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Experimental and Numerical Investigation of Inclined Edge Cracks in Glass Fiber Reinforced Composite Cantilever Beams

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***Abstract*—Inclined edge cracks are among the most critical forms of damage in composite beam-like structures, as they influence both bending and torsional behavior and may lead to sudden structural failure if not detected at an early stage. Glass fiber reinforced composite (GFRC) beams are widely used in aerospace, automotive, and structural applications, where damage tolerance and reliability are of primary importance. This paper presents a detailed experimental and numerical investigation of the dynamic behavior of GFRC cantilever beams containing inclined edge cracks. Vibration-based damage detection is employed by analyzing changes in natural frequencies and mode shapes obtained through experimental modal analysis using an FFT analyzer and numerical modal analysis using the finite element method (FEM). The effects of crack depth, crack location, and crack inclination on the dynamic characteristics of the beam are systematically studied. The results demonstrate that natural frequencies decrease with increasing crack severity and that cracks located closer to the fixed end produce more significant frequency reductions. A good agreement between experimental and numerical results validates the effectiveness of the proposed methodology for non-destructive crack identification in composite structures.**

***Keywords*— Composite beam, Inclined crack, Vibration-based damage detection, Modal analysis, FFT analyzer, Finite Element Method.**

I. INTRODUCTION

Fiber reinforced composite materials have gained extensive acceptance in modern engineering applications due to their high specific strength, high stiffness-to-weight ratio, corrosion resistance, and design flexibility. These advantages have led to their widespread use in aircraft structures, automotive components, wind turbine blades, marine structures, and civil engineering applications. However, despite their superior mechanical performance, composite materials are susceptible to damage mechanisms such as matrix cracking, fiber breakage, delamination, and interfacial debonding.

Among various damage types, cracks play a particularly significant role because they introduce local flexibility and alter load transfer mechanisms within the structure.

Inclined edge cracks are especially critical as they affect both flexural and torsional responses, making damage detection more challenging compared to transverse cracks. If such damage remains undetected, it can propagate under cyclic loading and result in catastrophic failure.

Conventional non-destructive testing (NDT) methods, including ultrasonic testing, radiography, and acoustic emission techniques, are widely used for composite inspection. However, these methods often require costly equipment, skilled operators, and localized inspection. In contrast, vibration-based damage detection techniques offer a global and economical approach for assessing structural integrity by monitoring changes in dynamic characteristics.

This study focuses on the experimental and numerical investigation of inclined edge cracks in glass fiber reinforced composite cantilever beams using vibration-based techniques. The influence of crack depth, location, and inclination on natural frequencies and mode shapes is examined in detail, providing valuable insight into crack identification in composite structures.

II. CRACK THEORY AND DYNAMIC BEHAVIOR OF CRACKED BEAMS

Over Cracks in structural elements introduce local reductions in stiffness and modify stress distribution, resulting in changes in dynamic behavior. In vibration-based damage detection, cracks are often modeled as open cracks, assuming that the crack remains open during vibration. This assumption leads to a constant reduction in stiffness and a corresponding shift in natural frequencies.

Inclined edge cracks differ from transverse cracks in that they introduce coupling between bending and torsional modes. The severity of an inclined crack is influenced by several parameters, including crack depth, crack location, and crack inclination angle. The dynamic response of a cracked beam is governed by changes in flexural rigidity (EI), mass distribution, and boundary conditions.

The Euler–Bernoulli beam theory is adopted in this study to model the free vibration behavior of the cantilever beam.

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Although more advanced theories such as Timoshenko beam theory may account for shear deformation and rotary inertia, the Euler–Bernoulli model provides sufficient accuracy for slender composite beams under low-frequency vibration.

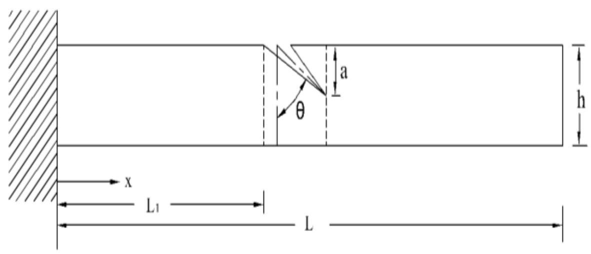

FIGURE I: SCHEMATIC REPRESENTATION OF INCLINED EDGE CRACK IN A COMPOSITE CANTILEVER BEAM.

III. METHODOLOGY

A. Specimen Preparation

Glass fiber reinforced composite beam specimens were fabricated using the hand lay-up technique. E-glass chopped strand mat was selected as the reinforcement material, while polyester resin was used as the matrix due to its cost-effectiveness and ease of processing. A mould release agent was applied to ensure easy removal of the cured laminate.

The fabrication process involved alternating layers of fiber mat and resin until the desired thickness was achieved. Manual compression was applied to remove air voids and ensure uniform thickness. The laminate was allowed to cure at room temperature for 48 hours.

The final dimensions of the composite beam specimens were:

- Length: 800 mm
- Width: 60 mm
- Thickness: 6 mm

Inclined edge cracks of controlled depth and inclination were introduced using a diamond cutter. Care was taken to maintain consistent crack geometry across specimens..

B. Experimental Modal Analysis

The experimental modal analysis was carried out to determine the natural frequencies and mode shapes of both uncracked and cracked composite beams. Each beam was rigidly clamped at one end to form a cantilever configuration.

An impact hammer was used to excite the beam with an impulse force, ensuring a broadband frequency input.

A piezoelectric accelerometer was mounted near the crack location to measure vibration responses. The force and response signals were processed using an FFT analyzer to obtain frequency response functions (FRFs). From the FRFs, the first three natural frequencies were extracted. Multiple tests were conducted to improve measurement accuracy and repeatability.

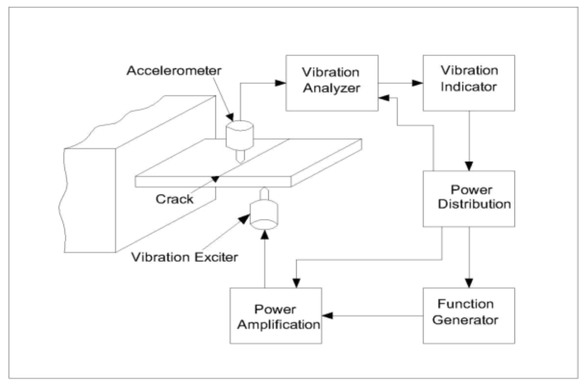

FIGURE II: EXPERIMENTAL MODAL ANALYSIS SETUP USING FFT ANALYZER

IV. FINITE ELEMENT MODELING

Finite Element Analysis (FEA) was carried out to numerically investigate the dynamic characteristics of glass fiber reinforced composite cantilever beams containing inclined edge cracks. The numerical study was performed using ANSYS Workbench, which provides a robust platform for modeling complex geometries, material behavior, and boundary conditions. The primary objective of the finite element modeling was to validate experimental observations and to study the influence of crack parameters under controlled and repeatable conditions.

A. Geometric Modeling

The geometric model of the composite cantilever beam was developed using Creo Parametric. The beam dimensions were identical to those used in the experimental investigation to ensure direct correlation between numerical and experimental results. The inclined edge crack was modeled explicitly by removing material along the crack plane at a specified location, depth, and inclination angle.

Special attention was given to accurately representing the crack geometry, as crack-induced stiffness reduction plays a dominant role in altering the dynamic response.

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The crack inclination angle was measured with respect to the longitudinal axis of the beam, and multiple crack configurations were modeled to study their effect on vibration characteristics.

B. Material Properties

The glass fiber reinforced composite beam was modeled as an equivalent homogeneous orthotropic material. This assumption is commonly adopted in vibration-based studies where the focus is on global dynamic behavior rather than micro-level damage mechanisms. The material properties used in the analysis were obtained from experimental characterization and literature.

The material properties assigned in ANSYS included:

- Young's modulus (E): Based on tensile testing of GFRC specimens
- Density (ρ): Determined from mass-to-volume ratio
- Poisson's ratio (ν): Taken from standard composite material data

Although composites exhibit anisotropic behavior, the equivalent material modeling approach provides sufficient accuracy for modal analysis of slender beams.

C. Meshing Strategy

Meshing plays a critical role in accurately capturing stress concentration and stiffness variations near the crack region. A three-dimensional solid mesh was generated using higher-order elements to improve solution accuracy. Mesh refinement was applied locally around the crack tip to capture steep displacement gradients, while a relatively coarser mesh was used in regions away from the crack to reduce computational cost.

A mesh convergence study was conducted by progressively refining the mesh until changes in natural frequencies became negligible. This ensured that the numerical results were independent of mesh density.

D. Boundary Conditions and Constraints

To replicate the experimental cantilever configuration, one end of the beam was fully constrained in all translational and rotational degrees of freedom. This fixed support condition accurately represents the clamped end used during experimental modal testing.

No external loads were applied during modal analysis, as the objective was to extract free vibration characteristics. The remaining surfaces of the beam were left unconstrained, allowing natural deformation during vibration.

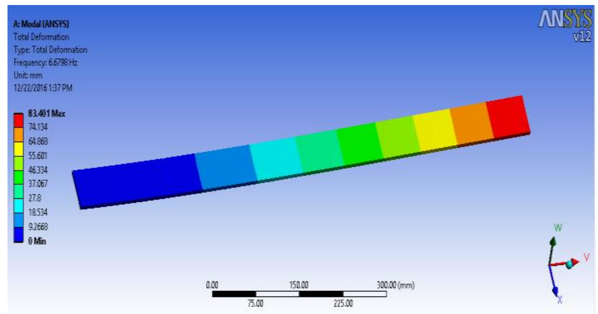

FIGURE III: FINITE ELEMENT MESH SHOWING REFINED REGION NEAR INCLINED CRACK

E. Modal Analysis Procedure

Modal analysis was performed to determine the natural frequencies and corresponding mode shapes of the composite beam. The Block Lanczos eigenvalue extraction method was employed due to its efficiency and accuracy for large-scale eigenvalue problems.

The first three natural frequencies were extracted for each crack configuration, as lower vibration modes are more sensitive to stiffness degradation caused by cracks. Mode shapes were examined visually to identify changes in deformation patterns due to crack presence and orientation.

F. Modeling Assumptions and Limitations

Several assumptions were made to simplify the numerical model:

1. The crack was assumed to be open and stationary during vibration.
2. Material damping was neglected, as its influence on natural frequencies is minimal.
3. Perfect bonding between fiber and matrix was assumed.

While these assumptions may introduce minor discrepancies, they are widely accepted in vibration-based damage detection studies and do not significantly affect the validity of the results.

The finite element modeling framework developed in this study provides a reliable numerical tool for analyzing cracked composite beams and complements the experimental investigation effectively.

V. RESULTS AND DISCUSSION

A. Effect of Crack Location

The experimental and numerical results indicate that crack location significantly influences the dynamic response of the beam.

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Cracks located closer to the fixed end resulted in greater reductions in natural frequencies due to higher bending moments near the support. As the crack moved toward the free end, its influence on global stiffness decreased, leading to relatively higher natural frequencies.

B. Effect of Crack Depth

An increase in crack depth caused a progressive reduction in natural frequencies for all vibration modes. Deeper cracks introduced greater local flexibility, resulting in more pronounced stiffness degradation.

TABLE II
EFFECT OF CRACK DEPTH ON FIRST NATURAL FREQUENCY

Crack depth ratio	Natural frequency (Hz)
0.1	Higher
0.3	Moderate
0.5	Lower

C. Effect of Crack Inclination

Crack inclination influenced higher vibration modes more significantly than the fundamental mode. Inclined cracks introduced bending–torsion coupling, altering mode shapes and frequency values. This behavior highlights the importance of considering crack orientation in vibration-based damage detection of composite beams.

D. Experimental and Numerical Correlation

A close agreement between experimental and finite element results was observed for all crack configurations. Minor discrepancies can be attributed to experimental uncertainties, material inhomogeneity, and idealized assumptions in numerical modeling.

TABLE III:
COMPARISON BETWEEN FEA AND EXPERIMENTAL RESULTS OF UNCRACKED BEAM

Sr. No	c	e	FEA			Experimental		
			ω_1 (Hz)	ω_2 (Hz)	ω_3 (Hz)	ω_1 (Hz)	ω_2 (Hz)	ω_3 (Hz)
1	0	0	6.728	42.15	66.671	7.000	43.85	70.00

TABLE IV
COMPARISON BETWEEN FEA AND EXPERIMENTAL RESULTS OF CRACKED BEAM WITH CRACK INCLINATION $\theta = 15°$

Sr. No	c	e	FEA			Experimental		
			ω_1 (Hz)	ω_2 (Hz)	ω_3 (Hz)	ω_1 (Hz)	ω_2 (Hz)	ω_3 (Hz)
1	0.25	0.30	6.68	42.1	66.49	6.88	43.85	63.53

VI. CONCLUSIONS

This paper presents a comprehensive experimental and numerical investigation of inclined edge cracks in glass fiber reinforced composite cantilever beams using vibration-based techniques. The study demonstrates that natural frequencies and mode shapes are highly sensitive to crack depth, location, and inclination. Cracks located near the fixed end and with greater depth produce more significant reductions in natural frequencies. The strong correlation between experimental modal analysis and finite element simulations validates the proposed approach as an effective non-destructive method for crack identification in composite structures. The methodology presented in this study can be extended to more complex composite components and real-time structural health monitoring applications.

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