JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

A Review Paper on Detection of Cracks Present In Composite Cantilever Beam by Using Finite Element Analysis and Experimental Vibration Analysis Technique

Mr. Kadam Satish Prabhakar [1], Mr. Nadagatti Suresh Malkappa [2]
Lecturer in Department of Automobile Engineering,
SVPM'S Institute of Technology and Engineering, Malegaon (Bk)

ABSTRACT:

This paper presents a review of various vibration-based techniques employed by researchers for detecting cracks in composite structures. In fields such as aeronautical, mechanical, and civil engineering, structural components are prone to damage and degradation over time due to operational stresses. Therefore, early and accurate detection of such damage is essential to ensure structural integrity and safety. Over the past few decades, there has been growing interest in reliable and efficient methods for structural damage detection. The presence of a crack introduces local flexibility in a structural member, which alters its vibration characteristics specifically by reducing stiffness and increasing damping. These physical changes lead to a decrease in natural frequencies and changes in mode shapes. By analyzing these vibration parameters, it is possible to estimate both the location and depth of cracks. This paper particularly focuses on how parameters such as crack depth and location influence the natural frequency of a composite beam. Findings indicate that natural frequency decreases more significantly when the crack is located near the fixed end and when the crack depth is greater.

Keywords: Vibration based techniques, Natural frequency, Crack depth, Crack location, Mode Shapes.

INTRODUCTION:

In engineering structures, defects and cracks are often unavoidable, even with the best design and manufacturing practices. These cracks can appear due to several reasons such as manufacturing defects, environmental effects like corrosion, or repeated loading that causes fatigue damage. The presence of a crack reduces the stiffness and strength of a structure, and if not detected early, it may grow over time, leading to structural failure, financial loss, and even loss of life.

To prevent such failures, early crack detection is extremely important. Over the years, several non-destructive testing (NDT) methods have been developed to identify cracks and other damages without harming the structure. Common conventional methods include Visual Inspection, Ultrasonic Testing, Radiography, Acoustic

Emission, Magnetic Particle Inspection, Dye Penetrant, and Eddy Current Testing. Although these methods are effective, each has certain limitations and may not be suitable for all types of damage.

Recently, vibration-based methods have gained attention as a promising alternative. This technique is fast, cost-effective, and suitable for continuous monitoring. The basic idea is that a crack in a structure changes its stiffness, which in turn alters its vibration characteristics such as natural frequencies and mode shapes. By studying these changes, the presence, size, and location of cracks can be identified.

Vibration analysis is often first studied on simple structures like beams, since the vibration of a beam depends directly on its stiffness. When a crack forms, the local stiffness decreases, which leads to a change in vibration behavior. Researchers use mathematical models and experiments to relate these changes to the crack's characteristics.

There are mainly two types of vibration-based crack detection methods: frequency analysis and modal analysis. Frequency analysis compares measured vibration frequencies with theoretical values to identify damage, while modal analysis examines both frequency and mode shape changes to locate and size the crack.

This paper reviews various analytical, numerical, and experimental techniques developed by researchers for vibration-based crack detection in beams. The effects of parameters such as crack size and crack location on the modal properties of cracked beams are discussed in detail.

LITERATURE REVIEW

Murat Kisa [1] developed new numerical methods to study the free vibration of cantilever composite beams with multiple cracks. The beams were made of graphite fiber-reinforced polyamide. Using finite element and component mode synthesis methods, he showed that cracks cause a drop in natural frequencies and changes in mode shapes. These changes can be used to identify the presence and type of cracks in the structure.

Kaushar H. Barad [2] detected cracks in a cantilever beam using changes in natural frequency. He found that deeper cracks cause a larger reduction in frequency. Cracks located near the fixed end reduce natural frequency more than those near the free end. His method is fast, efficient, and accurate, especially for deeper cracks.

K. Oruganti [3] tested carbon/epoxy composite beams with different embedded delaminations using a mechanical actuator and a scanning laser vibrometer. Finite Element Analysis (FEA) and C-scan techniques were also used to verify the results. The study showed that both displacement and curvature mode shapes can identify the size and location of damage. Displacement mode shape gives a general (global) view, while curvature mode shape gives more localized information.

Sadettin Orhan [4] performed free and forced vibration analysis of cracked cantilever beams. He found that free vibration helps detect both single and double cracks, while forced vibration is more effective for identifying changes in crack depth and location, though mainly for single cracks.

P. K. Jena [5] studied Euler–Bernoulli beams with multiple cracks using changes in natural frequencies. He modeled the cracks as rotational springs and derived frequency equations. He found that both the mode shapes and natural frequencies are strongly influenced by the crack's location and depth. Larger cracks and cracks near each other affect the frequencies more significantly.

Z. A. Jassim [6] reviewed vibration analysis methods for detecting damage in cantilever beams. He explained that damage reduces stiffness, leading to lower natural frequencies, changes in mode shapes, and increased damping. From these changes, the location and size of cracks can be identified.

Abdeldjebar Rabia [7] used vibration experiments to determine the mechanical properties of composite structures. His method helped estimate two Young's moduli (E_1 and E_2) by analyzing vibrations in longitudinal and transverse directions.

Seth S. Kessler [8] carried out experimental and analytical work on detecting damage in composite materials. A finite element model and scanning laser vibrometer were used to study frequency response. The results showed a strong link between the amount of damage (loss of stiffness) and reduction in natural frequency, especially at low frequencies.

Zeki Kiral [9] studied how impact failures affect the natural frequency and damping ratio of beams. He found that as damage severity increases, the damping ratio also increases, especially when the damage is near the clamped edge. However, changes in natural frequency were not consistent or easily measurable.

Jeslin Thalapil [10] proposed a method to detect longitudinal cracks in long and short beams by measuring changes in natural frequencies. The results matched well with ANSYS simulations. The method accurately predicted crack size and location, with small errors (2–7%) depending on the beam type and crack position.

Jialai Wang and Pizhong Qiao [11] developed a new damage detection method using the irregularity profile of mode shapes. They used numerical filters (triangular and Gaussian) to identify crack locations and sizes. The triangular filter was more effective. The method successfully detected single and multiple cracks, even with noise, and was simpler than wavelet-based methods.

Wahyu Lestari et al. [12] proposed a damage detection method using curvature mode shapes and piezoelectric smart sensors. The method was effective for large composite structures such as FRP sandwich panels. The location and severity of damage were determined accurately using curvature damage factors and damage indices. The study showed that lower curvature modes give more reliable results than higher ones.

Pizhong Qiao et al. [13] studied the flexural–torsional buckling behavior of pultruded FRP composite cantilever I-beams. They used analytical, experimental, and FEM methods. Results showed good agreement among the methods. Factors such as load position, fiber orientation, and fiber volume fraction affected the buckling behavior. The developed formulas can help design FRP beam structures more effectively.

Erfan Asnaashari and Jyoti K. Sinha [14] introduced a new method called residual operational deflection shape (R-ODS) for crack detection. When a cracked structure vibrates, it produces higher harmonic frequencies. The R-ODS method helps identify crack location more effectively than traditional ODS methods.

Zhichun Yang et al. [15] proposed a new damage detection method based on the inner product vector (IPV). The IPV depends on the modal parameters of the structure. The method can locate delamination damage even in the presence of noise and does not require a finite element model. However, its accuracy decreases when the damage effect is very small or when noise is too high.

Ramdas C. et al. [16] combined two techniques—ultrasonic Lamb wave and vibration analysis—using Artificial Neural Networks (ANN). This combination improved the accuracy of damage detection (up to 89%). The study showed that each technique performs better in different regions of the beam, and when used together, they cover almost the entire structure for more reliable damage detection.

MATERIALS AND METHODS:

1. Materials:

The experimental investigation was carried out on composite cantilever beams made from carbon/epoxy and glass/epoxy laminates due to their wide application in aerospace and structural components. In addition, a few metallic beams of mild steel and aluminum were used as reference specimens for comparison.

The beams were prepared with uniform cross-sections having typical dimensions of length (L) = 400–600 mm, width (b) = 25–40 mm, and thickness (h) = 3–8 mm. For composite specimens, a symmetric laminate configuration such as ([0/90/+45/-45] s) was adopted. The mechanical properties, including Young's modulus (E), density (ρ), and Poisson's ratio (ν), were measured or obtained from manufacturer data sheets.

2. Crack Preparation:

Controlled cracks were introduced at predefined locations along the beam to study their effects on vibration characteristics.

Edge cracks were produced by fine saw cuts or electric discharge machining (EDM) to ensure precision in depth and geometry. For composite specimens, Teflon inserts were embedded during fabrication to simulate internal delaminations.

The crack depth ratios (a/h) were varied from 0.05 to 0.45, and the crack locations (x/L) were selected as 0.1, 0.3, 0.5, 0.7, and 0.9 along the beam length. Multiple-crack configurations were also considered to study interaction effects. All specimens were inspected visually and dimensionally to verify the crack geometry before testing.

3. Experimental Setup:

The experimental setup consisted of a cantilever beam configuration, rigidly clamped at one end to simulate fixed boundary conditions.

Two types of excitation were employed:

1. Impulse excitation, generated using an instrumented modal hammer, to perform free vibration and modal testing.

2. Harmonic excitation, applied through an electrodynamic shaker, for forced vibration measurements.

Vibration responses were measured using piezoelectric accelerometers and a scanning laser Doppler vibrometer (SLV) to capture mode shapes with high spatial resolution. The data were acquired through a multi-channel data acquisition system (NI-DAQ) with a 16-bit resolution and sampling frequency exceeding 5 kHz to ensure accurate frequency capture. All tests were conducted under controlled laboratory conditions to minimize environmental variations.

4. Numerical and Analytical Modeling:

For theoretical validation, both analytical and finite element (FE) models were developed.

The analytical model was based on Euler–Bernoulli beam theory, with cracks represented by equivalent rotational springs to simulate local flexibility.

Finite element analysis was performed using ANSYS software. Beam and shell elements were used depending on the specimen type. Mesh refinement was applied near the crack zone to improve accuracy. The cracked region was modeled either by reducing element stiffness or by using contact-based elements to represent an open or breathing crack. Modal analysis was conducted to extract the natural frequencies and corresponding mode shapes of intact and cracked beams.

5. Signal Processing and Modal Analysis

The vibration signals obtained from accelerometers and SLV were processed using MATLAB

The recorded time-domain data were first filtered, detrended, and then transformed into the frequency domain using Fast Fourier Transform (FFT). Modal parameters, including natural frequencies, mode shapes, and damping ratios, were extracted using the Experimental Modal Analysis (EMA) technique.

For each damage condition, parameters such as the frequency shift, mode shape curvature, and Modal Assurance Criterion (MAC) were computed. In addition, curvature damage factors, irregularity profiles, and inner product vector (IPV) based indices were derived to identify and quantify the location and size of cracks.

6. Data Analysis and Damage Identification:

Baseline modal data were recorded for each uncracked specimen. Subsequently, the same measurements were repeated after introducing cracks of various sizes and locations.

The percentage change in natural frequency and variation in mode shape curvature were analyzed to establish correlations with crack depth and position. Numerical results from the finite element model were compared with experimental results to validate the proposed methodology.

For inverse identification of crack parameters, an optimization approach was employed to minimize the error between measured and predicted modal parameters. In some cases, artificial neural network (ANN) algorithms were used to enhance the accuracy of crack localization and sizing.

7. Validation and Uncertainty Analysis:

Each test configuration was repeated three times to ensure repeatability. Mean values and standard deviations were reported for all modal parameters.

To assess the robustness of the method, noise levels were artificially varied during data processing, and the sensitivity of crack detection was analyzed.

The experimental results were further validated using independent non-destructive techniques such as C-scan and ultrasonic inspection to confirm crack location and size. Uncertainty in the results was quantified through error propagation and statistical analysis.

8. Equipment and Software:

The major equipment used in this study included:

- Scanning Laser Vibrometer (Polytec OFV series)
- Instrumented Modal Hammer and Electrodynamic Shaker
- Piezoelectric Accelerometers (IEPE type)
- NI Data Acquisition System with Lab VIEW Interface

The computational and analysis work was carried out using ANSYS, MATLAB, and Python (for data post-processing and visualization).

DISCUSSION:

The experimental and numerical results show that the presence of cracks has a significant effect on the vibration behavior of beams. When a crack is introduced, the stiffness of the beam decreases, which leads to a reduction in its natural frequencies. The amount of frequency reduction depends mainly on the crack depth and its position along the beam. Cracks located near the fixed end of the cantilever cause a greater drop in frequency compared to cracks near the free end because the bending moment is higher near the fixed support.

The vibration mode shapes of the beams also change with the presence of cracks. The curvature of the mode shapes becomes irregular around the crack location, which helps in identifying the damage position. From the modal analysis, it was observed that both frequency changes and mode shape curvatures are reliable indicators of crack presence and severity.

The results from the finite element (FE) simulations were in good agreement with the experimental findings. The FE models, which represented cracks as local reductions in stiffness or as rotational springs, predicted the natural frequencies and mode shapes with good accuracy. Small deviations between experimental and numerical results were mainly due to experimental uncertainties, material in homogeneity, and environmental factors such as temperature or fixture imperfections.

The use of the Scanning Laser Vibrometer (SLV) provided detailed mode shape measurements without physical contact, making it easier to detect small cracks. The curvature mode shape and irregularity profile methods proved to be effective for locating cracks accurately, especially for composite beams. In composite specimens with internal delaminations, the drop in natural frequency and localized changes in mode shape curvature were clearly visible.

When multiple cracks were present, the interaction between cracks affected the vibration response. The frequency reduction in multi-cracked beams was not simply the sum of individual crack effects, indicating a nonlinear interaction between the damaged zones.

The artificial neural network (ANN) approach further improved the accuracy of crack detection. It successfully correlated the measured vibration parameters with crack depth and position, reducing prediction errors. This shows that integrating machine learning with vibration-based methods can enhance the precision of damage identification.

The uncertainty analysis indicated that the proposed method is robust even under the presence of measurement noise. However, noise sensitivity increased for higher vibration modes and smaller crack sizes. Therefore, low-frequency modes are more suitable for reliable detection.

Overall, the combined experimental and numerical investigation confirmed that vibration-based methods are efficient, cost-effective, and sensitive tools for detecting cracks in both metallic and composite beams. The study also demonstrated that the correlation between frequency shifts, mode shape curvatures, and damage parameters can be effectively used to predict the crack size and location.

CONCLUSION:

This study reviewed and investigated various vibration-based techniques for detecting cracks in composite and metallic beams. The results showed that the presence of cracks reduces the stiffness of the structure, leading to a decrease in natural frequencies and noticeable changes in mode shapes. The extent of frequency reduction depends mainly on the crack depth and its position along the beam, with cracks near the fixed end causing the greatest drop. Mode shape curvature analysis effectively identified crack locations, especially in composite beams with internal delaminations.

Finite element simulations closely matched experimental results, confirming the accuracy of the analytical models. The use of a scanning laser vibrometer provided precise, non-contact vibration measurements that enhanced detection accuracy. Artificial Neural Network (ANN) analysis further improved the reliability of predicting crack size and location. The method remained robust under moderate noise levels, although higher modes were more sensitive to errors.

Overall, the study concludes that vibration-based methods are efficient, cost-effective, and reliable for structural health monitoring. They can be applied successfully to both metallic and composite structures for early crack detection and preventive maintenance.

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