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Vibration-Based Crack Detection in Fiber Reinforced Composite Cantilever Beams Using Experimental and Finite Element Analysis

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***Abstract*— Early detection of cracks in composite structures is essential to ensure structural safety, reliability, and service life, especially in aerospace, automotive, and civil engineering applications. Fiber reinforced composite (FRC) materials, while offering excellent strength-to-weight and stiffness-to-weight ratios, are vulnerable to damage mechanisms such as matrix cracking, fiber breakage, and delamination. These defects may initiate internally and remain undetected until catastrophic failure occurs. This paper presents a comprehensive vibration-based approach for crack detection in glass fiber reinforced composite cantilever beams using a combination of experimental modal analysis and finite element analysis (FEA). Changes in natural frequencies and mode shapes are employed as damage-sensitive parameters for identifying crack presence, location, and severity. Experimental investigations are conducted using an FFT analyzer, impact hammer, and piezoelectric accelerometer, while numerical simulations are performed using ANSYS Workbench. The experimental and numerical results show good agreement, confirming that vibration-based techniques provide a reliable, economical, and non-destructive method for structural health monitoring of composite beam-like structures.**

***Keywords*— Crack detection, Composite beam, Vibration analysis, Modal analysis, FFT analyzer, Finite Element Analysis.**

I. Introduction

Fiber reinforced composite materials have become indispensable in modern engineering due to their superior mechanical properties, corrosion resistance, and design flexibility. These materials are extensively used in aerospace components, automotive structures, wind turbine blades, marine applications, and civil infrastructure. Despite these advantages, composite structures are susceptible to various types of damage during manufacturing, handling, and service life. Common damage modes include matrix cracking, fiber fracture, delamination, and interfacial debonding. Among these, cracks play a critical role in reducing stiffness and load-carrying capacity, often acting as initiation sites for further damage propagation.

Traditional non-destructive testing (NDT) techniques such as ultrasonic testing, radiography, eddy current testing, magnetic particle inspection, and liquid penetrant testing are widely used for damage detection. Although effective, these techniques often require expensive equipment, skilled personnel, surface accessibility, and localized inspection. Moreover, many conventional NDT methods are time-consuming and not suitable for continuous structural monitoring.

Vibration-based damage detection has emerged as an attractive alternative due to its global nature, simplicity, and cost-effectiveness. Structural damage alters stiffness, mass distribution, and damping characteristics, leading to measurable changes in dynamic properties such as natural frequencies, mode shapes, and frequency response functions. By monitoring these vibration parameters, it is possible to infer the presence and severity of damage. In composite beams, cracks introduce local flexibility, resulting in a reduction of natural frequencies and modification of mode shapes.

This study focuses on vibration-based crack detection in glass fiber reinforced composite cantilever beams. A combined experimental and numerical approach is adopted to investigate the influence of crack parameters on dynamic behavior. Experimental modal analysis using FFT techniques is complemented by finite element modeling to validate the results and provide deeper insight into crack-induced dynamic changes.

II. Literature Review

Over the past few decades, extensive research has been conducted on vibration-based damage detection in beam-like structures. Early studies demonstrated that cracks significantly reduce stiffness, leading to measurable reductions in natural frequencies. Behera et al. investigated inclined edge cracks in cantilever beams and reported a systematic decrease in natural frequencies with increasing crack depth. Their work highlighted the sensitivity of mode shapes to crack location and inclination.

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Kamble and Chavan employed wavelet transform techniques combined with experimental vibration data to identify crack parameters in cantilever beams. Their results showed high sensitivity to small cracks and demonstrated that higher vibration modes improve crack localization accuracy. Lakhdar et al. focused on damage detection in composite structures and emphasized that degradation of flexural rigidity directly affects modal parameters. Their experimental findings confirmed the effectiveness of vibration analysis for composite damage detection.

Several researchers have also explored finite element modeling for crack simulation, often representing cracks as local reductions in stiffness or as rotational springs. While numerous studies address metallic beams, fewer investigations focus on composite beams with inclined cracks using combined FFT-based experimental techniques and numerical validation. The present work aims to address this gap by providing a detailed experimental–numerical study on crack detection in FRC cantilever beams.

III. Methodology

A. Specimen Preparation

Glass fiber reinforced composite beams were fabricated using the hand lay-up technique, which is well-suited for laboratory-scale composite fabrication. E-glass chopped strand mat was used as the reinforcement material, and polyester resin served as the matrix. A wax-based release agent was applied to the mould surface prior to fabrication to prevent adhesion.

The fabrication process involved alternate placement of fiber mat and resin layers until the desired thickness was achieved. Care was taken to ensure proper wetting of fibers and removal of entrapped air using manual compression. The laminate was allowed to cure at room temperature for 48 hours.

The final beam dimensions were:

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

After curing, inclined edge cracks of known depth and location were introduced using a diamond cutter. Crack parameters were carefully controlled to ensure repeatability.

B. Experimental Modal Analysis

The composite beam specimen was rigidly clamped at one end to form a cantilever configuration. An impact hammer was used to excite the beam, providing a broadband input force.

A piezoelectric accelerometer was mounted near the crack location to measure the vibration response.

The excitation force and acceleration response signals were fed into an FFT analyzer, which computed the frequency response functions (FRFs). From the FRFs, the natural frequencies corresponding to the first three bending modes were extracted. Multiple trials were conducted to ensure consistency and accuracy of the measurements.

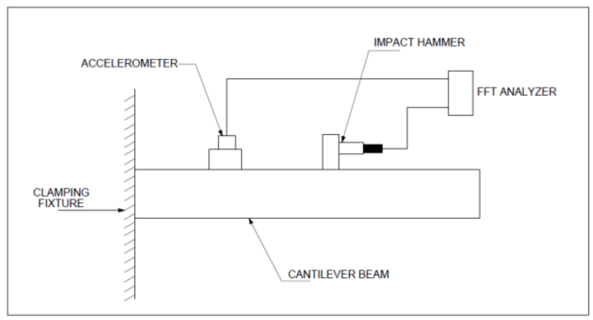

Figure I: Schematic diagram of experimental modal analysis setup.

IV. Finite Element Analysis

Finite Element Analysis (FEA) will be used in this project to analyze the vibration behaviour of composite beams under varying conditions. FEA will help predict the structural response and identify conditions that may lead to material failure. The analysis will be performed using ANSYS Workbench, where both 2D and 3D models can be evaluated.

A. Proposed Modal Analysis

Modal analysis will be carried out to determine the natural frequencies and mode shapes of the composite beam. This analysis is essential for understanding the dynamic characteristics of the structure and will also serve as the basis for further dynamic studies such as harmonic response or spectrum analysis.

Purpose of Modal Analysis

Modal analysis will be used to:

- Determine the natural frequencies of the beam
- Identify corresponding mode shapes
- Study the effect of cracks on vibration behaviour
- Support harmonic or transient dynamic analysis
- Evaluate prestressed or rotating structures (if applicable)
- Apply cyclic symmetry (when working with symmetric structures)

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In ANSYS Workbench, modal analysis is performed as a linear analysis, where nonlinearities such as contact or plasticity are ignored, even if defined.

Proposed Steps for Modal Analysis

a) Startup

The modal analysis will be initiated in ANSYS Workbench using the path:

ANSYS → Workbench → Modal Analysis

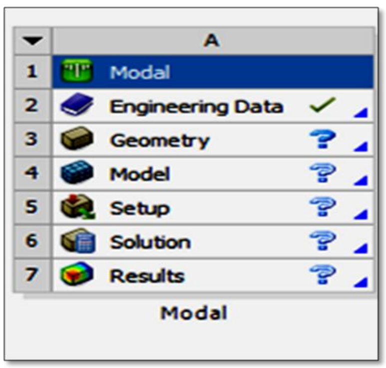

FIGURE II: STARTUP PATH

b) Engineering Data

Material properties of the composite beam will be defined under Engineering Data. A new material named E-Glass Epoxy will be created and assigned as the default material.

The proposed material properties are:

TABLE I
MATERIAL PROPERTIES (PROPOSED)

Property	Value	Unit
Mass Density (ρ)	2000	kg/m³
Young's Modulus (E)	39×10^{3}	N/mm²
Poisson's Ratio (ν)	0.30	—

c) Saving the Project

The ANSYS Workbench file will be saved at a preferred location for further analysis.

d) Geometry Preparation

The geometry of the cantilever beam will be modelled in Creo Parametric 2.0. Beams with various crack will be generated.

- depths
- locations
- inclinations

The final CAD model will be exported in .igs format and imported into ANSYS Workbench.

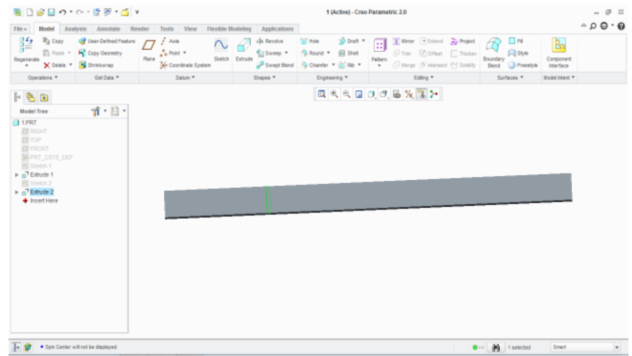

FIGURE III. MODEL HAVING CRACK IN CREO PARAMETRIC

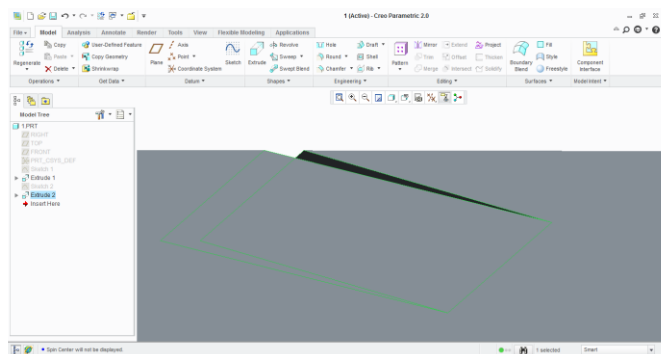

FIGURE IV: MAGNIFIED VIEW OF CRACK.

e) Modal Setup in ANSYS

Mesh Generation

A fine mesh will be generated to increase the accuracy of results.

Steps:

Mesh → Mesh Settings → Fine Mesh

Mesh → Right Click → Generate Mesh

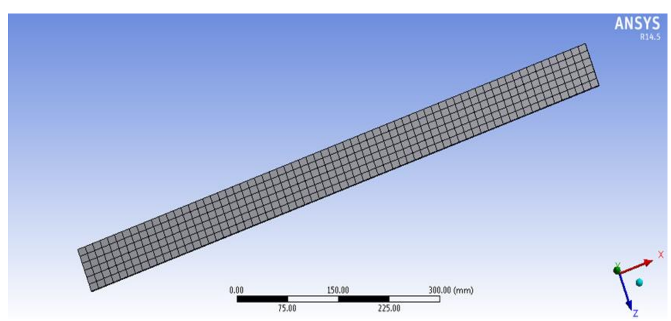

FIGURE V: MESH MODEL OF BEAM

Applying Boundary Conditions

A fixed support will be applied at one end of the beam to create a cantilever configuration.

Path:

Select Surface → Insert → Support → Fixed Support

Number of Modes

For the study, three to four mode shapes will be extracted.

Path:

Analysis Settings → Number of Modes → 3 (or 4)

f) Solution Phase

After all inputs are defined, the simulation will be solved to obtain the natural frequencies and corresponding mode shapes.

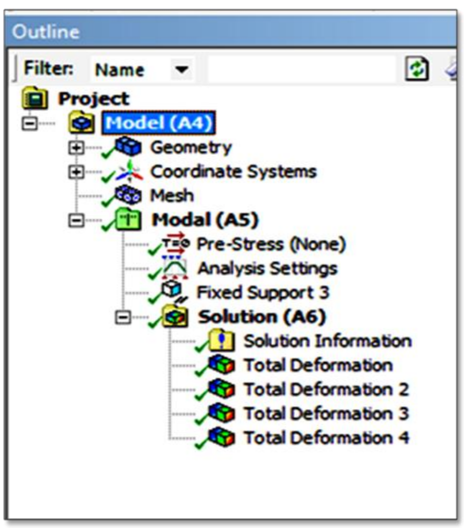

FIGURE VI: SOLUTION OF MODEL.

V. RESULTS AND DISCUSSION

A. Validation of Uncracked Beam Model

The natural frequencies obtained experimentally for the uncracked beam were compared with finite element predictions to validate the numerical model.

TABLE II
COMPARISON OF EXPERIMENTAL AND FEA NATURAL FREQUENCIES FOR UNCRACKED BEAM

Mode	FEA (Hz)	Experimental (Hz)
1	6.73	7.00
2	42.15	43.85
3	66.67	70.00

The close agreement between experimental and numerical values confirms the accuracy of the finite element model.

B. Effect of Crack Parameters

The presence of a crack resulted in a noticeable reduction in natural frequencies for all vibration modes. As crack depth increased, stiffness degradation became more pronounced, leading to larger frequency reductions. When the crack location moved away from the fixed end toward the free end, the influence on bending stiffness decreased, resulting in relatively higher natural frequencies.

TABLE III
NATURAL FREQUENCIES OF CRACKED BEAM (C = 0.25, E = 0.30)

Mode	FEA (Hz)	Experimental (Hz)
1	6.69	6.89
2	42.16	43.85
3	66.49	63.54

The results demonstrate that vibration-based parameters are sensitive to crack presence and severity. Higher vibration modes showed increased sensitivity to crack location and inclination.

VI. CONCLUSIONS

This study presents a comprehensive experimental and numerical investigation of vibration-based crack detection in fiber reinforced composite cantilever beams. The results confirm that cracks introduce local flexibility, leading to measurable reductions in natural frequencies and modifications in mode shapes. Experimental modal analysis using FFT techniques, combined with finite element modeling, provides an effective and reliable non-destructive evaluation approach. The close correlation between experimental and numerical results validates the proposed methodology. The findings of this work demonstrate the potential of vibration-based techniques for structural health monitoring of composite structures and can be extended to more complex geometries and real-time monitoring applications.

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