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Original Article

Advanced Ultrasonic Characterization of Areca Nut Natural Fiber Reinforced Composite Balustrades

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Abstract *- Balustrades are key functional elements in architecture for improved protection and add aesthetic value to various types of buildings. Industrialization allows a wide variety of materials in preparation of Balustrades for improved safety and style, but disposal of these composites (non-biodegradable) after their service life is a challenging task for materials engineers. Hence, researchers are now concentrating on natural fiber reinforced composites as an alternate solution for sustainability and eco-friendliness without compromising their strength and functionality. In this paper, we demonstrate the use of Areca nut natural fiber reinforced composites for the preparation of composite laminates as an application of building blocks as Balustrades and also explain the investigation of these Balustrades for their quality assurance. By using the Nonlinear Resonance Ultrasonic inspection method (NRUS), we demonstrate the finding of defects like cracks, porosity, density variation, delamination, and their location in the Areca nut fibre reinforced composite Balustrades. Also, we demonstrate the effect of the nonlinear coefficient with delamination location in the multi-layered composite sheet. Further, the same nonlinear coefficient variation occurs with the presence of defect types like cracks, porosity, etc., in the composite laminates.*

Keywords *- Areca nut, Natural fibers, Balustrades, Biodegradability, Delamination, Nonlinear resonance ultrasonics.*

1. Introduction

A balustrade is a functional architectural feature consisting of a row of balusters that support a rail, typically found along stairways, balconies, terraces, or bridges. The primary purpose of a balustrade is to provide safety by acting as a barrier to prevent falls while offering aesthetic appeal to the structure. The Key components of a balustrade are: Balusters, Handrail, Base Rail (optional) and Newel Post (optional). The following are the different types of Balustrades used in construction,

- Wooden Balustrades,
- Metal Balustrades,
- Glass Balustrades and
- Stone or Concrete Balustrades.

With the advanced technology, people also use composite materials as an alternative to wooden and stone balustrades.

Industrialization allows a wide variety of materials in preparation of Balustrades for improved safety and style, but disposal of these composites (non-biodegradable) after their service life is a challenging task for materials engineers. Hence, researchers are now concentrating on natural fiber reinforced composites as an alternative solution for sustainability and eco-friendliness without compromising their strength and functionality.

Although natural fibres such as jute, hemp, and sisal have long been used in composite applications due to their favorable mechanical properties and availability, the areca nut fibre presents a unique combination of advantages that justify its increasing attention in sustainable materials research:

1.1. Agricultural Waste Utilization

Areca nut husk is an agro-waste byproduct generated in large quantities in areca-growing regions (e.g., parts of India, Southeast Asia). Unlike jute or hemp, which are cultivated primarily for fibre, areca fibre is sourced from waste, making it an eco-positive solution by turning agricultural residue into value-added materials.

1.2. Environmental and Economic Sustainability

No need for dedicated cultivation: This avoids the additional land, water, and fertilizer inputs required for jute or hemp farming.

Cost-effective: Areca husk is abundantly available and inexpensive, reducing raw material costs for composite manufacturers.

1.3. Encouragement of Rural Livelihoods

Processing areca husk for fibre can create new microenterprise opportunities in rural and tribal areas, thereby promoting local employment and circular economy models in regions where areca nut is cultivated.

1.4. Competitive Material Properties

Recent studies have shown that areca nut fibre has Moderate tensile strength and stiffness suitable for semi-structural applications. Low density, making it favorable for lightweight composites. Good adhesion properties when surface-treated or modified for polymer compatibility.

1.5. Biodegradability and End-of-Life Disposal

Areca fibres, like other lignocellulosic materials, are biodegradable, but their use contributes to zero-waste farming and helps reduce the burden of non-degradable agro-waste.

1.6. Underexplored Yet Promising

Areca fibre is relatively less studied compared to jute or hemp, making it a novel area for research and innovation. Early studies suggest potential in applications such as acoustic panels, biodegradable composites, packaging, and interior automotive parts. While jute, hemp, and sisal remain important natural fibres with well-established supply chains, the upcycling of areca nut fibre offers a sustainable, cost-effective, and socially responsible alternative. Prioritizing it supports waste valorization, rural development, and innovation in bio-composite materials, aligning with global sustainability goals.

The recent trends and expanding markets in sustainable architecture validate the selection of areca nut fibre composites as a strategic, forward-looking material choice. Their alignment with global sustainability demands, potential for waste valorization, and growing utility in interior and modular systems offer significant scope for innovation and commercialization in architecture.

This paper represents a distinct advance in the field of sustainable materials by:

- Introducing areca nut fibre as a *regionally abundant, underutilized agro-waste fibre*.
- Employing advanced composite characterization tools to benchmark performance.
- Filling a niche in green architecture for low-cost, biodegradable, and acoustic-performing panels.
- Supporting circular economy goals through material upcycling and rural livelihood potential.

The increasing demand for sustainable and biodegradable materials has led to widespread research into Natural Fibre-Reinforced Composites (NFRCs) for applications ranging from automotive to construction.

Among these, green composites derived from agro-waste fibres such as areca nut husk present an eco-friendly and economically viable alternative to more established fibres like jute, flax, and hemp. However, to fully integrate such materials into structural and semi-structural applications, particularly in architecture and interiors, there is a critical need to ensure material integrity and long-term performance, which necessitates advanced Non-Destructive Evaluation (NDE) methods.

One such promising technique is Nonlinear Resonant Ultrasound Spectroscopy (NRUS), which offers high sensitivity to early-stage defects, fiber–matrix debonding, voids, delaminations, and other nonlinear behaviors in composite materials. While NRUS has been widely applied to synthetic composites and aerospace-grade carbon-epoxy systems, its application to green composites remains relatively nascent.

Several recent studies have explored the use of NRUS or related nonlinear NDE methods on natural fibre composites. Despite several advancements, very few studies have applied NRUS to composites developed from waste-derived fibres, particularly areca nut fibre, whose internal porosity, lower density, and unique fibre morphology may introduce distinct nonlinear mechanical signatures.

Furthermore, prior works have typically employed NRUS in limited contexts, mostly laboratory fatigue setups, without translating findings to architectural relevance, such as acoustic panels, thermal insulators, or prefabricated building materials.

1.7. Preservation of Material Integrity (NDT)

NDT methods allow for the inspection and evaluation of materials without altering their physical or chemical properties. This is particularly crucial for composite components, which are often expensive and complex to manufacture. Techniques like ultrasonic testing, thermography, and radiography enable quality assurance during manufacturing and in-service monitoring, ensuring safety and reliability while preserving the usability of the component.

1.8. Detection of Subsurface and Microscopic Defects

Conventional NDT methods can detect delaminations, voids, fiber breakages, and resin-rich/lean regions that are not visible to the naked eye. Ultrasonic testing, in particular, provides insights into the internal structure of the composite, offering valuable data on velocity and attenuation that correlate with material stiffness and homogeneity.

1.9. Sensitivity to Early-Stage Damage (NRUS)

NRUS is a highly sensitive acoustic method for detecting micro-damage in composite materials. Unlike linear ultrasonic methods, NRUS detects changes in the nonlinear elastic response of materials, which often precede visible or detectable damage. This makes it a powerful tool for identifying early degradation, such as micro-cracking, fatigue, and thermal damage, before they evolve into critical failures.

1.10. Evaluation of Elastic Moduli

Both NDT and NRUS can be used to determine elastic properties such as Young's modulus, shear modulus, and Poisson's ratio. These properties are essential for understanding the stiffness, deformation behavior, and structural performance of composite materials, especially under mechanical loads.

1.11. Environmental and Economic Benefits

By enabling preventive maintenance and reducing unnecessary replacements, NDT and NRUS contribute to cost savings and sustainability. These methods also support the use of biodegradable and eco-friendly composites by providing reliable testing solutions that align with green engineering practices.

1.12. Advanced Research and Quality Control

In research and development, NDT and NRUS techniques are indispensable for material characterization, optimization of fabrication processes, and validating simulation models. They also play a critical role in establishing quality control protocols in industrial production lines of composite materials.

NDT and NRUS are invaluable for ensuring the structural integrity, safety, and longevity of composite materials. Their ability to detect early-stage damage, evaluate mechanical properties, and monitor in-service degradation makes them essential tools in both industrial and research settings. Their application is especially significant in the current shift towards sustainable material solutions, including natural fiber-reinforced composites.

This paper organized as follows: First, it starts with an introduction to the balustrades and problem statement, followed by the areca nut natural fiber reinforced composite laminate preparation methods. Then explain the potential applications of the prepared composite laminates as building blocks and their quality assurance NDT methods by using the nonlinear resonance ultrasonic test. Finally, the paper concluded with results and discussions.

The increasing reliance on composite laminates in critical engineering applications necessitates reliable techniques for early detection of structural damage, particularly delamination, which is one of the most prevalent and dangerous failure modes in laminated composites. Traditional linear ultrasonic techniques have shown limitations in detecting small-scale or incipient delaminations, prompting researchers to explore nonlinear acoustic techniques such as Nonlinear Resonant Ultrasound Spectroscopy (NRUS). NRUS is based on the principle that the nonlinear elastic properties of materials are significantly more sensitive to micro-level damage than their linear counterparts. The technique involves exciting a material at its natural resonance frequency and observing shifts in frequency, amplitude-dependent resonance behavior, and non-classical damping effects that indicate the presence of damage such as delaminations, cracks, or disbonds.

Meo M., Polimeno U., Zumpano G. (2008) demonstrated that nonlinear elastic wave spectroscopy (NEWS) methods, specifically, nonlinear resonance ultrasound spectroscopy (NRUS) and nonlinear wave modulation spectroscopy (NWMS), are highly sensitive to detecting barely visible impact damage (BVID) in fibre reinforced plastic composites.

KY Jhang (2009) explained that the Nondestructive evaluation of service-induced damage in components is crucial for effective condition monitoring and accurate estimation of their remaining service life.

Liu P., Sohn H., Kundu T. (2014) the Laser Nonlinear Wave Modulation Spectroscopy (LNWMS) technique offers a noncontact method using a pulse laser, which enables the early detection of fatigue cracks with greater sensitivity than traditional linear ultrasonic methods. Its broadband input induces nonlinear responses in materials, allowing effective localization and characterization of early-stage damage without requiring physical contact or multiple frequency inputs.

Lim H.J., Sohn H., and Kim Y. (2018) demonstrated that an integrated online monitoring approach combining nonlinear ultrasonic modulation with an Artificial Neural Network (ANN) can accurately quantify fatigue crack growth and estimate the remaining fatigue life in plate-like aluminum structures. By using piezoelectric transducers to capture ultrasonic responses during constant-amplitude cyclic loading, and feeding these data into a carefully trained ANN, the method reliably differentiates specimen conditions across varying thicknesses.

Bunget G., Henley S., Glass C., et al. (2020) the study highlights that while the acoustic nonlinearity parameter is an effective indicator of microstructural damage due to cyclic loading in metals, conventional nonlinear ultrasonic techniques show significant limitations, namely, response saturation and reduced resolution.

Delamination affects the local stiffness and interfacial bonding between layers in composite laminates. When excited at resonant frequencies:

- The damaged material exhibits nonlinear behavior, such as modulation of resonance peaks and harmonic generation.
- The resonance frequency decreases with the increase in delamination due to reduced stiffness.
- NRUS can also detect contact acoustic nonlinearity resulting from partially open or breathing delaminations.

Advantages of NRUS in Delamination Detection: High sensitivity to micro-level damage not detectable by conventional ultrasonic methods. Quantitative capability, as nonlinear parameters can be correlated with damage size and type. Non-invasive and repeatable, suitable for in-service monitoring and predictive maintenance. Capable of detecting closed or subsurface delaminations, which are typically hard to find.

2. Methodology

The methodology involved in this paper was divided into two stages: first, the preparation of Areca Nut reinforced composite laminates, and second, the prepared laminates were tested using the Nonlinear Resonance Ultrasonic (NDT) testing method.

2.1. Preparation of Areca Nut Reinforced Composite Laminates

The areca nut husk fiber and epoxy resin were used in the manufacturing of the composite laminates. For the panel preparation, chemically treated areca nut husk fiber and epoxy resin ROTO EP-306 with epoxy hardener ROTO EH-758 were used.

The following steps were involved in the fabrication of the composite laminate:

- Soak the areca nuts in water for one day to soften the husks.
- Dry the soaked areca nuts under sunlight for 5 to 10 days to facilitate easier separation of fibers.
- Alkali (NaOH) Treatment of Areca Nut Fibres
- Fibre Pre-cleaning: Collect areca nut husk fibres and manually remove dust, debris, and any visible impurities. Wash thoroughly in distilled water to eliminate surface dirt and water-soluble impurities.
  Air dry the fibres for 12–24 hours.
- Preparation of NaOH Solution: Prepare a 5% (w/v) sodium hydroxide (NaOH) solution by dissolving 50 grams of NaOH pellets in 1 litre of distilled water. Stir the solution until fully dissolved and homogenous.
- Fibre Immersion: Submerge the clean, dried fibres in the prepared NaOH solution. Maintain the treatment for 4 hours at room temperature (25–30 °C). Ensure the fibres are fully immersed and occasionally stir the mixture to ensure uniform treatment.
- Washing and Neutralization: After 4 hours, remove the fibres from the NaOH solution. Rinse them repeatedly in distilled water until the pH of the wash water becomes neutral (pH ~7). Optionally, immerse the fibres in a 0.1% acetic acid or dilute HCl solution for 10 minutes to neutralize any remaining alkali, followed by an additional rinse in distilled water.
- Drying: Spread the washed fibres on trays or racks and place them in a hot air oven. Dry the fibres at 60–80 °C for 24 hours, or until they are fully moisture-free. Avoid drying above 100 °C to prevent thermal degradation.
- Storage: Once dried, store the treated fibres in airtight containers with desiccants (e.g., silica gel) to avoid moisture absorption before composite fabrication.
- This treatment improves: Surface roughness for better matrix bonding, Fibre–matrix adhesion and Crystallinity: Mechanical and acoustic performance of the composite. Use the hand layup technique to separate the fibers from the husks. Take a smooth-surfaced tile for the molding process. Spray a wax release agent on the tile surface to prevent sticking of the composite material. Prepare the epoxy resin and hardener mixture in a 1:1 ratio.
- Apply a thin layer of the resin-hardener mixture evenly onto the wax-sprayed tile surface.
- Arrange the areca nut fibers into a sheet of dimensions 20cm x 20cm on the resin-coated tile surface.
- Apply another layer of resin-hardener mixture evenly over the arranged fibers to ensure proper bonding.
- A 50/50 resin-to-fibre ratio is used for the preparation of the laminate.
- Use a roller to uniformly press and bond the fibers with the resin layer, ensuring a smooth and even surface.
- Place another smooth-surfaced tile over the composite sheet to sandwich it.
- Apply weights on top of the upper tile to provide pressure and ensure proper setting of the composite sheet.
- Allow the composite sheet to cure and harden under pressure (normal conditions with a weight of 4 to 5 kg) for 2-3 days.
- After curing, carefully remove the weights and upper tile from the composite sheet.
- Trim any excess material to obtain the desired dimensions of the composite sheet.
- Inspect the sheet for any defects or unevenness and make necessary adjustments if required.
- The composite sheet made from areca nut fibers is now ready for use in various applications.
- The properties of this composite sheet are brittle and become more resistant to various tests.

Fig. 1 Preparation of composite sheets made with areca nut husk fiber

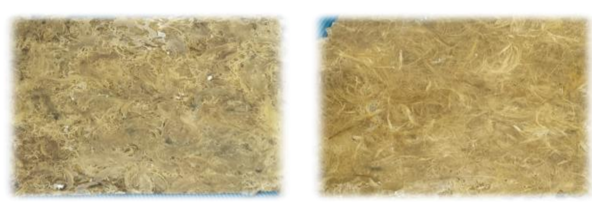

Fig. 2 images of Areca nut fiber reinforced composite laminates with and without treating with NaOH

Epoxy resins are used in the preparation of the above composite laminate, which provides high-performance advantages.

Their environmental drawbacks: non-renewable origin, toxicity, lack of biodegradability, and poor recyclability—are significant. These issues underline the need for:

- Green alternatives (e.g., bio-epoxy, hybrid bioresins).
- Process modifications to reduce hazards.
- Design for disassembly or recyclability in composite product planning.

The life cycle of Areca nut natural fiber composites involves several key stages, from raw material sourcing to end-of-life disposal.

These composites, made using Areca nut fibers and typically biodegradable or partially recyclable matrices (like epoxy or bio-resins), are gaining popularity due to their eco-friendliness and sustainable attributes.

2.1.1. Raw Material Sourcing

- Areca nut fibers are extracted from the husk or shell of Areca palm fruits, which are agricultural waste products. This makes fiber extraction low-cost, renewable, and sustainable.

2.1.2. Composite Fabrication

- Techniques like hand layup, compression molding, or resin infusion are used. Matrices can range from thermosetting resins (e.g., epoxy) to biopolymers (e.g., PLA, PHB), depending on performance needs and biodegradability goals.

2.1.3. Use Phase

- Applications include interior components, light-duty panels, furniture, and decorative balustrades. Lightweight and moderate mechanical strength make them suitable for semi-structural uses.

2.1.4. End-of-Life

- At the end of their service life, composites must be disposed of responsibly to ensure environmental sustainability.

Areca nut fibre composites offer a promising route toward eco-friendly materials; however, the choice of matrix plays a critical role in determining their end-of-life impact.

To fully realize their sustainability potential, manufacturers and users must align with life cycle thinking, encouraging biodegradability, recyclability, and low-carbon disposal methods.

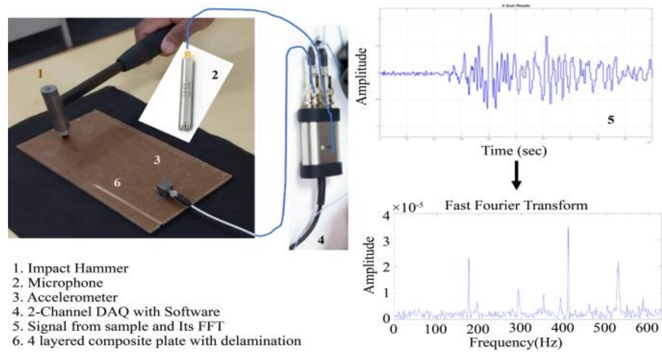

Fig. 3 experimental setup used for the detection of delamination in a composite sample

2.2. Testing of the Composite Laminates using the NRUS Method

The above prepared composite laminates (20x20 cm wide, 2 sheets) were tested for quality using the Nonlinear Ultrasonic Testing method (6 samplings were taken and averaged for better results). These samples were prepared in accordance with ASTM/ISO standards and tested using ASTM E1876 (although not a direct ASTM standard, it was adapted from ASTM E1876). The details of the composite laminate are tableted in Table 1.

Table 1. Summary of composite fabrication variables

Parameter	Specification
Fibre Type	Areca nut fibre (cleaned, NaOH-treated)
Fibre Treatment	5% NaOH solution, 4 h at room temperature, neutralized with 0.1% acetic acid, dried at 70 °C for 24 h
Matrix Material	Epoxy resin (bisphenol-A type) with standard hardener (10:1 ratio)
Fibre/Resin Ratio	50 wt.% fibre: 50 wt.% resin (optimized for strength and processability)
Fabrication Technique	Hand layup followed by compression moulding
Panel Dimensions	200 mm × 200 mm
Panel Thickness	5 mm ± 0.2 mm
Curing Conditions	24 h at room temperature + post-cure at 60 °C for 3h
Surface Finish	Smooth (using glass mould plates and release agent)
Number of Replicates per Test	Minimum 5 specimens per test (tensile, flexural, impact, NRUS, etc.). We followed 6 specimens/readings.
Conditioning Before Testing	48 h at 23 °C and 50% RH (as per ASTM D618)

The test procedure is as follows:

1. Excite the given sample ultrasonically (or) hit the sample with an impact hammer (Model Number: 086C01).

2. Record the response (on time trace) from the sample either by microphone or accelerometer (actually signal recorded with accelerometer will have good signal to noise ratio and provide high quality information. refer to Figure 1). 2 Channel Signal conditioner (MODEL 485B39 PORTABLE ICP® SIGNAL CONDITIONER) is also used for data recordings.
3. Convert the time domain signal to the frequency domain (take the FFT: Fast Fourier Transmission).
4. Record the natural frequency of the sample and its amplitude from the FFT.
5. Repeat the above steps from 1 to 4 for different amplitudes, at least repeat 3 times (for three different amplitudes, the higher the points, the smoother the curve is smooth).
6. The above procedure is repeated 5 times for the two samples (one is NaOH-treated and the other is untreated fiber samples).

3. Results and Discussion

Experimental results of resonance plots (amplitude vs Frequency) for both treated (with NaOH) and untreated Arica nut fiber reinforced laminates are shown in Figure 4.

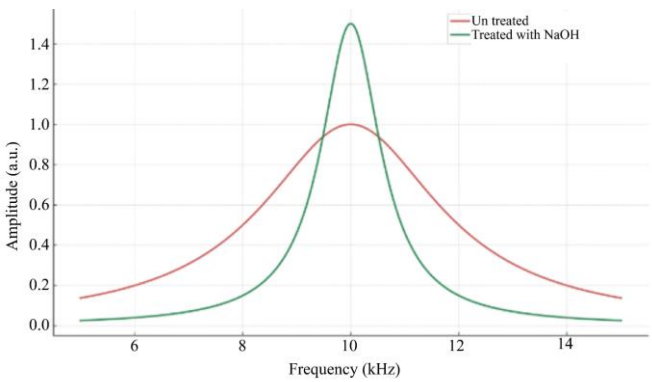

Fig. 4 Resonance curves (Amplitude vs Frequency) for areca nut fibre reinforced composite laminates.

The above plot illustrates resonance curves (Amplitude vs Frequency) for Areca nut fibre reinforced composite laminates, comparing:

Untreated fibres (broader, lower peak): Indicates energy loss due to internal defects, poor interfacial bonding, or fibre disorder.

Treated fibres (NaOH): Sharper and higher peak reflects improved stiffness, better fibre, matrix bonding, and minimal delamination.

After completion of the above experiments, record the frequency (from the FFT) for each reputation. Say for 1st trial f-1, 2nd trial f-2, etc., as shown in Table 2. Then draw the frequency Vs. amplitude plot as shown in Figure 5. Compute the slope from the above graph (refer to Figure 5).

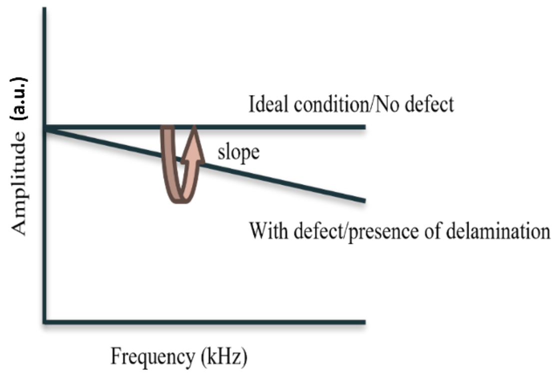

Fig. 5 Frequency response obtained from the experiments for the defective sample

The slope is directly related to the delamination in a composite laminate. The measure of the nonlinearity (slope of the curve) can determine the level of delamination in the given sample.

Table 2. Resonance slopes or peak amplitudes of frequency responses from the sample

Sl.No	Sample type	Repetitions	Frequency (a.u.)
1	Untreated (no defect)	1	4.3
2	Untreated (no defect)	2	4.6
3	Untreated (no defect)	3	4.2
4	Treated (no defect)	1	17.9
5	Treated (no defect)	2	18.2
6	Treated (no defect)	3	19.1
7	Untreated (with defect)	1	4.8
8	Untreated (with defect)	2	7.9
9	Untreated (with defect)	3	6.8
10	Treated (with defect)	1	14.3
11	Treated (with defect)	2	15.9
12	Treated (with defect)	3	17.8

4. Conclusion

From the above results it is clear that high slope (usually greater than 25 degrees) indicates that the delamination is in the outer layers, medium slope (between 5 to 20 degrees) indicates the delamination is at intermediate (core) levels and smaller slope (less than 5 degrees) concludes that disorder of the fiber orientation and damages in the fiber (fiber breakages and micro voids etc. in the matrix), as shown in Table 3.

Table 3. Interpretation of slope values in amplitude-frequency response for damage detection

Slope of Resonance Curve	Slope Range	Indicative Damage Location/Type
High Slope	> 25°	Delamination near outer surface layers (close to skin/layer boundaries)
Medium Slope	5° to 20°	Delamination at intermediate/core layers (mid-plane internal defects)
Low Slope	< 5°	Fibre orientation disorder, micro-voids, matrix microcracks, or fibre breakage

The suggested NRUS method may be able to detect the different types of defects present in composite laminates used for aerospace applications, automobile bodies, and industrial components.

The test method described above provides only a qualitative assessment, indicating whether a given object or sample is defective or not. However, it does not offer information about the nature, size, or location of the defect. For detailed defect characterization and type identification, it is essential to employ other advanced Non-Destructive Testing (NDT) techniques such as Ultrasonic Testing (UT), Imaging methods, or Computed Tomography (CT) scanning.

In the future, this qualitative test can be integrated with advanced NDT methods to develop a hybrid inspection framework. Incorporating real-time imaging, AI-based defect recognition, and data fusion from multiple NDT modalities could enhance diagnostic accuracy. Additionally, efforts can be made to automate the detection process and link qualitative results to predictive maintenance systems, enabling more effective lifecycle management of components and structures.

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All authors contributed equally to this work.

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