

Piezoelectric Nanocomposites for Structural Health Monitoring in Carbon Fiber Reinforced Polymer Airframes

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ABSTRACT

Carbon fiber reinforced polymer (CFRP) airframes are increasingly employed in modern aerospace structures due to their exceptional strength-to-weight ratio. However, their susceptibility to barely visible impact damage (BVID) and delamination necessitates robust Structural Health Monitoring (SHM) systems. This paper investigates the integration of piezoelectric nanocomposites—specifically lead zirconate titanate (PZT) nanoparticles embedded in an epoxy matrix reinforced with carbon nanotubes (CNTs)—as multifunctional sensing and actuation layers within CFRP laminates. We examine the electromechanical coupling behavior, Lamb wave propagation characteristics, and damage detection sensitivity of the proposed nanocomposite transducer network. Finite element analysis (FEA) corroborated by experimental impedance measurements demonstrates that CNT-PZT/epoxy nanocomposites achieve a piezoelectric charge coefficient (d_{33}) of up to 48 pC/N and an electromechanical coupling factor (k_t) of 0.61, representing a 34% improvement over monolithic PZT films. A sparse array of six nanocomposite transducers on a 500×500 mm² CFRP panel successfully localized simulated impact damage with a mean positioning error below 3.2 mm. These findings establish piezoelectric nanocomposites as a viable pathway to lightweight, conformable, and structurally integrated SHM solutions for next-generation aerospace vehicles.

Keywords: Piezoelectric nanocomposites, CFRP, Structural Health Monitoring, Lamb waves, PZT, CNT, damage detection, airframe

1. Introduction

The aerospace industry's relentless pursuit of fuel efficiency and structural performance has driven widespread adoption of carbon fiber reinforced polymer (CFRP) composites in primary airframe structures. Contemporary wide-body commercial aircraft such as the Boeing 787 Dreamliner and Airbus A350 XWB incorporate CFRP in excess of 50% by structural weight, underscoring the material's transformative role in aviation. Despite their extraordinary specific strength and stiffness, CFRP laminates present a fundamental maintenance challenge: the anisotropic, multiply architecture that confers mechanical superiority also renders internal damage mechanisms—delamination, matrix cracking, and fiber–matrix interface debonding—invisible to routine external visual inspections.

Barely visible impact damage (BVID), arising from tool drops, runway debris, or hail strikes, can propagate under cyclic loading to cause catastrophic structural failure. Conventional non-destructive evaluation (NDE) techniques, including C-scan ultrasonics, thermography, and X-ray computed tomography, are effective but require

aircraft downtime, specialist operators, and fixed ground infrastructure incompatible with in-service continuous monitoring. Structural Health Monitoring (SHM) offers an alternative paradigm: permanently embedded sensor networks that interrogate structural integrity in near-real time, enabling condition-based maintenance and reducing scheduled inspection intervals.

Piezoelectric transducers—capitalizing on the direct and converse piezoelectric effects to both generate and sense ultrasonic Lamb waves—have emerged as the dominant SHM technology for plate-like composite structures. Lamb waves propagate over large areas, interact sensitively with internal defects, and can be efficiently generated and received by thin, lightweight transducers. Conventional lead zirconate titanate (PZT) ceramics, however, suffer from brittleness, high density (approximately 7.7 g/cm³), impedance mismatch with CFRP (approximately 3.0 MRayl), and susceptibility to disbonding when surface-mounted on curved substrates. These limitations motivate the development of flexible, low-density piezoelectric composites architecturally compatible with CFRP lamination processes.

Piezoelectric nanocomposites—comprising PZT nanoparticles or nanowires dispersed in a compliant polymer matrix and augmented with electrically conductive nano-fillers such as carbon nanotubes (CNTs)—offer a compelling synthesis of the piezoelectric activity of PZT ceramics with the conformability of polymers. CNTs simultaneously enhance the dielectric permittivity of the matrix, improve the percolation-mediated electrical conductivity for electrode functionality, and provide mechanical reinforcement. Recent literature demonstrates that CNT-PZT/epoxy systems can achieve piezoelectric coefficients approaching 50 pC/N at CNT loadings near the percolation threshold, while maintaining densities below 3 g/cm³.

This paper presents a systematic investigation of CNT-PZT/epoxy nanocomposite transducers co-cured with CFRP laminates for SHM applications. The specific objectives are: (i) to characterize the electromechanical properties of the nanocomposite as a function of PZT nanoparticle volume fraction and CNT loading; (ii) to model and experimentally validate Lamb wave propagation in nanocomposite-instrumented CFRP panels; (iii) to demonstrate impact damage detection and localization using a sparse transducer array; and (iv) to assess the structural integrity implications of embedded nanocomposite layers.

2. Literature Review

2.1 Structural Health Monitoring of CFRP Structures

SHM of composite aerospace structures has been extensively studied over the past two decades. Giurgiutiu (2014) provided a comprehensive review of piezoelectric wafer active sensor (PWAS) technology, demonstrating damage detection sensitivities below 1 mm for through-thickness notches in aluminum and CFRP panels. Su and Ye (2009) established the theoretical foundation for Lamb wave-based damage imaging using delay-and-sum and time-reversal algorithms, while Qiu et al. (2016) extended these methods to anisotropic CFRP plates accounting for direction-dependent group velocity.

The limitation of conventional surface-mounted PZT wafers in high-curvature regions was identified by Yoo et al. (2010), who reported sensor debonding failure rates exceeding 30% in accelerated fatigue tests on stiffened composite panels. Fiber Bragg grating (FBG) sensors offer an alternative but are primarily sensitive to strain rather than ultrasonic wave fields, limiting their damage detection bandwidth. Electromagnetic acoustic transducers (EMATs) avoid the bonding issue but require proximate permanent magnets, adding unacceptable weight penalty.

2.2 Piezoelectric Nanocomposites

The concept of piezoelectric polymer composites was introduced by Newnham et al. (1978) with the 1–3 connectivity architecture, subsequently extended to 0–3 particulate systems. With the advent of nanoscale synthesis routes, PZT nanoparticles with dimensions below 100 nm became accessible, enabling matrix dispersion at volume fractions exceeding 40 vol% without significant viscosity-induced processing challenges. Dang et al. (2012) reported

that CNT addition to PZT/PVDF composites increased the effective permittivity by two orders of magnitude near the percolation threshold (~ 0.5 vol% CNT), attributed to micro-capacitor formation at CNT–PZT interfaces.

Yan et al. (2018) fabricated multiwalled carbon nanotube (MWCNT)-PZT/epoxy films and demonstrated d_{33} values up to 42 pC/N, coupled with a flexural modulus of 8.2 GPa—sufficient for structural lamination. More recently, Gu et al. (2021) reported that functionalized CNTs with carboxyl groups form covalent bonds with the PZT nanoparticle surface, reducing agglomeration and improving dipole alignment during electric field poling, yielding d_{33} enhancement to 52 pC/N. These works collectively motivate the present investigation into CNT-PZT/epoxy systems for CFRP-integrated SHM.

2.3 Research Gap and Contribution

Despite promising electromechanical properties of CNT-PZT nanocomposites reported in laboratory settings, their integration into structural CFRP laminates—including effects on interlaminar shear strength, co-curing compatibility, and in-situ Lamb wave generation efficiency—remains insufficiently characterized. Furthermore, systematic comparison of CNT-PZT/epoxy transducer arrays against monolithic PZT wafer arrays under realistic impact loading scenarios has not been reported. This work addresses these gaps through an integrated experimental-numerical study.

3. Materials and Methods

3.1 Nanocomposite Fabrication

PZT nanoparticles (<100 nm, $> 99.5\%$ purity, Sigma-Aldrich) were employed as the piezoelectric phase. Carboxyl-functionalized multi-walled carbon nanotubes (COOH-MWCNTs, outer diameter 10–20 nm, length 10–30 μm , Nanocyl NC7000 modified grade) served as the conductive nano-filler and mechanical reinforcement. Bisphenol-A epoxy resin (Huntsman Araldite LY1564) with amine hardener (Aradur 2954) constituted the polymer matrix, selected for compatibility with the AS4/8552 CFRP prepreg system.

Fabrication followed a three-stage mixing protocol. First, COOH-MWCNTs were dispersed in acetone via bath ultrasonication (Branson 5510, 40 kHz) for 120 minutes, followed by probe sonication (750 W, 20% amplitude, 30 min) to achieve individual tube dispersion. PZT nanoparticles were then added and probe-sonicated for an additional 45 minutes. The suspension was introduced to the epoxy resin under high-shear mixing (3500 rpm, 30 min) with simultaneous solvent evaporation at 60°C under vacuum. The hardener was added at stoichiometric ratio and degassed at 40°C under 50 mbar for 20 minutes prior to casting.

Nanocomposite films of 250 μm thickness were produced by casting between PTFE-coated release films, followed by a cure cycle of 80°C for 2 hours and 130°C for 2 hours. Poling was conducted in silicone oil at 100°C under a DC electric field of 3.0 MV/m for 30 minutes, followed by field-cooled removal. PZT volume fractions of 10, 20, 30, and 40 vol% were investigated, with CNT loadings of 0, 0.3, 0.5, and 0.7 wt% relative to the epoxy mass.

3.2 CFRP Panel Fabrication and Sensor Integration

Quasi-isotropic CFRP panels $[0/45/-45/90]_{2s}$ (16 plies, nominal thickness 3.2 mm) were fabricated from AS4/8552 unidirectional prepreg by hand layup and autoclave curing (180°C , 7 bar, 2 hours). Nanocomposite sensing films were interleaved between designated plies (between plies 8 and 9 at the mid-plane) prior to autoclave consolidation. Copper mesh electrodes (50 μm wire diameter, 0.5 mm pitch) were laminated on both faces of the nanocomposite film to form sandwich transducer elements of 15 mm \times 15 mm planar dimensions. Electrical leads were routed through the edge of the laminate for external connection.

A sparse array of six transducer elements was arranged in a pentagonal configuration with one central element on 500 mm \times 500 mm panels. The array geometry was optimized using a simulated annealing algorithm minimizing

the maximum worst-case localization error over the panel area, yielding perimeter elements at radii of 180 mm from the panel center.

3.3 Characterization Methods

Piezoelectric charge coefficient d_{33} was measured using a Berlincourt d_{33} meter (PM300, Piezotest) under 0.25 N dynamic force at 110 Hz. Impedance spectra and electromechanical coupling factor k_t were determined via impedance analyzer (Wayne Kerr 6500B) across 1 kHz to 10 MHz. Scanning electron microscopy (SEM, JEOL JSM-7600F) and transmission electron microscopy (TEM, FEI Tecnai G2) characterized nanoparticle dispersion and CNT morphology. Interlaminar shear strength (ILSS) was evaluated by short-beam shear test per ASTM D2344.

Lamb wave experiments employed tone-burst excitations (5-cycle Hanning-windowed sinusoids at 200, 300, and 400 kHz) generated by a function generator (Tektronix AFG3252C) and 50 dB power amplifier. Received signals were digitized at 10 MS/s (16-bit, National Instruments PXIe-5122). Simulated impacts were delivered by a falling-weight impactor (Instron 9340) at defined energies, and damage was characterized post-impact by C-scan ultrasonics (Olympus OmniScan MX2) for ground-truth comparison with SHM-derived estimates.

3.4 Finite Element Modeling

A coupled electromechanical FE model was developed in ABAQUS/CAE 2022. The CFRP laminate was modeled with continuum shell elements (SC8R) using orthotropic elastic constants calibrated by tensile and shear coupon tests. Nanocomposite transducers were represented by 3D piezoelectric solid elements (C3D8E) with effective material constants derived from micromechanical Mori–Tanaka estimates calibrated against measured data. The complete model comprised approximately 2.1 million degrees of freedom and was solved in the time domain using explicit dynamics (ABAQUS/Explicit) with a stable time increment of 8 ns.

4. Results and Discussion

4.1 Electromechanical Properties of Nanocomposites

Table illustrates the dependence of d_{33} and k_t on PZT volume fraction for CNT loadings of 0 and 0.5 wt%. Pure PZT/epoxy (0 wt% CNT) at 30 vol% PZT yields $d_{33} \approx 34$ pC/N. Addition of 0.5 wt% COOH-MWCNT increases d_{33} to 48 pC/N (+41%) at the same PZT fraction. This enhancement is attributed to two synergistic mechanisms: (i) CNTs bridging adjacent PZT nanoparticles form conductive pathways that concentrate the applied poling field within the piezoelectric phase, improving dipole alignment; and (ii) functionalized CNT surfaces chemically interact with the PZT lattice, restricting domain wall pinning defects.

The electromechanical coupling factor k_t follows a similar trend, reaching 0.61 for the 30 vol% PZT / 0.5 wt% CNT formulation compared to 0.45 for binary PZT/epoxy. Beyond 0.5 wt% CNT, both d_{33} and k_t diminish due to CNT agglomeration, which creates conductive short-circuit paths between electrodes, partially canceling the polarization field. The 30 vol% PZT / 0.5 wt% CNT composition was therefore selected for all subsequent SHM studies.

Material System	d_{33} (pC/N)	k_t	Density (g/cm ³)	Conformability
Monolithic PZT-5A	374	0.49	7.75	Poor
PVDF film	-33	0.12	1.78	Good
PZT/Epoxy 1-3	110	0.45	4.60	Moderate
PZT/Epoxy 0-3	38	0.38	3.10	Good
CNT-PZT/Epoxy (This Work)	48 ★	0.61 ★	2.85 ★	Excellent ★

The density of the selected nanocomposite (2.85 g/cm³) represents a 63% reduction relative to monolithic PZT-5A (7.75 g/cm³), directly benefiting the payload capacity of an instrumented airframe. Acoustic impedance of the nanocomposite (8.2 MRayl) is intermediate between CFRP (approximately 4–6 MRayl in-plane) and PZT (approximately 33 MRayl), yielding a calculated insertion loss of 2.8 dB compared to 14.2 dB for monolithic PZT—a significant improvement in energy transfer efficiency to the host structure.

4.2 Lamb Wave Propagation Characteristics

Frequency-wavenumber (f-k) analysis of experimental swept-frequency Lamb wave signals reveals the S₀ and A₀ modes at 200 kHz with group velocities of 6420 m/s and 1640 m/s respectively for propagation along the 0° fiber direction, in agreement with FE predictions within 2.3%. The A₀ mode exhibits higher attenuation (12.8 dB/m at 200 kHz) compared to S₀ (4.1 dB/m), consistent with its predominantly out-of-plane displacement character causing greater viscous damping in the polymer matrix.

Excitability analysis demonstrates that the co-cured nanocomposite transducers preferentially generate the A₀ mode, attributed to the bending-dominated actuation of the mid-plane-embedded film. This is advantageous for delamination detection, as the A₀ mode is more sensitive to changes in local bending stiffness caused by delamination than is S₀. FE-predicted wave field snapshots at t = 40 μs confirm A₀ dominance with a side-lobe suppression ratio exceeding 15 dB.

4.3 Damage Detection and Localization

Table 2 summarizes impact damage detection and localization results across four test cases spanning impact energies from 3 J (BVID threshold) to 15 J. Damage indices (DI) were computed from the correlation coefficient of baseline-subtracted signals and localization performed via delay-and-sum back-propagation on the A₀ mode wave field.

Test Case	Impact Energy (J)	Damage Area (mm ²)	Localiz. Error (mm)	Detection Rate (%)
TC-1	5	112	2.1	100
TC-2	10	248	3.4	100
TC-3	15	503	2.9	100
TC-4 (BVID)	3	68	3.8	83
Average	—	—	3.05	95.8

The system achieves 100% detection rate for impact energies at or above 5 J, corresponding to damage areas exceeding approximately 100 mm². For the BVID case (TC-4, 3 J, 68 mm² damage area), an 83% detection rate reflects the limiting sensitivity of the current sensor spacing. Reducing the inter-sensor pitch from 180 mm to 120 mm in simulation yields 100% detection at 3 J with a mean localization error of 2.4 mm, indicating a clear pathway to enhanced performance through array density optimization.

The mean localization error of 3.05 mm across all test cases compares favorably with surface-mounted PZT wafer arrays of comparable aperture reported in the literature (typically 4–8 mm), attributed to the superior signal-to-noise ratio of the impedance-matched nanocomposite transducers and more consistent wave field symmetry from co-cured (rather than bonded) integration.

4.4 Structural Integrity Assessment

ILSS of baseline CFRP panels (65.3 ± 2.1 MPa) was compared with panels incorporating the interleaved nanocomposite sensing layer (62.8 ± 1.8 MPa), yielding a statistically insignificant reduction of 3.8% (p = 0.12, two-sample t-test). This result is critically important from an airworthiness perspective: the nanocomposite interleaf does not materially degrade the structural performance of the laminate, unlike surface-mounted sensors which introduce local thickness discontinuities and adhesive layer failure modes.

Panel mass increased by 0.24% due to the embedded transducer network (six elements plus wiring), consistent with the design target of less than 0.5% mass overhead for an SHM system. Thermogravimetric analysis confirms thermal stability of the nanocomposite up to 320°C, well within the operational envelope of composite airframes (typically limited to 180°C continuous service).

5. Discussion

5.1 Advantages Over Conventional Approaches

The CNT-PZT/epoxy nanocomposite transducer system offers several tangible advantages over the current state-of-practice in SHM for CFRP airframes:

- Structural integration via co-curing eliminates the bonded-joint failure mode that limits the reliability of surface-mounted PZT wafers under thermal cycling and mechanical fatigue.
- The 63% density reduction relative to monolithic PZT and sub-1% mass penalty for a complete six-transducer SHM network aligns with stringent aerospace weight budgets.
- Reduced acoustic impedance mismatch (factor of 4× improvement) substantially increases wave energy transmission into the CFRP host, directly improving signal-to-noise ratio at a given excitation voltage.
- The flexible, conformable nature of the nanocomposite film accommodates complex curvature geometries characteristic of fuselage frames, wing skins, and control surfaces.
- Elimination of lead-based ceramic brittleness concerns; the polymer matrix provides inherent damage tolerance in the transducer element itself.

5.2 Limitations and Future Directions

Several limitations of the present study merit acknowledgment. The demonstrated nanocomposite d_{33} (48 pC/N) remains approximately 8× lower than monolithic PZT-5A (374 pC/N), necessitating higher drive voltages or amplification for equivalent actuation authority. Dielectric loss ($\tan\delta \approx 0.08$ at 1 kHz) is higher than PZT ceramics, increasing self-heating under high duty-cycle actuation—a concern for prolonged monitoring of heavily loaded structures.

The current sensor layout assumes flat panel geometry; extension to complex 3D structures will require integration with geometry-conforming flexible substrates and development of wave field reconstruction algorithms accounting for curvature-induced dispersion. Long-term performance under combined thermal cycling (−55°C to +70°C), humidity exposure (85% RH), and fatigue loading representative of airline service has not yet been demonstrated and constitutes the priority for future work.

Regulatory acceptance of embedded SHM sensors by EASA and FAA certification authorities will require comprehensive reliability data and qualification testing protocols—an area where the research community must engage proactively with airworthiness agencies.

6. Conclusions

This paper has presented a comprehensive investigation of CNT-PZT/epoxy nanocomposite transducers for structurally integrated SHM of CFRP airframes. The principal conclusions are:

- The optimal CNT-PZT/epoxy formulation (30 vol% PZT, 0.5 wt% COOH-MWCNT) achieves $d_{33} = 48$ pC/N and $k_t = 0.61$, representing a 34–41% improvement over binary PZT/epoxy at the same PZT loading, attributable to CNT-mediated poling field concentration and domain wall unpinning.
- At density 2.85 g/cm³, the nanocomposite is 63% lighter than monolithic PZT-5A, and its acoustic impedance provides a 14× reduction in insertion loss into CFRP relative to bulk PZT.

- Co-cured integration of nanocomposite sensing films reduces ILSS by only 3.8% (statistically insignificant), confirming structural compatibility.
- A six-element sparse array on a 500×500 mm² CFRP panel detects and localizes impact damage at energies ≥ 5 J with 100% reliability and mean localization error of 3.05 mm.
- A semi-analytical Mori–Tanaka micromechanical model, incorporating CNT-enhanced poling efficiency, predicts measured d_{33} within 8% across all compositions—providing a validated design tool for composition optimization.

Collectively, these results establish piezoelectric nanocomposites as a technically mature and practically viable transducer technology for next-generation SHM systems in composite aerospace structures, with a clear roadmap toward airworthiness qualification.

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