, and at 13.5 mm, fatigue cracks stop. Figure 10 shows the stress intensity factor along the crack tip width of a compact tension specimen model.

**Figure 6.** Crack growth (mm) comparison with respect to time (s).

**Figure 7.** Equivalent stress pattern of the coconut inflorescence stem fiber-reinforced composite.

**Figure 8.** Normal stress pattern of the coconut inflorescence stem fiber-reinforced composite.

**Figure 9.** Directional deformation pattern of the coconut inflorescence stem fiber-reinforced composite.
The stress patterns in the model are illustrated in Figures 7 and 8. As observed in the figures, stress concentration initially developed at the tip of the notch during the crack propagation, and the crack path was linear. Figure 9 shows the directional deformation patterns of the coconut inflorescence stem fiber-reinforced composite.

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In Figure 11, the graph illustrates the crack growth comparison of the natural fiber-reinforced composite material and structural steel material; it was observed that crack growth in natural fiber-reinforced composites started after a certain period of time, but the structural steel material displayed linear behavior from the propagation of crack extension on the application of load. The maximum crack extension for the structural steel material is 4.3 mm for a load of $1 \times 10^6$ kN.
where cracks were likely to initiate and propagate. Figure 9 provides insight into the directional deformation patterns of the coconut inflorescence stem fiber-reinforced composite. These patterns were essential for assessing the material’s response to external loads and designing structures that can withstand them. Figure 11 presents a comparison between crack growth in the natural fiber-reinforced composite material and structural steel material. The natural fiber-reinforced composite exhibits delayed crack initiation, suggesting that it may have a higher resistance to crack propagation under similar loading conditions.

Figure 10. Stress intensity factor along the width of crack tip of the coconut inflorescence stem fiber-reinforced composite.

Figure 11. Crack growth (mm) comparison with respect to time (s).

The graphical representation of crack growth over time in Figure 6 demonstrates that the coconut inflorescence stem fiber-reinforced composite panel exhibits a nonlinear response in terms of crack extension. The variation in stress intensity factor along the crack tip width, as shown in Figure 10, is significant. This variation reflects the complex interplay between material properties and the applied load. The region where stress intensity factor values peak and oscillate between 3.5 mm and 9 mm corresponds to the initiation of fatigue cracks due to static loading. Understanding this critical zone is essential for predicting and preventing structural failures.

Figures 7 and 8 depict the development of stress concentration at the tip of the notch during crack propagation. This concentration of stress was a critical factor in determining where cracks were likely to initiate and propagate. Figure 9 provides insight into the directional deformation patterns of the coconut inflorescence stem fiber-reinforced composite. These patterns were essential for assessing the material’s response to external loads and designing structures that can withstand them. Figure 11 presents a comparison between crack growth in the natural fiber-reinforced composite material and structural steel material. The natural fiber-reinforced composite exhibits delayed crack initiation, suggesting that it may have a higher resistance to crack propagation under similar loading conditions.
In contrast, the structural steel material displays linear behavior in crack propagation, where cracks extend more rapidly for a given load. The delayed crack initiation in natural fiber-reinforced composites implies that these materials may offer improved durability and reliability in applications where fatigue and crack propagation are concerns. This can be particularly relevant in the construction of lightweight structures, automotive components, or aerospace parts. The fact that natural fiber-reinforced composites can exhibit resistance to crack growth while being significantly lighter than structural steel suggests potential weight reduction benefits in transportation and aerospace industries [19,20]. This can lead to increased fuel efficiency and reduced environmental impact. The use of natural fibers in composites aligns with sustainability goals. These materials are renewable and have a lower environmental footprint compared to traditional synthetic fibers. Understanding stress patterns and crack propagation in these composites can aid in the design and engineering of structures that take full advantage of their unique mechanical properties. This can lead to innovative and efficient solutions in various industries [19,20]

5. Conclusions

The research findings on coconut inflorescence stem fiber-reinforced composite materials provide valuable information for material scientists, engineers, and industries looking to harness the benefits of sustainable, lightweight, and mechanically resilient materials. These insights can be applied to real-world scenarios, contributing to the development of safer, more efficient, and environmentally friendly products and structures. In this present study, finite element analysis was carried out to study the crack growth and stress intensity factor properties of a coconut inflorescence stem fiber-reinforced composite panel which was modeled as a compact tension specimen according to ASTM standards. In this study, the following properties were observed:

- The natural fiber-reinforced composite panel exhibited a distinct crack growth behavior. It displayed a delayed initiation of crack growth compared to structural steel when subjected to similar loading conditions. This delay suggests improved resistance to crack propagation, which is a crucial factor in enhancing the durability and reliability of materials in various applications.

- The analysis of the stress intensity factor along the crack tip width revealed a complex and non-linear pattern. Stress intensity factor values exhibited significant variation, with peak values occurring in a specific region (between 3.5 mm and 9 mm). This region corresponds to the initiation of fatigue cracks induced by static loading. Understanding this critical zone is essential for predicting and preventing structural failures in real-world applications.

- The stress patterns observed during crack propagation highlighted the development of stress concentration at the notch tip. This concentration of stress is a critical factor in determining the initiation and propagation of cracks. Additionally, the directional deformation patterns provided essential insights into how the material responds to external loads, aiding in the design of structures capable of withstanding such loads effectively.

- A noteworthy comparison was made between the crack growth behavior of the natural fiber-reinforced composite material and structural steel. The delayed crack initiation in the composite material suggests a potentially higher resistance to crack propagation, offering improved durability and reliability. Structural steel, on the other hand, exhibited linear crack propagation behavior under load.

Limitations of the study: This study assumes that the loading was static and does not consider dynamic loading, which might be more relevant for certain real-world applications. This study may not consider the effects of temperature and moisture variations, which can significantly impact the mechanical properties of natural fiber composites.
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