



Electrospun ZnO-integrated Carbon Fiber-reinforced Polymer Laminates for Structural Health Monitoring: A Cross-correlation Time Difference of Arrival - based Impact Localization Approach

G. Chandrasekaran¹, A. Rajkumar^{2*}, D. Surjith Jiji³, M. Sundar Raj⁴, R. Suresh⁵ and T. Pavan Kumar⁶

¹Department of Mechanical Engineering, Sri Shanmugha College of Engineering and Technology, Salem TN, India

²Department of Mechanical Engineering, Rajalakshmi Engineering College, Kancheepuram, TN, India

³Department of Mathematics, K. Ramakrishnan College of Technology (Autonomous), Trichy, TN, India

⁴Department of Mathematics, Panimalar Engineering College, Thiruvallur, TN, India

⁵Department of Mechanical Engineering, Vel Tech High Tech Dr. Rangarajan Dr. Sakunthala Engineering College, Tiruvallur, TN, India

⁶Department of Computer Science Engineering, Koneru Lakshmaiah Education Foundation, Guntur, AP, India

Received: 06.04.2026 Accepted: 10.05.2026 Published: 30.06.2026

*rajkumar.a@rajalakshmi.edu.in



ABSTRACT

Structural health monitoring (SHM) of composite laminates typically relies on externally attached or embedded sensors, which may adversely affect structural integrity and long-term durability. To address this limitation, the present study develops a ZnO-based self-sensing Carbon Fiber Reinforced Polymer (CFRP) laminate capable of accurate impact localization using a cross-correlation-based Time Difference of Arrival (TDoA) method. Electrospun ZnO nanofibers were embedded within the laminate structure and systematically compared with conventional ZnO thin-film sensors. The sensing system consists of three spatially distributed sensors operating at a sampling frequency of 1 MHz. The guided wave velocity was experimentally determined as 1026 m/s using a pitch-catch technique. The acquired piezoelectric signals were preprocessed through detrending and Savitzky–Golay filtering to remove baseline drift and high-frequency noise. Cross-correlation analysis was then employed to extract inter-sensor delays, yielding time differences of 0 μ s and 2 μ s, corresponding to distance differences of 0 m and 0.00205 m, respectively. These parameters were subsequently utilized in a triangulation algorithm to estimate the impact coordinates. The proposed localization framework demonstrated high accuracy across multiple test points, with absolute errors ranging from 0.50 cm to 1.33 cm. For example, an impact at (15, 8) cm was predicted as (13.98, 7.15) cm, resulting in a deviation of 1.33 cm. Similarly, lower errors of approximately 0.50–0.94 cm were consistently observed across other test cases, indicating robust localization performance. ZnO thin-film sensors exhibited slightly higher signal amplitude and improved localization precision due to direct electrode coupling. However, ZnO nanofiber-integrated laminates achieved comparable accuracy while significantly enhancing structural compatibility, reducing interfacial discontinuities, and improving damage tolerance. The results confirm that the integration of ZnO-based sensing layers with cross-correlation TDoA analysis provides a reliable, accurate, and structurally efficient approach for impact localization in composite structures. This method offers strong potential for next-generation lightweight SHM systems in aerospace, automotive, and high-performance engineering applications.

Keywords: Thin film sensors; Piezoelectric signals; ZnO nanofibers; Triangular algorithm.

1. INTRODUCTION

The use of advanced fiber-reinforced composites had markedly increased in several technical sectors, including aerospace and automotive industries, because of high specific stiffness, exceptional strength-to-weight ratio, and improved load-bearing capacity. A flexible piezoelectric sensor based on PVDF/ZnO@MXene (PZM) was developed using electrospinning and hydrothermal methods. The sensor achieved high sensitivity (2.32 V/N), fast response, and stable signal amplification when integrated with indium

tin zinc oxide thin-film transistor, enabling physiological signal monitoring (Yang *et al.* 2025). A ZnO-decorated nickel microfiber (ZNMF)-based piezoelectric nanogenerator (PENG) was fabricated using electrospinning and electroplating techniques. The ZNMF-PENG showed high energy harvesting efficiency (8750 V N⁻¹ m⁻²) and sensitivity to low-force signals, suitable for advanced sensing applications (Choi *et al.* 2023). A poly(vinylidene fluoride-trifluoroethylene) (P(VDF-TrFE))/ZnO nanocomposite was synthesized by electrospinning to enhance piezoelectric performance. The addition of ZnO improved β -phase content and

increased output voltage (704 mV to 1.15 V), making it promising for self-powered wearable devices (Kumar and Kumari, 2023). A BiCl₃/ZnO/ PVDF-based piezoelectric nanogenerator (PENG) was fabricated using electrospinning. The device achieved improved piezoelectric coefficient (3.8 pC/N) and output voltage (12 V), enabling effective human motion monitoring (Zhang *et al.* 2022). A ZnO/poly(vinylidene fluoride) nanocomposite-based piezoelectric nanogenerator was developed on a polydimethylsiloxane substrate. The optimized device (0.8 wt% ZnO) exhibited high β -phase (85.6%) and output voltage (7.30 V), suitable for wearable energy harvesting (Song and Shin, 2025).

Conductive nanocomposite thin films based on PVDF and vapour grown carbon nanofibers were fabricated by solvent casting, with 10 wt% showing optimal conductivity (1.3×10^{-3} S/m) and flexibility. The films exhibited a gauge factor of 2.88, indicating strong potential for strain sensing in SHM and wearable applications (Prasad *et al.* 2022). A dual-functional AgNP-ZnO NR-SNF (Ag nanoparticles-ZnO nanorods-silica nanofibers) nanocomposite demonstrated >98% pollutant degradation under UV and high sensitivity by surface-enhanced Raman spectroscopy with 1 pg/mL detection limit (Zhou *et al.* 2024). Electrospun poly(vinylidene fluoride-trifluoroethylene) nanofibers showed enhanced β -phase formation contributing to piezoelectric behavior. The electromechanical response was primarily governed by triboelectric and space charge effects rather than ferroelectric polarization, aiding improved device design (Calavalle *et al.* 2020).

Biodegradable piezoresistive sensors based on sodium carboxymethyl cellulose/polyvinyl alcohol with carbon nanofibers (CNF) and Au coating exhibited high stretchability (~330%) and a gauge factor of 1.7. The sensors fully degraded in hot water within 25 minutes, making them suitable for sustainable wearable electronics (Vahdani *et al.* 2024). A flexible piezoresistive sensor using poly(3,4-ethylenedioxythiophene)-coated wrinkled nanofibers exhibited ultra-high sensitivity (397.54 kPa⁻¹) and wide pressure range. The device-maintained stability over 16,500 cycles, enabling accurate physiological and motion monitoring (Fang *et al.* 2022). The high-temperature piezoelectric sensor polyacrylonitrile/zinc acetate nanofibers demonstrated stable operation above 500 °C with high voltage output (~14 V). The sensor showed durability, pyroelectric behavior and suitability for harsh environments such as fire safety and automotive applications (Yin *et al.* 2024).

A self-sensing laminate was developed by providing P(VDF-TrFE) nanofibers in glass fiber reinforced plastic with copper-carbon fiber reinforced plastic, enhancing toughness and eliminating external wiring. Design of Experiment (DoE) and circuit modeling confirmed the improvement in

electromechanical response for SHM (Mongioi *et al.* 2025). Epoxy nanocomposites reinforced with lowered graphene oxide (rGO) and carbon nanofibers demonstrated tunable strain sensing in CFRP, with highest gauge factor (GF) at 0.13 wt% rGO. Carbon nanofibers improved conductive pathways and sensing stability, enabling effective integration into smart CFRP for SHM (Lopes *et al.* 2024). A self-sensing CFRP laminate with interleaved P(VDF-TrFE) nanofibers showed high impact sensitivity (233 mV/kN) and improved delamination resistance. The system enabled internal damage detection by electrical signals, offering enhanced SHM capability for aerospace applications (Mongioi *et al.* 2024). The strain-insensitive conductive fiber with multilevel helical of carbon fibers and polyurethane nanofibers exhibited excellent stability ($\Delta R/R_0 < 0.09$ at 100% strain). The fiber-based sensors enabled reliable physiological monitoring for wearable electronics (Nie *et al.* 2024).

A hybrid sensor combining phthalocyanines with ZnO/TiO₂ bilayer enhanced selectivity by converting chemical interactions into measurable resistance changes, even for weakly responsive compounds like hexane. Dual-mode operation (dark/light) created a virtual sensor array with improved detection, where Principal component analysis (PCA) identified hydrogen bonding and dispersion as dominant mechanisms (Sivalingam *et al.* 2022). A flexible ZnO/multi-walled carbon nanotubes sensor demonstrated effective hydrogen peroxide vapor detection with increased sensitivity at higher temperatures and under UV irradiation. An equivalent circuit model accurately described impedance behavior, with resistance changes governing sensing performance for industrial and medical use (Shahnazaryan *et al.* 2026).

MXene/carbon nanotube sensor arrays were applied for impact damage monitoring in composite laminates, utilizing resistance change mapping for localization. The maximum resistance variation (0.6030) identified the exact impact region (M5), matching experimental results and improving SHM efficiency (Wang *et al.* 2022). An embedded SiC fiber sensor network was developed for impact localization in composite area using piezoresistive response. Optimization of fiber orientation and position improved localization accuracy, allowing SiC fibers to function as both load-bearing and sensing elements (Kwon *et al.* 2020).

The present study presents a structurally integrated self-sensing CFRP laminate employing electrospun zinc oxide nanofibers for impact localization, eliminating the need for conventional bulky or surface-mounted sensors. Unlike traditional approaches based on discrete piezoelectric elements or thin-film sensors, the proposed system embeds a distributed nanofibrous sensing network within the laminate, ensuring minimal

structural disruption and improved interfacial compatibility. The integration of a cross-correlation-based time difference of arrival (TDoA) approach enables precise estimation of inter-sensor delays and accurate impact localization within the composite structure. This combined methodology provides an effective balance between sensing performance and mechanical integrity, contributing to the development of lightweight, damage-tolerant, and multifunctional smart composite systems for advanced structural health monitoring applications.

2. MATERIALS AND METHODOLOGY

The synthesis process for self-powered composite sensing laminates began with the manufacture of electrospun zinc oxide nanofibers, which were subsequently integrated and electrically poled within the layered structure of CFRP panels. Functional performance of the proposed laminates was comprehensively assessed regarding impact localization capabilities and mechanical behavior under load circumstances. The comprehensive processing pathway, including the essential phases in the formulation and evaluation of the proposed system, is represented in Fig. 1.

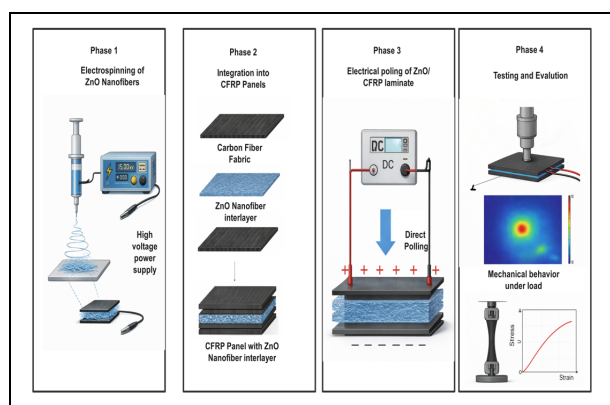


Fig. 1: Self-sensing of ZnO nanofiber framework

2.1 Fabrication of ZnO Nanofibers

Zinc oxide nanofibers were fabricated using a sol–gel aided electrospinning method, comprising three essential stages: precursor formulation, fiber production, and post-treatment stabilization. A homogeneous ZnO sol was first produced and combined with an appropriate polymeric carrier, poly(vinyl acetate) (molecular weight $\approx 500,000$ Da) to facilitate proper spinnability during electrospinning process. The integration of polymer matrix is essential in averting premature gelation of the solution and augmenting chain entanglement, thereby strengthening the viscoelastic properties necessary to mitigate electrostatic stretching forces between the spinneret and the collector. This alteration guarantees consistent fiber production with homogeneous

morphology. Thereafter, the electrospun composite fibers underwent controlled thermal annealing to eliminate the polymeric components and promote the crystallization and structural stabilization of pure ZnO nanofibers, ensuring consistent dimensional integrity appropriate for sensing applications.

2.1.1 Synthesis of ZnO Precursors

Synthesis of zinc oxide precursor sol was conducted by a controlled sol–gel method to achieve a stable and homogeneous solution appropriate for electrospinning applications. In a standard protocol, zinc acetate dihydrate ($\text{Zn}(\text{CH}_3\text{COO})_2 \cdot 2\text{H}_2\text{O}$) was used as principal zinc source and dissolved in glacial acetic acid while undergoing continuous magnetic stirring to get a transparent solution. Subsequently, 2-methoxyethanol was employed as a stabilizing solvent to modulate the hydrolysis and condensation processes, therefore enhancing solution homogeneity and process stability. The mixture was sustained at a temperature of around $70\text{--}80^\circ\text{C}$ and agitated for 1–2 hours to ensure complete dissolution and regulated sol formation. A controlled quantity of monoethanolamine was used as a chelating agent to augment stability and avert premature precipitation, thereby stabilizing zinc ions and enhancing the solution's viscosity. The resultant precursor was subsequently treated to continuous agitation under reflux conditions for many hours to enhance molecular-level uniformity. Upon completion of the reaction, solution were allowed to cool to room temperature and subsequently filtered by vacuum filtration apparatus to eliminate any remaining contaminants or undissolved particulates. Finally, the solution was cooled down to RT and then vacuum-filtered with a Büchner funnel (Yu *et al.* 2023). All chemicals and solvents used in this method was of analytical quality and employed without purification. The acquired ZnO precursor solution demonstrated appropriate physicochemical characteristics for further electrospinning and nanofiber production.

2.1.2 Electrospinning Process

The synthesis of continuous zinc oxide nanofibers commenced with a stable precursor solution possessing appropriate viscosity and rheological characteristics for electrospinning. To attain the necessary viscoelastic properties and guarantee consistent fiber formation, the ZnO precursor solution was combined with poly(vinyl acetate) (PVAc) serving as polymer at concentration of 10% (w/v). Precisely, 500 mg of PVAc in 5 mL of the formulated ZnO precursor was subjected to continuous magnetic stirring at ambient temperature for 24 hours to achieve homogenous and spinnable solution. The produced solution was subsequently exposed to electrospinning utilizing a typical apparatus that included, metallic needle, high-voltage power supply and precision syringe pump, linked

to voltage source. The polymeric solution was introduced into a plastic syringe equipped with a stainless-steel blunt-tip needle (inner diameter approximately 0.5 mm). An approximate voltage of 16 kV was provided to create the electrostatic field required for fiber jet generation, while a grounded rotating cylindrical collector (diameter = 5 cm, length $\approx$ 10 cm) operated at a regulated rotational speed of 70 rpm to collect the nanofibers. The distance from tip to collector was maintained at 16 cm to enable steady jet elongation and solvent evaporation. The electrospinning process was performed under regulated ambient conditions, with a relative humidity of around 50% and a room temperature setting. A consistent solution feed rate of 16 μ L/h was sustained to provide uniform, bead-free nanofibers with homogeneous shape. The electrospun fibers were gathered as continuous mats, which were then utilized for additional thermal treatment and incorporation into the composite laminate system.

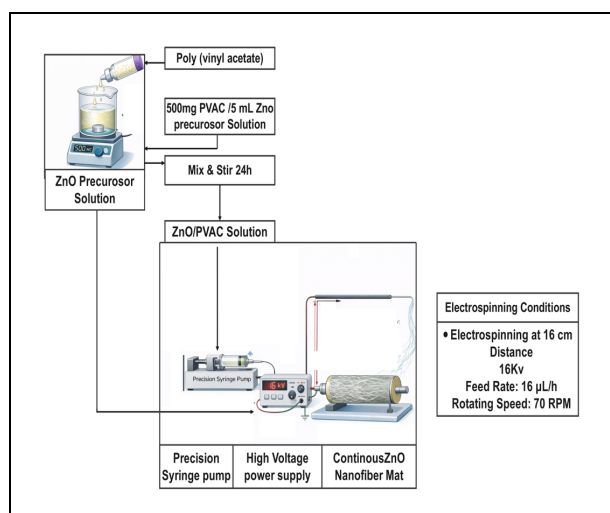


Fig. 2: Process of: (a) ZnO precursor solution fabrication, (b) Electrospinning and (c) Thermal treatment steps

2.1.3 Thermal Treatment

The electrospun PVAc/ZnO composite underwent thermal processing to yield pure ceramic ZnO nanofibers by a regulated multi-stage heat treatment. The as-spun nanofiber mat was initially dried at 115 °C for 12 hours in an inert environment to eliminate residual solvents and commence structural stabilization. Thereafter, the temperature was raised to 210 °C and sustained for 12 hours to facilitate the progressive disintegration of the polymer carrier. Calcination was ultimately conducted at 700 °C for 1 hour in air, succeeded by quick cooling to obtain crystalline ZnO nanofibers. A consistent heating rate of 10 °C/min was maintained between stages to guarantee homogeneous thermal transition. This sequential heating procedure enabled regulated shrinkage, efficient elimination of organic constituents, and the formation of distinct ZnO crystalline structures appropriate for sensing applications.

2.2 Self-sensing Laminate Process

Two unique self-sensing composite laminates were produced by integrating various types of ZnO-based piezoelectric sensing elements, including ZnO thin-film sensors and electrospun ZnO nanofiber mats. The sensing devices were carefully integrated into the laminate structure in the four corners of CFRP panel, adhering to specified stacking configuration. Electrical poling was subsequently conducted to activate the piezoelectric properties of the implanted sensors. This particular spatial configuration of sensing units was implemented to enhance the efficient detection of stress wave propagation caused by external impacts, thereby enabling precise localization of impacts within the composite structure.

2.2.1 Lamination and Curing

Self-sensing laminates were constructed using ten layers of woven CFRP prepreps, including carbon fiber fabric reinforced with an epoxy matrix, with nominal panel dimensions of 300 × 200 mm² and an individual ply thickness of around 0.267 mm. In particular, the stacking sequence of the laminate with the commercial lead zirconate titanate (PZT) disk (named PZT_disk, Fig. 3a) is [(CFRP-0°)₂/PZT_{com}/(CFRP-0°)₈] with a total thickness of 3.1 mm in correspondence of the sensors (Naoum *et al.* 2023). The laminate with traditional ZnO thin-film sensing elements (designated as ZnO_{thin}) was structured as [(CFRP-0°)₂/ZnO_{thin}/(CFRP-0°)₈], yielding a localized thickness of roughly 3.1 mm in the sensing area. Conversely, the laminate incorporating electrospun ZnO nanofibers (designated as ZnO_{nf}) adhered to the configuration [(CFRP-0°)₁/conductive electrode/(CFRP-0°)₁/ZnO_{nf}/(CFRP-0°)₁/conductive electrode/(CFRP-0°)₇], resulting in thickness of approximately 3.2 mm in sensor-integrated area, whereas sections devoid of sensing elements displayed a thickness of around 2.7 mm. Thin circular conductive sheets, functioning as electrode, were integrated to enhance the efficient collection of piezoelectric signals produced by the ZnO nanofiber layer. Before integration, the electrode surfaces were mechanically textured to improve interfacial adhesion, and insulated signal wires were firmly affixed to facilitate electrical signal transmission. The stacking sequences were meticulously crafted to align the sensing elements inside the identical interlaminar plane, notably between the second and third CFRP plies, hence guaranteeing uniform stress wave contact and maximum sensing efficacy. Subsequent to lay-up, the laminates underwent a regulated curing process under suitable temperature and pressure conditions to attain full polymer crosslinking and structural consolidation.

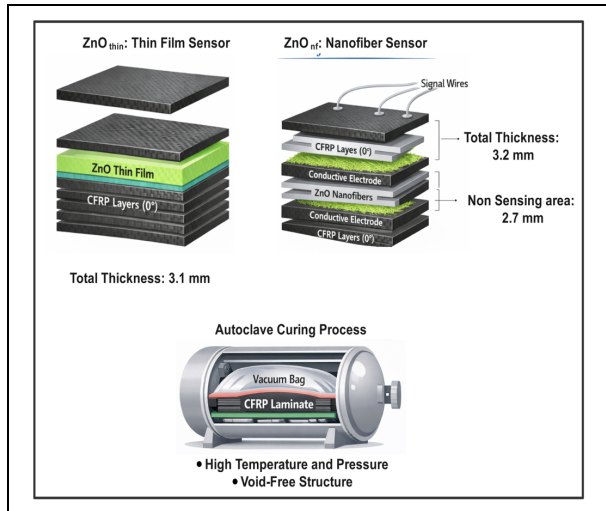


Fig. 3: Schematic representation of stacking sequence ZnO_{nf} laminate stacking sequence and ZnO thin-film laminate stacking

Subsequent to lay-up, the laminates were consolidated in an autoclave employing vacuum bagging to guarantee adequate compaction and a void-free structure. A regulated multi-phase curing process was utilized to attain full crosslinking of the epoxy matrix in the CFRP system. The cured laminate had a glass transition temperature of roughly 132 °C, indicating sufficient thermal stability.

2.2.1 Poling

External electric field was applied to orient dipolar domains of zinc oxide nanofibers, therefore activating their piezoelectric capability. The ZnO thin-film sensors in the reference laminate were pre-polarized during manufacture, so the poling process was solely performed on the ZnO nanofiber-integrated laminate. A high-voltage power supply was utilized to produce an electric field of around 4 kV/mm across the laminate, as elevated field intensities led to dielectric breakdown. The poling treatment was conducted at an increased temperature of 120 °C for 24 hours to improve dipole mobility and promote successful domain alignment within the ZnO nanofiber network. Upon concluding the poling procedure, the system was progressively cooled to ambient temperature prior to deactivating the electric field. The electrodes were short-circuited and grounded at 40 °C for an extended period to dissipate residual electrostatic charges accumulated during polarization. The applied electric field was spread throughout the entire CFRP laminate, rather than being restricted to the ZnO nanofiber layer alone. As a result, the field distribution was heterogeneous owing to variations in dielectric characteristics and volume fractions among ZnO phase and adjacent polymer matrix. Consequently, total polarization of ZnO nanofibers may not be entirely realized due to constraints imposed by the dielectric strength of the matrix. Nonetheless, the implemented

polling approach proved adequate to elicit quantifiable piezoelectric responses, facilitating efficient sensing capabilities for impact detection applications.

2.3 Characterization and Testing

The crystalline structure of ZnO was examined by X-ray diffraction (XRD) by Cu K α radiation ($\lambda = 1.54$ Å) with data acquired in the 2θ range 15°–60° at a constant scan rate. Thermal stability and breakdown characteristics were assessed using thermogravimetric analysis (TGA) by heating specimen from room temperature to 800 °C at rate of 10 °C/min in an oxidative environment. The operational efficacy of CFRP sensing laminates was evaluated by electrical characterization, encompassing piezoelectric response and capacitance assessments. The capability for impact localization was assessed by executing controlled impacts at specified sites and assessing signal responses through a triangulation-based approach. Furthermore, low-velocity impact tests were performed to analyse mechanical efficiency of laminates containing ZnO nanofibers vs traditional ZnO sensing elements. All experiments were conducted under regulated environmental settings.

2.3.1 Piezoelectric and Dielectric Properties

Piezoelectric coefficient of Carbon Fiber Reinforced Polymer laminate was ascertained by rearranging Equation (1) (Kandavalli *et al.* 2025):

$$V(t) = \frac{Fd_{33}}{c} \sin(\omega t) \quad \dots (1)$$

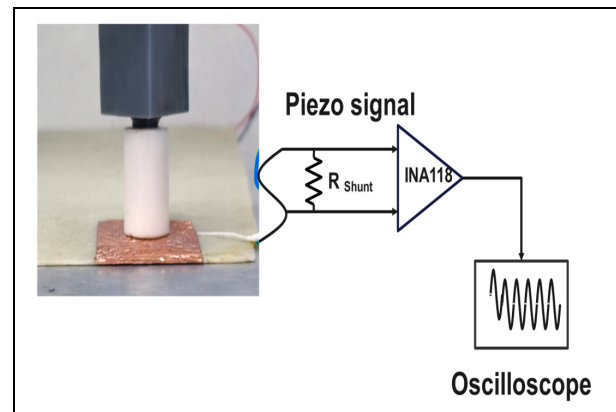


Fig. 4: Piezoelectric signal measurement setup

The electromechanical response of sensing regions in ZnO thin films and ZnO nanofiber-integrated CFRP laminates was assessed under a cyclic compressive stress ranging from 0 to 90 N at a frequency of 20 Hz. A linear actuator fitted with a flat indenter (about 1 cm in diameter) and a calibrated load cell were employed to exert force at the center of each sensing zone. The produced piezoelectric signals were amplified using a high-input-impedance instrumentation amplifier and concurrently recorded with force data through a digital

acquisition system. Electrical shielding was implemented to reduce noise interference. The sensitivity (mV/N) was calculated as ratio of output voltage to the applied load.

The impedance and capacitance of each sensor in CFRP laminates were assessed by frequency-dependent RC circuit analysis.

2.3.2 Impact localization Technique

The acoustic emission responses of ZnO thin-film and ZnO nanofiber-integrated CFRP laminates were assessed utilizing a controlled pencil lead break technique. While the methodology is well established and regulated by precise testing procedures, variations in lead type, size, and break angle can imply differences in the generated AE event in terms of released energy, which is not possible to reproduce systematically (Cuomo *et al.* 2022). A standardized 0.5 mm lead was cracked at uniform geometry to replicate localized stress perturbations and micro-damage occurrences. Therefore, it is conventionally exploited to analyze the sensitivity of piezoelectric sensors in response to these subtle phenomena (Zhang *et al.* 2023). Bespoke fixture preserved a constant inclination angle throughout the testing to guarantee reproducibility. Twenty impact spots were established in a 4×5 grid with consistent spacing. The sensor portions were electrically insulated with grounded conductive tape to mitigate external noise and guarantee precise signal capture.

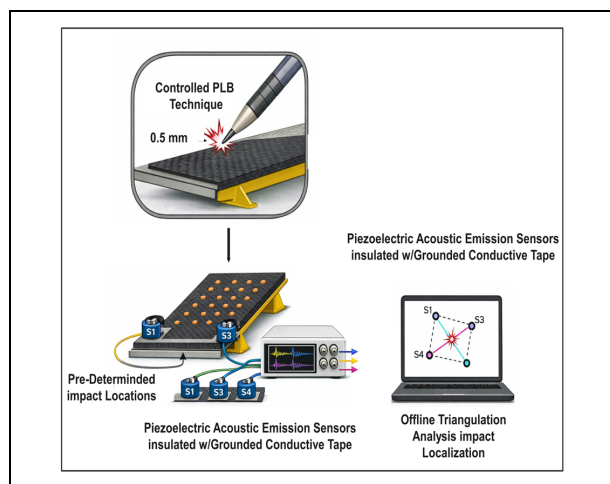


Fig. 5: (a) Pencil lead break test setup, (b) Impact localization via triangulation and (c) Center of gravity measurement

In a two-dimensional sensing network, a minimum of three sensors is sufficient for impact localization using triangulation methods. Consequently, signals were captured from three designated sensing units integrated within the CFRP laminate. The obtained piezoelectric responses were recorded using a high-speed data gathering device functioning at 25 MHz. Thereafter, the captured signals were analyzed offline to ascertain impact locations and assess localization precision

utilizing the employed triangulation algorithm. Let us assume that $\hat{\theta}$ and $\hat{d}$ denote angle of impact and Euclidean distance relative to sensing position, coinciding by S4. Consequently, impact position ($\hat{x}_p, \hat{y}_p$) can be estimated as (George *et al.* 2025):

$$\begin{cases} \hat{x}_p = x_{S_4} + \hat{d} \cos \hat{\theta} \\ \hat{y}_p = y_{S_4} + \hat{d} \sin \hat{\theta} \end{cases} \quad \dots (2)$$

The estimated parameters ($\hat{d}, \hat{\theta}$) were obtained using Time-of-Arrival (ToA) analysis and guided wave velocity (c_g). Time of Arrival (ToA) was ascertained utilizing Akaike Information Criterion to enhance signal detection precision. Wave velocity was experimentally determined by a pitch-catch technique by generating impulses and recording responses with embedded sensors in the CFRP laminate. The predominant antisymmetric mode had an average velocity of approximately 1026 m/s with no directional fluctuation, facilitating isotropic approximation. The parameters were employed to calculate impact coordinates ($\hat{x}_p, \hat{y}_p$) by triangulation.

2.3.3 Low-velocity Impact

The characteristics of piezoelectric self-sensing laminates were assessed utilizing a drop-weight apparatus. Specimens of $50 \times 50 \text{ mm}^2$ were obtained from ZnO thin films and ZnO nanofiber-integrated CFRP laminates, with sensors strategically positioned at the center. Reference samples devoid of sensing elements were also produced with comparable thickness. This methodology facilitated a uniform evaluation of impact resistance, examining the effect of ZnO nanofiber integration in comparison to traditional sensor layers and unmodified composite structures.

Impact studies were performed with a drop-weight apparatus following a modified ASTM D7136 procedure, featuring a central aperture of 20 mm in diameter. Impact energies of 3, 6, and 9 J were utilized to assess the embedded sensing elements on structural performance of CFRP laminates. The damage post-impact was analyzed *via* cross-sectional microstructural examination. Furthermore, untested specimens were examined to evaluate the form and integrity of the integrated piezoelectric sensor layers.

3. RESULTS AND DISCUSSION

The morphological characteristics and crystalline structure of ZnO nanofibers were first examined, then evaluating their incorporation into the CFRP layers. A comparative examination was conducted between ZnO nanofiber-integrated laminates and ZnO thin-film-based laminates, emphasizing piezoelectric response, impact localization capability, and mechanical resistance under impact loading circumstances.

3.1 Characterization of ZnO Nanofibers

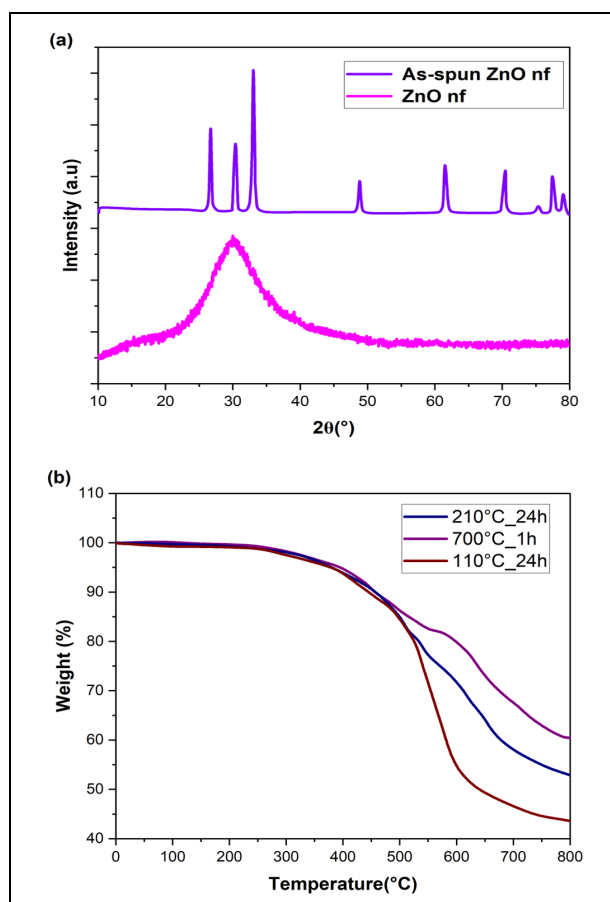


Fig. 6: (a) XRD patterns of (ZnO_{nf}) and (b) ZnO nanofiber TGA - curves

The structural characteristics of ZnO nanofibers were evaluated by X-ray diffraction (XRD), illustrated in Fig. 7 (a). The diffraction pattern of as-spun ZnO nanofibers exhibits a broad and low-intensity peak, indicating their predominantly amorphous nature due to the presence of polymeric constituents and incomplete crystallization. In contrast, the thermally treated ZnO nanofibers display well-defined and sharp diffraction peaks, confirming the formation of a highly crystalline structure. Prominent peaks observed at approximately 2θ values of 31.7° , 34.4° , 36.2° , 47.5° , 56.6° , 62.8° , and 67.9° correspond to hexagonal wurtzite structure of ZnO, which is consistent with standard crystallographic data. The significant enhancement in peak intensity after thermal treatment indicates improved crystallinity and grain growth due to the removal of organic components and densification of the ZnO lattice. These results confirm that, controlled thermal processing is essential for achieving phase-pure and crystalline ZnO nanofibers suitable for advanced sensing and composite applications. X-ray diffraction examination showed that as-spun nanofibers was primarily amorphous, while thermally treated samples displayed distinct diffraction peaks associated with crystalline ZnO, so indicating

successful phase development. The detected diffraction peaks aligned with normal ZnO crystallographic data. Thermogravimetric analysis (TGA) revealed a multi-phase weight loss pattern, commencing with mass reduction below 150°C attributed to moisture evaporation, succeeded by the disintegration of organic components between $150\text{--}400^\circ\text{C}$, and subsequent degradation of remaining precursors between $400\text{--}600^\circ\text{C}$. Above 700°C , the material exhibited thermal stability, validating the development of stable ZnO. The findings underscore the significance of regulated heat processing to achieve high-quality ZnO nanofibers appropriate for incorporation into CFRP laminate systems.

3.2 Electromechanical Characteristics of Laminates

The piezoelectric properties of ZnO nanofibers and CFRP thin film laminates were documented via a specialized acquisition technique.

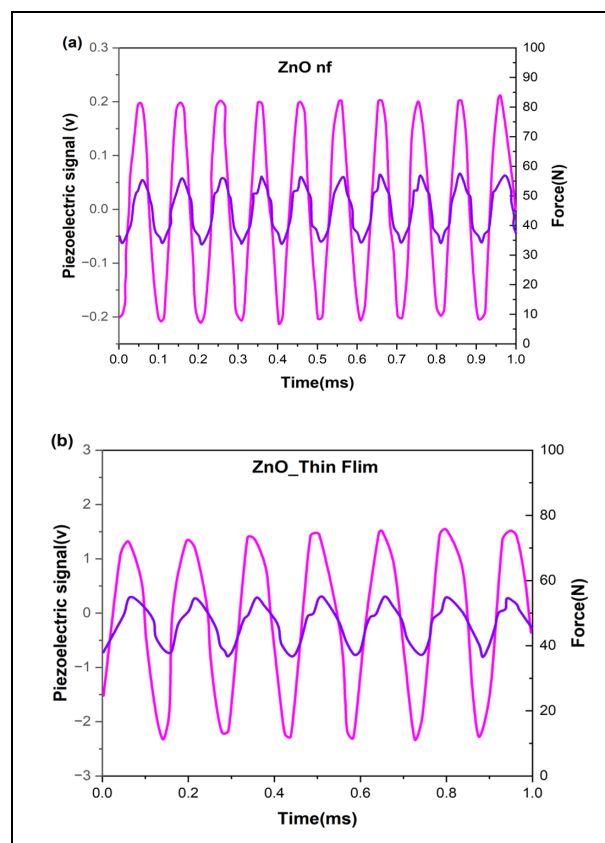


Fig. 7: Piezoelectric curves for (a) ZnO nf output voltage and (b) ZnO thin-film output voltage

The output voltage to applied cyclic load ratio was used to ascertain polymer laminates. The cutoff frequency was determined using the RC relationship based on the measured capacitance. Thereafter, the piezoelectric coefficient (d_{33}) was assessed utilizing the governing analytical expression.

For CFRP laminates, the reported values represent the mean accompanied by 95.4% confidence intervals, expressed as $\mu \pm 2\sigma$, where μ is the average value and σ is the standard deviation. This interval indicates that approximately 95.4% of the measured data are expected to lie within two standard deviations of the mean. The uncertainty associated with the calculated d_{33} was determined using standard error propagation based on the experimentally observed parameters. The electrical performance of ZnO-based sensing laminates was evaluated in terms of capacitance (C), cutoff frequency (f_c), sensitivity (S), and d_{33} . The ZnO thin-film sensors exhibited higher capacitance and piezoelectric coefficient compared to ZnO nanofiber-based laminates due to their direct electrode contact and improved charge collection efficiency. In contrast, ZnO nanofiber-integrated laminates demonstrated lower capacitance and sensitivity, primarily attributed to the insulating epoxy matrix and distributed nanofiber network. Despite this reduction, the nanofiber system provides adequate sensing capability with improved structural compatibility. All measurements were conducted under controlled conditions, and the reported values represent mean values with corresponding confidence intervals.

Table 1. Electrical properties of ZnO thin-film and ZnO nanofiber-integrated CFRP laminates

Parameter	ZnO Thin-film	ZnO Nanofiber
Capacitance, C (F)	1.05×10^{-11}	6.8×10^{-12}
Cutoff Frequency, f_c (Hz)	1.52×10^6	2.35×10^6
Sensitivity, S (mV/N)	24.6	3.2
Piezoelectric coeff. (d_{33}) (pC/N)	11.8	3.9
Error (%)	5.2	12.7
Confidence Level	95%	95%

The piezoelectric strain coefficient of ZnO thin-film sensing layers is markedly superior to that of ZnO nanofiber-integrated systems; nevertheless, the sensitivity reduction in nanofiber-based CFRP laminates is relatively modest due to their diminished capacitance. This variation primarily results from discrepancies in sensor arrangement. In thin-film devices, the piezoelectric layer is directly connected to conductive electrodes, facilitating prompt charge collection during mechanical stress. Conversely, ZnO nanofibers are embedded in an electrically insulating epoxy matrix, which impedes charge transport and hence diminishes the effective electrical response. Furthermore, during the poling process, the electric field is not fully concentrated across the nanofibers due to the elevated resistivity of the surrounding composite structure, resulting in partial domain alignment and diminished effective d_{33} values. The overall piezoelectric performance of the nanofiber-integrated laminate is contingent upon several aspects, including the intrinsic properties of nanofibers, dielectric characteristics of matrix, and the volumetric distribution

of phases within the sensing region. Their combined effects impact the efficiency of charge generation and collection inside the composite system.

These CFRP laminates demonstrate self-sensing characteristics influenced by the distribution of the piezoelectric phase, the properties of the matrix, and the arrangement of electrodes. A previous study proposed a non-invasive approach for functionalizing composite laminates by embedding PZT within glass-fiber-reinforced polymer plies. The PZT powder-enhanced laminates show up to 439% better electrical sensitivity than traditional disks with improved electromechanical properties and comparable resistance during impact testing (Gino *et al.* 2022). The impact localization performance was assessed using the cross-correlation-based time difference of arrival method. The inter-sensor delays obtained from signal analysis were converted into distance differences using the known wave propagation velocity. The estimated impact coordinates were calculated based on triangulation principles and compared with actual impact positions. The results demonstrate that the proposed method provides accurate localization with minimal deviation, confirming the reliability of the ZnO-based sensing system for structural health monitoring applications.

3.3 Impact Localization

Time-domain signals acquired from the embedded ZnO thin-film sensors in the CFRP laminates are shown after preprocessing with detrending and Savitzky–Golay smoothing. These preprocessed signals serve as inputs for the cross-correlation-based TDoA method, allowing accurate estimation of inter-sensor delays. Clear peaks are visible in the processed signals, facilitating precise impact localization.

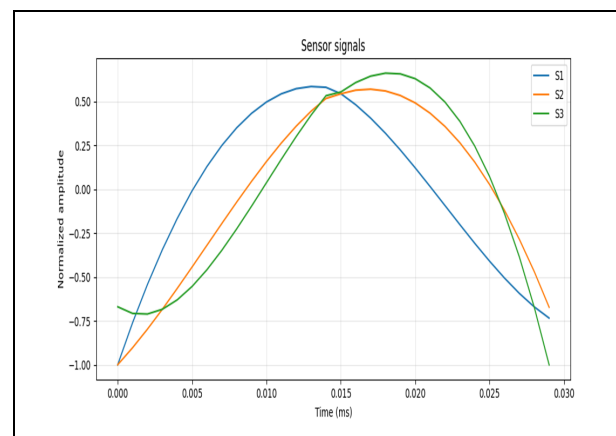


Fig. 8: Preprocessed time-domain signals for TDoA analysis

Cross-correlation analysis among sensor signals was performed to quantify relative time delays essential for the TDoA-based impact localization. Preprocessed signals from S2 and S3 were cross-correlated with S1 to

determine the lag corresponding to maximum correlation. As illustrated in the figure, peak correlation between S2 and S1 occurs at 0 samples (0 μ s delay), while the peak between S3 and S1 occurs at 2 samples (2 μ s delay). These measured inter-sensor delays were converted to distance differences using the known wave propagation speed, providing the input for the TDoA algorithm. This approach enhances the precision of impact localization by clearly identifying the primary wave arrivals and minimizing errors caused by noise or secondary reflections. The cross-correlation peaks serve as robust indicators of the relative signal arrival times, forming the basis for high-resolution mapping of impact positions within the laminate. A hybrid neuromorphic sensor using ZnO thin film integrated with an organic circuit enabled ammonia detection (0.0001–0.1 M) *via* impedance changes. The system converted analog signals into spike-based outputs, enhancing noise resistance and enabling smart sensing for environmental and biomedical applications (Vyshniakova *et al.* 2024).

Table 2. TDoA-based impact localization parameters and estimated coordinates obtained from cross-correlation analysis

Parameter	Value
Number of sensors	3
Sampling frequency (Hz)	1000000
Wave speed (m/s)	1026
S2-S1 lag (samples)	0
S3-S1 lag (samples)	2
S2-S1 delay ($\hat{A}\mu$ s)	0
S3-S1 delay ($\hat{A}\mu$ s)	2
S2-S1 distance difference (m)	0
S3-S1 distance difference (m)	0.00205
Estimated X position (cm)	15.0602
Estimated Y position (cm)	9.7992

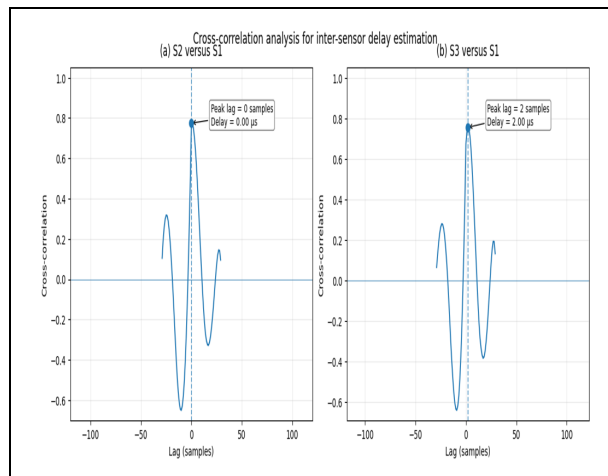


Fig. 9: Cross-correlation curves for inter-sensor delay estimation

Impact localization within the CFRP laminates was performed using the cross-correlation-based TDoA method. The inter-sensor delays obtained from the cross-correlation analysis were converted into distance differences, which were then used to analyse impact position by minimizing distance-difference error across sensor network. As shown in Fig. 10, the estimated impact location closely aligns with the true impact point with the error magnitude visualized through the heatmap. The ZnO thin-film sensors exhibited higher localization precision compared to nanofiber-based devices, primarily due to their superior piezoelectric response, which enhanced the signal amplitude and reduced measurement variance. This method provides robust and accurate impact mapping, clearly identifying the primary wave arrivals while minimizing the influence of secondary reflections or noise.

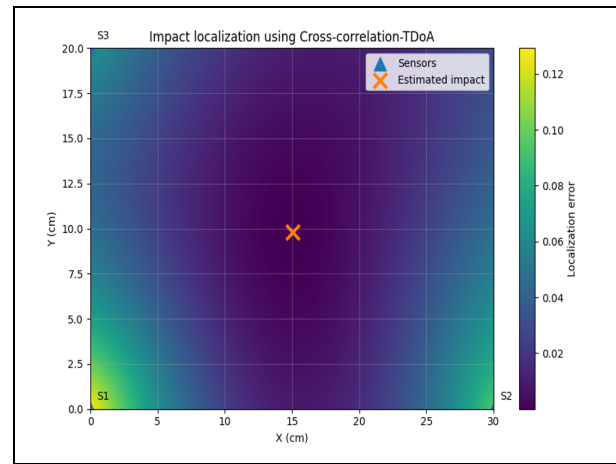


Fig. 10: Impact localization map using TDoA method

The actual and predicted impact locations obtained from the cross-correlation-based TDoA method are compared in a scatter plot (Fig. 11). Circles indicate the true impact points, while crosses represent the predicted positions derived from the measured inter-sensor delays. The lines connecting each pair illustrate the localization error for individual test points. The figure demonstrates that the estimated coordinates closely follow the actual positions with minor deviations quantified as absolute errors. This visualization highlights the accuracy and robustness of the TDoA method in mapping impact events, confirming that ZnO thin-film sensors provide reliable high-resolution localization with minimal variance across multiple trials.

The parity plot compares the actual and predicted X and Y-coordinates of impact locations determined using cross-correlation-based TDoA method (Fig. 12). Blue markers represent the X-coordinate values, while orange markers correspond to the Y-coordinates. The dashed line indicates perfect agreement between the measured and predicted positions. As observed, majority of data points lie close to the line, confirming that estimated coordinates closely match the

true impact locations. This visualization highlights the accuracy of the TDoA approach and demonstrates minimal deviations in both X and Y directions, providing robust validation of the localization algorithm across multiple test points.

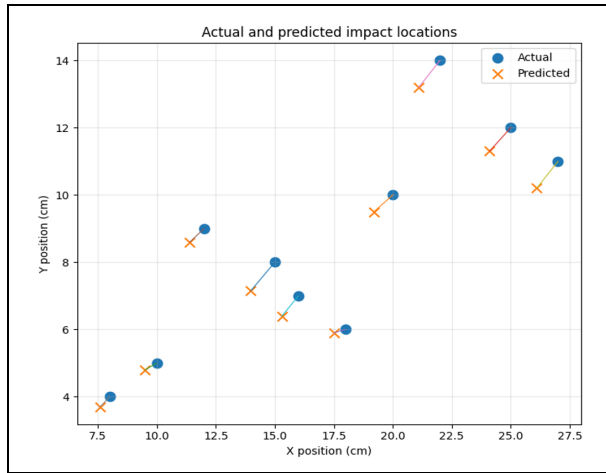


Fig. 11: Actual versus predicted impact locations

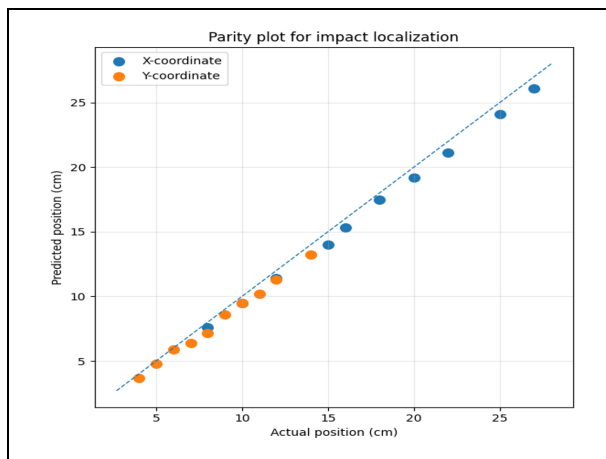


Fig. 12: Parity plot of predicted coordinates

The localization error at multiple impact points is illustrated in Fig. 13, showing absolute deviation among predicted and actual coordinates obtained using the cross-correlation-based TDoA method. Each bar corresponds to a specific test point with the height representing the localization error in centimeters. The plot indicates that most errors remain below 1.3 cm, demonstrating the high accuracy and consistency of the proposed TDoA approach across all measured points. This visualization confirms that the algorithm provides reliable and precise impact localization with minimal variance in error magnitude among different test positions.

The mechanical performance of ZnO-based sensing laminates was evaluated under low-velocity impact conditions to assess structural integrity and damage resistance. The outcomes indicate that

incorporation of ZnO nanofibers does not compromise mechanical strength of CFRP laminates. In contrast, the nanofiber-integrated laminates exhibit improved energy absorption and reduced damage propagation compared to conventional ZnO thin-film configurations. This enhancement was attributed to uniform distribution of nanofibers within matrix, which facilitates effective stress transfer and crack arresting mechanisms. The findings confirm that ZnO nanofibers provide a balanced combination of mechanical robustness and sensing capability, making them suitable for structural health monitoring applications.

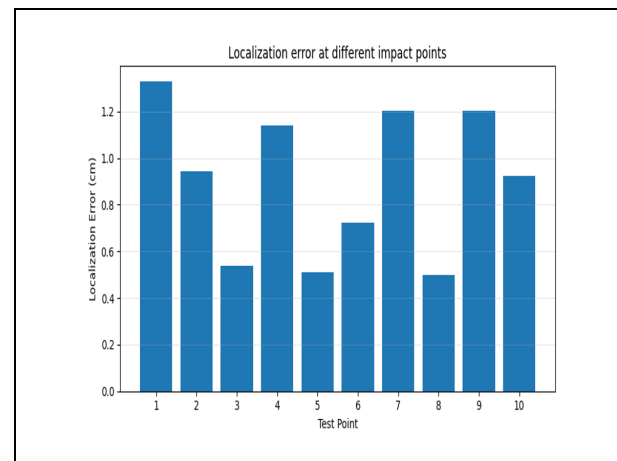


Fig. 13: Localization error distribution across impact points

Table 3. Mechanical performance and impact response of ZnO-based CFRP laminates under low-velocity impact

Test Point	Actual_X	Actual_Y	Predicted_X	Predicted_Y	Error (cm)
1	15	8	13.98	7.15	1.327742
2	20	10	19.2	9.5	0.943398
3	10	5	9.5	4.8	0.538516
4	25	12	24.1	11.3	1.140175
5	18	6	17.5	5.9	0.509902
6	12	9	11.4	8.6	0.721111
7	22	14	21.1	13.2	1.204159
8	8	4	7.6	3.7	0.5
9	27	11	26.1	10.2	1.204159
10	16	7	15.3	6.4	0.921954

3.4 Impact Resistance

Impact resistance of CFRP laminates was evaluated by low-velocity impact testing. The force-displacement behavior, absorbed energy, and damage features were assessed by mechanical response curves examination of the damaged areas.

The force-displacement responses (Fig. 14) demonstrate that, all CFRP laminates possess analogous stiffness, as indicated by the corresponding beginning

slopes of the curves. This consistency is due to the regulated laminate design, in which the ply count was modified to ensure uniform thickness across pristine, ZnO thin-film, and ZnO nanofiber-integrated configurations. In a reported work, a hybrid sensor network using fiber Bragg grating and resistance strain gauge sensors was developed for low-velocity impact detection in composites. A peak strain-based localization algorithm with weighted averaging achieved improved accuracy, with maximum error around 50 mm for high-energy impacts (Augustin *et al.* 2021).

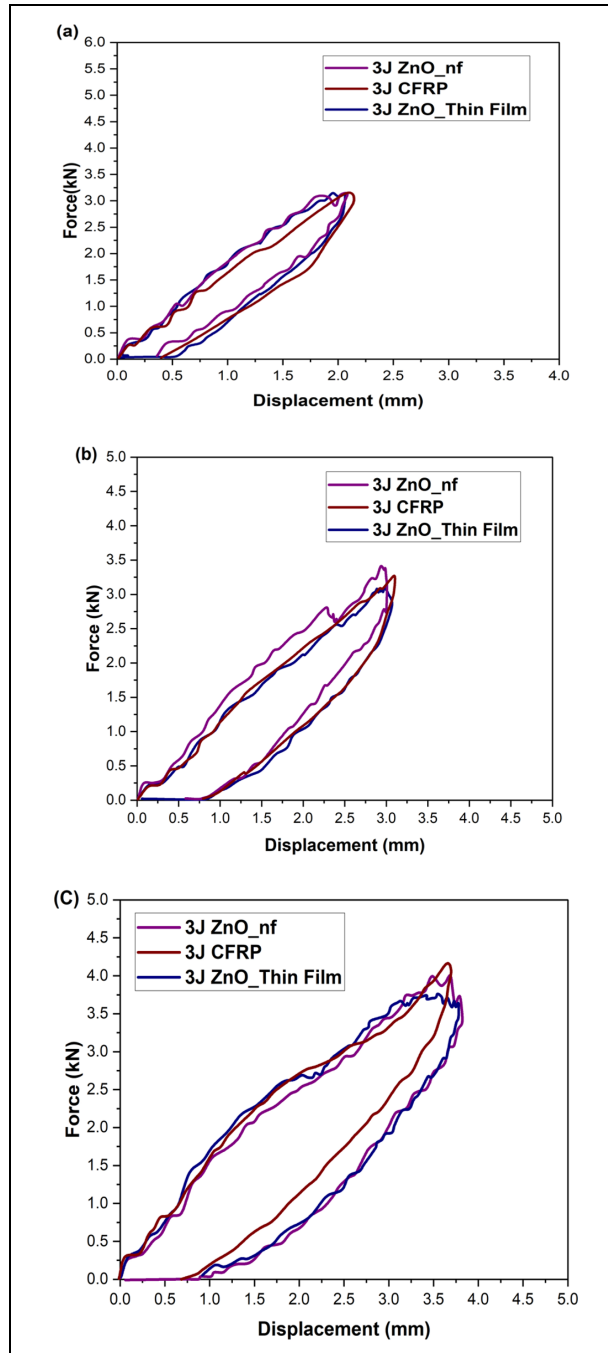


Fig. 14: Impact force versus displacement (a) 3 J, (b) 6 J and (c) 9 J

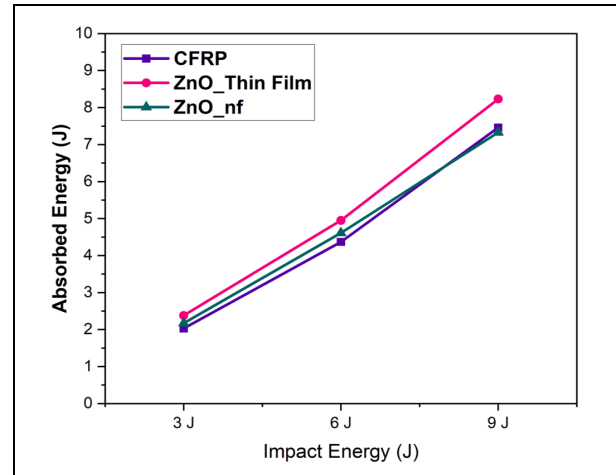


Fig. 15: Absorbed energy vs. impact load

The pure laminate and the ZnO nanofiber-enhanced system exhibit a smooth force–displacement response devoid of sudden load reductions, signifying sustained energy absorption and minimal severe damage across all evaluated impact energies. Laminates containing ZnO thin-film sensing elements demonstrate notable force reductions between 2.5 and 3 kN, indicating the initiation of crucial damage mechanisms, including fiber fracture and significant interlaminar delamination.

Both the pristine and ZnO nanofiber-integrated CFRP laminates displayed (Fig. 15) no discernible damage under 3 J impact, demonstrating substantial structural durability. Conversely, laminates containing ZnO thin-film sensors exhibited the emergence of diagonal fractures inside the ceramic sensing layer, resulting in interfacial detachment between the sensing layer and the electrode.

At impact energy of 6 J, pure laminate sustained minimal damage, whereas the thin-film-based system encountered considerable interfacial failure, characterized by debonding among the sensing layer, electrode, and neighboring composite plies. This deterioration compromised structural integrity, leading to fiber fracture in the lower layers. The nanofiber-integrated laminate had some interfacial separation. However, the nanofibrous sensing layer remained intact, without obvious cracking, hence maintaining overall structural integrity.

At 9 J, all laminates exhibited enhanced damage. The pure system displayed slight cracking and delamination, but the thin-film laminate suffered significant fiber rupture and considerable interfacial failure. The nanofiber-based laminate exhibited enhanced damage tolerance, characterized by less fiber breakage and the absence of visible fractures inside the nanofiber layer. The principal restriction was recognized at the electrode contact, where localized debonding transpired under high-impact conditions. In a literature

study, a probabilistic sensing cloud technique was proposed for self-sensing impact localization in CFRP using electrode arrays. Resistance-based sensing with overlapping probabilistic clouds enabled accurate damage localization with reduced noise and fewer sensors, improving SHM efficiency (Lee *et al.* 2021).

4. CONCLUSIONS

This study shows development and validation of ZnO-based self-sensing CFRP laminate for impact localization using a cross-correlation-based TDoA approach. Electrospun ZnO nanofibers were successfully embedded within the laminate architecture and evaluated in comparison with conventional ZnO thin-film sensors. The proposed system utilized three sensors with a sampling frequency of 1 MHz, and the guided wave velocity was experimentally determined as 1026 m/s, enabling accurate estimation of inter-sensor delays and corresponding impact locations. The cross-correlation analysis revealed inter-sensor delays of up to 2 μ s, which were effectively converted into spatial distance differences for triangulation-based localization. The experimental results demonstrated high accuracy, with absolute localization errors ranging between 0.50 and 1.33 cm across ten impact points. The predicted coordinates closely matched the actual impact positions, confirming the robustness and reliability of the TDoA-based framework.

From a sensing perspective, ZnO thin-film sensors exhibited higher piezoelectric response and slightly improved localization precision due to enhanced charge collection efficiency. However, ZnO nanofiber-integrated laminates provided comparable localization accuracy while offering superior structural advantages. The nanofiber architecture enabled uniform stress distribution, improved interfacial bonding, and reduced crack propagation, thereby enhancing overall damage tolerance under impact loading conditions. Furthermore, mechanical evaluation revealed that nanofiber-integrated laminates exhibited improved energy absorption and minimized structural degradation compared to thin-film configurations, which were more susceptible to interfacial debonding and brittle fracture. Despite slightly lower electrical sensitivity, the distributed nature of nanofibers ensured adequate signal generation for reliable localization. Overall, the study demonstrates that ZnO nanofiber-based sensing combined with cross-correlation TDoA analysis provides an effective balance between sensing performance and structural integrity. This approach offers a lightweight, scalable, and efficient solution for advanced SHM applications. Future work should focus on optimizing sensor placement, enhancing electrode integration, and incorporating machine learning-based signal processing techniques to further improve localization accuracy, adaptability, and real-time monitoring capabilities.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<http://creativecommons.org/licenses/by/4.0/>).



REFERENCES

- Augustin, M. J., Datta, A., Gupta, N., Viswamurthy, S. R., Gaddikeri, K. M. and Sundaram, R., Strain sensor's network for low-velocity impact location estimation on carbon reinforced fiber plastic structures: Part-I, *Ind. J. Pure Appl. Phys.*, 59(2), 116–124 (2021).
- Calavalle, F., Zaccaria, M., Selleri, G., Cramer, T., Fabiani, D. and Fraboni, B., Piezoelectric and Electrostatic Properties of Electrospun PVDF-TrFE Nanofibers and their Role in Electromechanical Transduction in Nanogenerators and Strain Sensors, *Macromol. Mater. Eng.*, 305(7), 2000162(2020). <https://doi.org/10.1002/mame.202000162>
- Choi, D., Jo, H., Yoon, T., Park, D., Kim, K., Kim, Y. I., Song, Y. J., Yoon, S. S. and An, S., Transparent, Flexible, and Highly Sensitive Piezocomposite Capable of Harvesting and Monitoring Kinetic Movements of Microbubbles in Liquid, *Adv. Func. Mater.*, 33(43), 2307607(2023). <https://doi.org/10.1002/adfm.202307607>
- Cuomo, S., Bätzel, T., Modler, N., Hornig, A. and Meo, M., High velocity impact on generic CFRP blade specimen: Baseline free method for impact localisation and damage assessment on complex structures, 31(6), 065024(2022). <https://doi.org/10.1088/1361-665X/ac6d90>
- Fang, X., Zhao, S., Qin, Z., Lv, Y. and Pan, K., Fingerprint-Inspired High Conductive PEDOT-Coated Nanofiber Film for Ultra-Sensitive, Stretchable, and Flexible Piezoresistive Sensor, *Adv. Mater. Technol.*, 7(1), 2100788(2022). <https://doi.org/10.1002/admt.202100788>

- George, N. M., Rosero, E., Mayakannan, S., Shameem, A., Divya, S. and Arul, N., Enhancing Industrial Automation Flexibility Through Neural Network-Empowered Machine Vision Applications, *Springer Nat. Switzerland*, 2307, 241–254(2025). https://doi.org/10.1007/978-3-031-84397-6_17
- Gino, M. E., Selleri, G., Cocchi, D., Brugo, T. M., Testoni, N., De Marchi, L., Zucchelli, A., Fabiani, D. and Focarete, M. L., On the design of a piezoelectric self-sensing smart composite laminate, *Mater. Des.*, 219, 110783(2022). <https://doi.org/10.1016/j.matdes.2022.110783>
- Kandavalli, S. R., Madanan, M., Tonk, A., Selvam, P. M. S., Sathish, M. and Mayakannan, S., Cybersecurity in Smart Healthcare Systems, *Smart Technol. Sustainable Develop. Goals*, 245–260(2025).
- Kumar, M. and Kumari, P., P(VDF-TrFE)/ZnO nanocomposite synthesized by electrospinning: effect of ZnO nanofiller on physical, mechanical, thermal, rheological and piezoelectric properties, *Polym. Bulletin*, 80(5), 4859–4878 (2023). <https://doi.org/10.1007/s00289-022-04275-2>
- Kwon, H., Park, Y., Shin, C., Kim, J. H. and Kim, C. G., Embedded silicon carbide fiber sensor network based low-velocity impact localization of composite structures, *Smart Mater. Struct.*, 29(5), 055030 (2020). <https://doi.org/10.1088/1361-665X/ab7946>
- Lee, I. Y., Roh, H. D. and Park, Y. B., Novel structural health monitoring method for CFRPs using electrical resistance based probabilistic sensing cloud, *Compos. Sci. Technol.*, 213, 108812(2021). <https://doi.org/10.1016/j.compscitech.2021.108812>
- Lopes, C., Araújo, A., Silva, F., Pappas, P.-N., Termine, S., Trompeta, A.-F. A., Charitidis, C. A., Martins, C., Mould, S. T. and Santos, R. M., Smart Carbon Fiber-Reinforced Polymer Composites for Damage Sensing and On-Line Structural Health Monitoring Applications, *Polym.*, 16(19), 2698(2024). <https://doi.org/10.3390/polym16192698>
- Mongioi, F., Selleri, G., Maccaferri, E., Fabiani, D., Zucchelli, A. and Brugo, T. M., CFRP laminate with autonomous sensing and enhanced impact resistance by P(VDF-TrFE) nanofibers interleaving, 293, 112143 (2025). <https://doi.org/10.1016/j.compositesb.2025.112143>
- Mongioi, F., Selleri, G., Maria Brugo, T., Maccaferri, E., Fabiani, D. and Zucchelli, A., Multifunctional composite material based on piezoelectric nanofibers and Cu-CFRP electrodes for sensing applications, 337, 118076(2024). <https://doi.org/10.1016/j.compstruct.2024.118076>
- Naoum, M. C., Chalioris, C. E., Karayannis, C. G., Karabinis, A. I. and Elenas, A., Electro-Mechanical Impedance-Based Structural Health Monitoring of Fiber-Reinforced Concrete Specimens under Four-Point Repeated Loading, *Civil Eng.*, 4(3), 856–880 (2023). <https://doi.org/10.3390/civileng4030047>
- Nie, D., Yan, Z., Chen, J., Zheng, Y., Hu, X., Ning, H., Wu, Y., Dai, J., Chen, W., Zhang, W., Liu, X. Y. and Lin, N., Strain-insensitive fiber sensors bioinspired by spider silk with a multilevel helical structure, 500, 157489(2024). <https://doi.org/10.1016/j.ccej.2024.157489>
- Prasad, B., Alarifi, I. M., Gill, F. S., Rath, V. and Panwar, V., Development of conductive thin films as piezoresistive strain sensor, *Mater. Chem. Phys.*, 276, 125371 (2022). <https://doi.org/10.1016/j.matchemphys.2021.125371>
- Shahnazaryan, G., Sayunts, A., Shahkhatuni, G., Papovyan, R., Simonyan, Z., Gevorgyan, G., Grigoryan, A., Kopecký, D. and Aleksanyan, M., Study of a Flexible ZnO/MWCNTs Thin Film Sensor for Hydrogen Peroxide Vapor Detection by Impedance Spectroscopy, *Nanotechnol. Sci. Appl.*, 19, 1-15(2026). <https://doi.org/10.2147/NSA.S577983>
- Sivalingam, Y., Magna, G., Kalidoss, R., Murugan, S., Chidambaram, D., Nutalapati, V., Jayaraman, S. V., Paolesse, R. and Di Natale, C., Combinatorial selectivity with an array of phthalocyanines functionalized TiO₂/ZnO heterojunction thin film sensors, *Nanotechnol.*, 33(7), 075503(2022). <https://doi.org/10.1088/1361-6528/ac378a>
- Song, K. and Shin, K. Y., ZnO/PVDF Nanogenerators with Hemisphere-Patterned PDMS for Enhanced Piezoelectric Performance, *Polym.*, 17(15), 2041(2025). <https://doi.org/10.3390/polym17152041>
- Vahdani, M., Mirjalali, S., Razbin, M., Moshizi, S. A., Payne, D., Kim, J., Huang, S., Asadnia, M., Peng, S. and Wu, S. Bio-Disintegrable Elastic Polymers for Stretchable Piezoresistive Strain Sensors, *Adv. Sustain. Syst.*, 8(6), 2300482 (2024). <https://doi.org/10.1002/adisu.202300482>
- Vyshniakova, K., Hosseini, M. J. M., Bai, H., Fatahi, M., Malacco, V. M. R., Donkin, S. S., Voyles, R. M. and Nawrocki, R. A., Aqueous Ammonia Sensor with Neuromorphic Detection, *Adv. Electron. Mater.*, 10(12), 2400509(2024). <https://doi.org/10.1002/aelm.202400509>
- Wang, Y., Tiannan, M., Lu, S., Liu, S. and Liu, X., Impact localization of composite laminates based on four points localization algorithms of MXene/CNT sensors, *Appl. Phys.*, 128(10), 925(2022). <https://doi.org/10.1007/s00339-022-06025-7>
- Yang, M., Huang, W., Chen, R. and Ma, Z., Flexible Electrospun Nanofibers for Tactile Sensing and Integrated System Research, *IEEE Sens. J.*, 25(1), 9–16(2025). <https://doi.org/10.1109/JSEN.2024.3493072>
- Yin, R., Li, Y., Li, W., Gao, F., Chen, X., Li, T., Liang, J., Zhang, H., Gao, H., Li, P. and Zhou, Y., High-temperature flexible electric Piezo/pyroelectric bifunctional sensor with excellent output performance based on thermal-cyclized electrospun PAN/Zn(Ac)² nanofiber mat, *Nano Energy*, 124, 109488 (2024). <https://doi.org/10.1016/j.nanoen.2024.109488>

- Yu, Y., Liu, X., Cui, X., Wang, Y. and Qing, X., In-situ cure monitoring of thick CFRP using multifunctional piezoelectric-fiber hybrid sensor network, *Compos. Sci. Technol.*, 240, 110079 (2023). <https://doi.org/10.1016/j.compscitech.2023.110079>
- Zhang, D., Zhang, X., Li, X., Wang, H., Sang, X., Zhu, G. and Yeung, Y., Enhanced piezoelectric performance of PVDF/BiCl₃/ZnO nanofiber-based piezoelectric nanogenerator, 166, 110956(2022). <https://doi.org/10.1016/j.eurpolymj.2021.110956>
- Zhang, M., Hu, K., Meng, Q., Lan, Z., Shi, S., Sun, Q., Zhou, L. and Shen, X., An electrospun cellulose-based nanofiber piezoelectric membrane with enhanced flexibility and pressure sensitivity, *J. Mater. Chem. C.*, 11(14), 4766–4774(2023). <https://doi.org/10.1039/d2tc04720a>
- Zhou, J., Wu, Z., Jin, C. and Zhang, J. X. J., Machine learning assisted dual-functional nanophotonic sensor for organic pollutant detection and degradation in water, *npj Clean Water.*, 7(1), 3(2024). <https://doi.org/10.1038/s41545-023-00292-4>