

Article

Sensor-Based Structural Health Monitoring of Composite Laminates Under Low-Velocity Impact

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Abstract

Low-velocity impacts during manufacturing and maintenance (e.g., tool drops) can induce barely visible impact damage in composite aircraft structures, motivating sensing-assisted approaches for rapid post-event assessment. This study proposes and validates a strain-based structural health monitoring framework for carbon-fiber-reinforced polymer (CFRP) panels by combining surface-mounted strain gauges with explicit finite element analysis (FEA). Drop-weight tests were conducted in accordance with ASTM D7136 using a 1.0 kg hemispherical impactor at drop heights of 250–400 mm. Three strain gauges were positioned at 1.25 mm, 32.5 mm, and 52.5 mm from the impact point to quantify the spatial attenuation of peak surface strain. The measured peak strains exhibited clear-dependent decay and increased with impact energy up to 350 mm, whereas the 400 mm case showed a non-monotonic response and a pronounced deviation from an elastic energy-scaling baseline, consistent with a transition to damage-dominated energy dissipation. Dedicated MSC Apex/Nastran Implicit simulations reproduced experimental trends and provided a physics-based digital twin for interpreting strain signatures in elastic regions, correlating them with likely damage states.

Keywords: composite materials; structural health monitoring (SHM); impact testing; finite element analysis (FEA); strain gauges; aerospace

1. Introduction

The increasing use of composite materials in aerospace engineering is driven by their high strength-to-weight ratios, corrosion resistance, and design flexibility [1,2]. As modern aircraft rely more heavily on these materials, the need for dependable monitoring and inspection strategies has become a safety-critical requirement rather than an optional capability [3]. Structural health monitoring (SHM) provides a systematic framework for assessing structural integrity and enabling condition-based or predictive maintenance before damage reaches a critical level [4,5].

A particularly challenging threat for composite airframes is low-velocity impacts during manufacturing, handling, and maintenance (e.g., tool-drop events). These impacts can trigger internal damage mechanisms—including matrix cracking, delamination, and fiber failure—with limited or ambiguous surface indications. As a result, barely visible impact damage can substantially reduce residual stiffness and strength while remaining undetected by visual inspection alone [6–8].

Among the diverse array of sensor technologies used in SHM, strain gauges are especially attractive for operational deployment because they are relatively low-cost,



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lightweight, and well established in aerospace test practice. When strategically placed on critical composite panels, strain gauges can capture localized transient and residual deformation signatures associated with impact events, enabling post-event assessment even when damage is not immediately apparent. When combined with computational techniques such as finite element analysis (FEA), these measured strain signatures can be mapped to likely damage zones and stress redistribution patterns, improving interpretability and supporting a digital-twin workflow for maintenance decision-making [9–11].

A central maintenance challenge is not only detecting that an impact occurred, but also distinguishing whether the event remained essentially elastic or produced permanent, damage-driven changes (e.g., delamination and fiber failure). In practice, this distinction determines whether an aircraft can safely continue operation until the next scheduled inspection or requires immediate nondestructive testing (NDT) and repair. A strain-gauge network provides a direct pathway to this discrimination: by comparing (i) the spatial decay of peak strain with distance from the impact point and (ii) the energy-normalized strain level expected under elastic scaling, deviations from the baseline can be used as indicators of damage initiation and stiffness redistribution [6–8].

Despite the potential of strain-based SHM, several practical challenges persist. These include sensor placement optimization (to ensure adequate sensitivity to unknown impact locations), calibration and repeatability in anisotropic laminates, and robust feature extraction from noisy, high-rate time signals [12,13]. Furthermore, the impact response is intrinsically nonlinear once damage initiates: as impact energy increases, a larger fraction of kinetic energy is dissipated through progressive failure mechanisms (e.g., matrix cracking and delamination growth), which can alter the measured strain history relative to a purely elastic response [6,8].

This study evaluates the impact response of carbon-fiber-reinforced polymer (CFRP) composite panels through a coordinated experimental and numerical framework using surface-bonded strain gauges and validated FEA.

The primary motivation of this study is to demonstrate that strain-gauge instrumentation can provide actionable indicators of impact presence and severity for maintenance-relevant low-speed events. Specifically, we investigate: (i) the spatial decay of peak strain magnitude with increasing distance from the impact center (using multiple gauges); (ii) the dependence of peak strain on impact energy (controlled via drop height); and (iii) the observed reduction in strain at the highest-energy case (400 mm), which is interpreted as evidence that a meaningful portion of the impact energy is absorbed by permanent damage (e.g., fiber breakage, matrix cracking, and delamination) rather than being returned elastically.

In contrast to studies that focus exclusively on either experimental trials or numerical simulations, this work integrates both to quantify their agreement, thereby strengthening the case for using strain-based sensing supported by simulation as a practical SHM pathway for composite aircraft structures [14,15].

This research makes the following contributions:

- Development of a dedicated impact test platform for composite panels equipped with high-precision strain-gauge instrumentation [16].
- Development and validation of detailed 2D and 3D finite element models for low-velocity impact.
- Quantitative comparison between measured and simulated strain responses across multiple impact energy levels.
- Assessment of strain trends, including spatial relationships relative to the impact point.
- Discussion of feasibility considerations for implementing strain-based SHM in operational aerospace structures.

In practice, the proposed workflow aims to reduce inspection uncertainty after discrete-source impacts (e.g., tool drops) and to support condition-based decisions (continue operation vs. immediate NDT/repair) by converting sparse strain-gauge measurements into interpretable indicators of impact severity and likely damage state. For clarity, the main contributions are summarized as follows:

- A strain-gauge-based SHM workflow for rapid post-impact assessment of CFRP panels, focused on maintenance-relevant low-velocity impacts.
- A validated experimental–numerical “digital-twin” pipeline (drop-weight tests + MSC Apex 2024.1/Nastran 2024.2 Implicit elastic models) to interpret strain signatures and relate them to damage regime transitions.
- An energy-normalized indicator for identifying departures from elastic scaling at higher impact energies (e.g., the 400 mm case), consistent with damage-dominated dissipation.

2. Background and Literature Review

Modern aircraft structures are typically described by three primary components—the fuselage, wings, and tail—each of which is critical to aerodynamic performance and structural integrity [17,18].

Historically, aircraft construction relied on high-strength steels and aluminum alloys. While magnesium parts offered lightweight alternatives, the industry has increasingly pivoted toward composite materials due to their superior performance-to-weight ratios [19]. Figure 1 illustrates the distribution of materials used in modern aircraft structural components.

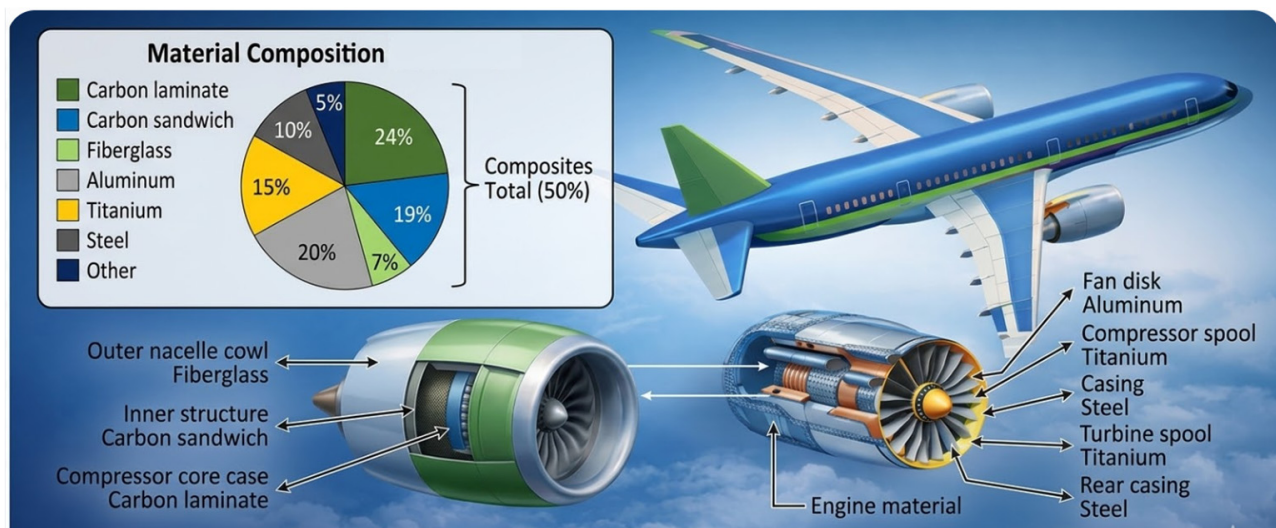


Figure 1. Material types of aircraft structural components.

2.1. Composite Classifications and Properties

Composite materials are generally classified into the following categories:

- Polymer matrix composites (PMCs): Typically use thermoset resins such as epoxy and polyester.
- Metal matrix composites (MMCs): Incorporate metals such as aluminum or titanium.
- Ceramic matrix composites (CMCs): Employ ceramics such as silicon carbide for high-temperature applications [20].

These materials can be further categorized by reinforcement type (e.g., fiber-reinforced or hybrid composites) and are typically manufactured through advanced processes (e.g., autoclave curing) to optimize mechanical properties [21–23].

A comprehensive understanding of damage mechanisms in composite materials is essential for maintaining aircraft safety [24]. Due to their layered architecture, composites are susceptible to various damage modes originating from low-velocity impacts, fatigue, and environmental stressors [6,25]. These degradation factors can significantly reduce structural stiffness and residual strength, necessitating rigorous monitoring and maintenance strategies [7].

Importantly, the dominant damage mechanisms depend on composite class:

- PMCs: In laminated CFRP/GFRP, the polymer matrix and ply interfaces govern many failure processes. Under service loading, PMCs commonly exhibit matrix cracking, fiber/matrix debonding, and interlaminar delamination; these modes can interact and lead to rapid stiffness degradation and residual strength loss [8].
- MMCs: MMCs tend to show more ductile deformation features (in-dentation/plasticity in the matrix) together with reinforcement-related damage such as particle cracking/fracture and particle–matrix inter-facial debonding; the relative contribution depends on matrix alloy, reinforcement type/volume fraction, and impact severity [26].
- CMCs: CMCs are generally more brittle at the matrix scale, so damage may initiate as matrix/cone cracking and evolve with fiber/matrix debonding, yarn or fiber breakage, and delamination in laminated architectures. Even when surface indications are small, internal cracking and delamination can significantly affect residual properties [27].

Low-velocity impact is particularly critical for aerospace PMCs because it can create extensive subsurface delamination and matrix cracking while leaving only a small indentation (i.e., Barely Visible Impact Damage (BVID)). This sensitivity has been widely reported in classic impact literature and in NASA experimental programs on orthotropic and quasi-isotropic laminates, which show that the onset of internal damage (often reflected by a load drop in the impact history) is decisive for post-impact residual properties [28]. More recent work continues to highlight how matrix toughness and stacking sequence influence delamination resistance and energy absorption; for example, thermoplastic composites often exhibit reduced damage area and depth compared to thermoset systems under comparable impact energies [29].

In MMCs, low-velocity impacts typically produce localized indentation and plastic strain in the metal matrix, while repeated or higher-energy impacts can promote reinforcement cracking and interfacial debonding; these mechanisms alter local hardness and can accumulate damage progressively [26].

In CMCs, low velocity impact can generate a spectrum from barely visible surface damage to penetrating damage, with internal cone cracks, yarn breakage, and delamination observed in SiC/SiC laminates. These damage modes can measurably reduce residual tensile and compressive strength even at BVID levels [27].

Figure 2 schematically illustrates the typical damage mechanisms in laminated composites. Specific damage types identified in laminated structures include delamination, matrix cracking, and resin-rich areas. Manufacturing inconsistencies can introduce voids and porosity that act as initiation points for failure [30]. Other flaws include broken fibers, debonding at the fiber–matrix interface, wrinkles, and foreign objects within the laminate stack [31]. Impact-induced damage can manifest through crater formation at the contact point, transverse cracks, and interlaminar fiber breakage [8].

2.2. Advanced Maintenance Methodologies and Monitoring Techniques for Mitigating Composites Impact Damage

Major airworthiness frameworks explicitly recognize that composite structures may experience discrete-source impact damage that is difficult to detect by routine visual inspection and therefore require damage tolerance substantiation and inspection planning

for composite primary structure. Certification guidance emphasizes residual strength and damage-growth considerations for impact damage, including the detectability threshold associated with the chosen inspection method [32,33]. Complementary research has examined the reliability of visual inspection of composite structures and highlighted the strong dependence of detectability on surface finish, lighting, and human factors, motivating sensing-assisted approaches to increase confidence in damage discovery [34].

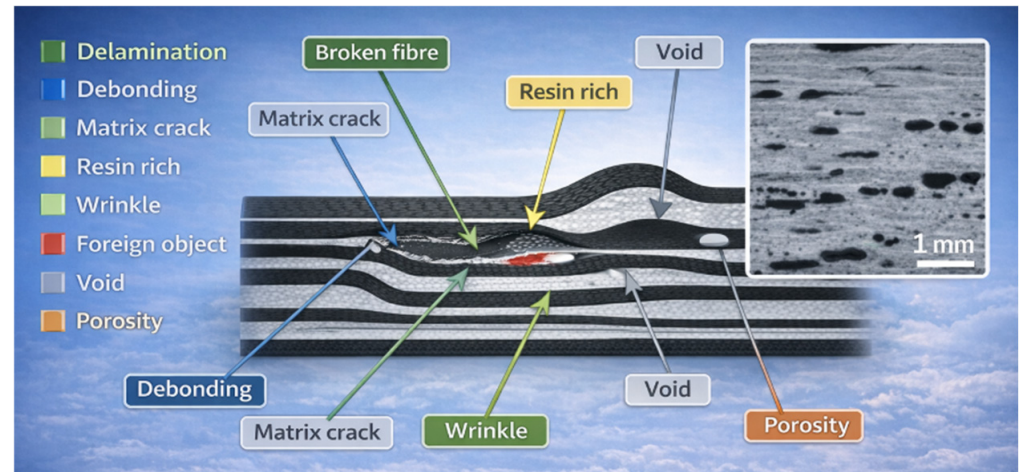


Figure 2. Schematic representation of complex internal damage mechanisms (e.g., matrix cracking, delamination) in composite laminates, which often manifest as Barely Visible Impact Damage (BVID) targeted by the proposed strain-based SHM framework.

From an operational standpoint, maintenance-related impact events (e.g., inadvertent tool drops) are a practical concern because internal damage may occur with limited external evidence. While publicly available accident investigations rarely attribute major accidents solely to undetected composite BVID, regulators and industry safety bodies consistently treat impact-damage detectability and damage tolerance as central risks for composite airframes and therefore encourage robust inspection protocols and, increasingly, SHM technologies to reduce uncertainty [32,34].

Modern aircraft maintenance programs emphasize proactive and preventive measures to mitigate the risks associated with material damage [35,36]. These protocols incorporate tool management systems, environmental controls, and specialized operational procedures designed to avoid accidental damage during routine maintenance activities [37]. Reliability-centered maintenance (RCM), condition-based maintenance (CBM), and predictive maintenance (PDM) are commonly adopted methodologies [36].

SHM systems play a vital role in early detection and assessment of damage within composite materials [38]. Common sensing approaches include:

- Fiber-optic sensors (e.g., fiber Bragg grating (FBG)) for strain and temperature measurements.
- Acoustic emission testing to detect microcracking and internal damage [39].
- Piezoelectric and electromagnetic sensors for real-time integrity monitoring and life-cycle prediction [40].

In the last decade, SHM research for composite aircraft structures has increasingly focused on detecting and characterizing barely visible impact damage (BVID) using multiphysics sensing and data-driven interpretation. Ultrasonic guided waves excited and sensed by piezoelectric transducer networks remain a leading approach due to their sensitivity to local stiffness discontinuities associated with delamination and matrix cracking [41,42]. In parallel, optical fiber sensing (e.g., fiber Bragg grating (FBG) sensors and distributed

optical methods) has gained momentum for capturing impact-induced strain redistribution over larger areas and enabling embedded or minimally intrusive instrumentation [43].

Beyond wave-based methods, there is renewed interest in strain-based SHM strategies that use multipoint strain measurements to identify compliance changes and damage states. Recent studies have shown that correlating strains from multiple locations can detect and localize changes in structural behavior without requiring full knowledge of the operational loads, thereby improving applicability to in-service monitoring [44]. For impact scenarios, recent experimental programs have also reported that measured strain signatures can be systematically related to impact parameters (location and energy) and coupled with simulation to provide actionable diagnostics for composite panels [45].

3. Materials and Methods

3.1. Materials

The composite plates were manufactured using Hexcel 8552/AS4 carbon/epoxy prepreg arranged in a 5H satin weave configuration. Panels were produced by hand lay-up followed by autoclave curing at 180 °C under 6 bar pressure for 2 h. The prepreg manufacturer is Hexcel Corporation (Stamford, CT, USA) [16,17].

To accurately model the mechanical response, the orthotropic properties of the CFRP laminate were defined as follows: longitudinal modulus $E_1 = 77$ GPa, transverse modulus $E_2 = 75$ GPa, in-plane shear modulus $G_{12} = 6.5$ GPa, and Poisson's ratio $\nu_{12} = 0.06$. Because the finite element analysis was intentionally maintained within the linear elastic regime to establish a theoretical damage-free baseline, ultimate strength parameters for progressive failure were not incorporated into the material definition.

Each impact condition was tested on a single specimen; therefore, statistical scatter and repeatability could not be evaluated in the present study. Future studies should include multiple specimens for each impact condition to assess experimental repeatability and statistical variability.

3.2. Surface Preparation

Prior to sensor installation, surfaces were cleaned using acetone and a clean white cloth to remove contaminants. Bonding areas were prepared with fine-grit sanding to ensure strong adhesive bonding, improving strain gauge adhesion and measurement accuracy. Specimens were cut to the dimensions recommended by ASTM D7136/D7136M-20 [16].

3.3. Strain Gauge Installation and Equipment

Strain gauges measure deformation through changes in electrical resistance and are commonly integrated into Wheatstone bridge circuits. Quarter-bridge, half-bridge, or full-bridge configurations are selected depending on sensitivity and experimental constraints [46,47].

Micro Measurement CEA-13-125UR-350 (Micro-Measurements, Raleigh, NC, USA) strain gauges, which feature an active gauge length of 1.57 mm, were bonded using M-Bond 200 adhesive (Micro-Measurements, Raleigh, NC, USA). The primary gauges evaluated in this study (located at 1.25 mm, 32.5 mm, and 52.5 mm) were aligned parallel to the primary fiber direction of the top ply. Signals were captured using a National Instruments NI-9237 data acquisition module (National Instruments, Austin, TX, USA) configured in a Wheatstone half-bridge arrangement, with a sampling rate of 20,000 samples per second (20 kS/s). The module's integrated anti-aliasing filters were utilized to ensure accurate high-speed dynamic strain measurements during the impact event. Peak strains were extracted based on the absolute maximum value recorded within the primary impact duration window.

To ensure the reliability of the experimental data, each impact test was repeated three times. Statistical dispersion was strictly analyzed. At sub-critical impact heights (250 mm to 350 mm), the standard deviations across all primary gauges remained exceptionally low (strictly below 2% to 8.5% of the mean values), confirming high measurement repeatability. However, at the 400 mm impact height, while the outer gauges (32.5 mm and 52.5 mm) maintained low scatter (4.2% and 7.0%, respectively), the gauge closest to the impact center (1.25 mm) exhibited a massive spike in standard deviation ($\pm 403.1 \mu\epsilon$, corresponding to a 45.4% variance). This abrupt, localized statistical scatter is a physical hallmark of unpredictable material failure initiating directly beneath the impactor.

3.4. Impact Test Setup

Low-velocity impact experiments were conducted using a custom drop-weight apparatus compliant with ASTM D7136/D7136M-20 Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event. ASTM International: West Conshohocken, PA, USA, 2020. The rig employed a 1.0 kg impactor with a 16 mm-diameter hemispherical steel tip (AISI 1025). The specimens were clamped and instrumented with strain gauges connected to a Wheatstone bridge, as shown in Figure 3, and were subjected to central impacts by varying the drop height between 250 mm and 400 mm.

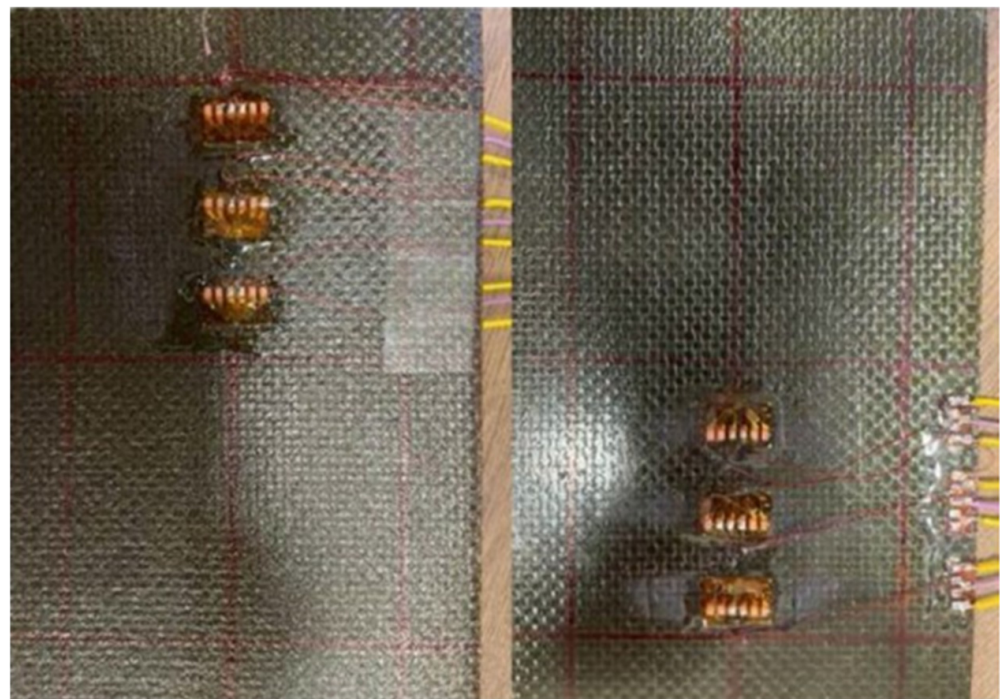


Figure 3. Test plates with installed strain gauge and Wheatstone half bridge (upper and lower surface).

Assuming free fall with negligible air resistance, the impact of velocity v at contact and the potential energy available for transfer to specimen E are

$$v = \sqrt{2gh}, \quad (1)$$

$$E = mgh \quad (2)$$

where m is the impactor mass, h is the drop height, and $g = 9.81 \text{ m/s}^2$. The calculated impact velocities and corresponding available impact energies for each drop height are presented in Table 1.

Table 1. Calculated impact velocity and available impact energy for the drop-weight tests ($m = 1.0$ kg).

Drop Height (mm)	Velocity (m/s)	Energy (J)
250	2.215	2.453
300	2.426	2.943
350	2.621	3.434
400	2.801	3.924

3.5. Finite Element Model

The finite element method (FEM) enables prediction of stress distributions, deformations, and potential failure points with high fidelity. In this study, numerical simulations are integrated with experimental data to provide a comprehensive understanding of composite response under impact loading [48,49].

A finite element model was developed in MSC Apex/Nastran Implicit to simulate the low-velocity impact response of the composite panel. The CFRP plate was represented using a 2D laminated shell discretization with quadrilateral elements. Although a traditional mesh convergence study involving multiple mesh densities was not independently conducted, the optimal element size was established through rigorous experimental validation. The selected 2.5 mm shell element discretization was validated by the close agreement between the implicit numerical strain predictions and the experimental measurements, confirming that it adequately captures the localized strain gradients under the investigated load levels. The impactor was modeled as a 16 mm-diameter spherical steel body using a 3D tetrahedral mesh with a nominal element size of 1 mm, yielding 3616 tetrahedral elements. The complete model comprised 17,918 nodes. To facilitate a direct comparison with the experimental data, numerical strains were extracted by querying the directional in-plane strains at the shell elements corresponding to the exact spatial coordinates and fiber orientations of the surface-mounted strain gauges (i.e., at 1.25 mm, 32.5 mm, and 52.5 mm from the impact center).

The laminate lay-up in the shell model followed the tested configuration and was defined as five plies of 0.20 mm thickness each (total thickness 1.0 mm) with stacking sequence [0/45/90/45/0]. Orthotropic ply properties were assigned to the CFRP laminate, whereas isotropic material properties were used for the steel impactor.

To evaluate the predictive capability of the model, the expected peak strains at 400 mm drop height—obtained by linear extrapolation of the experimental strain–impact energy relationship using 250–350 mm data—were compared with the measured values, as summarized in Table 2.

Table 2. Expected 400 mm peak strains assuming an elastic trend (linear extrapolation of experimental strain vs. impact energy using 250–350 mm data) compared to measured values.

	1.25 mm	32.5 mm	52.5 mm
Expected at 400 mm ($\mu\epsilon$)	1223.4	2069.1	3456.6
Measured at 400 mm ($\mu\epsilon$)	887.0	1918.7	2819.3
Difference (%)	−27.5	−7.3	−18.4

Boundary conditions were defined to replicate the ASTM D7136 fixture. The experimental impact setup, including the clamping configuration and drop-weight apparatus, is shown in Figure 4. Based on the clamping regions, the specimen was constrained at the four corners over 12.5 mm $\times$ 15 mm areas by fixing the translational degrees of freedom in X, Y, and Z and the rotational degrees of freedom about X, Y, and Z. This modeling choice

follows the intent of ASTM D7136, which emphasizes that impact response and damage state are strongly dependent on support conditions and boundary constraints [16].

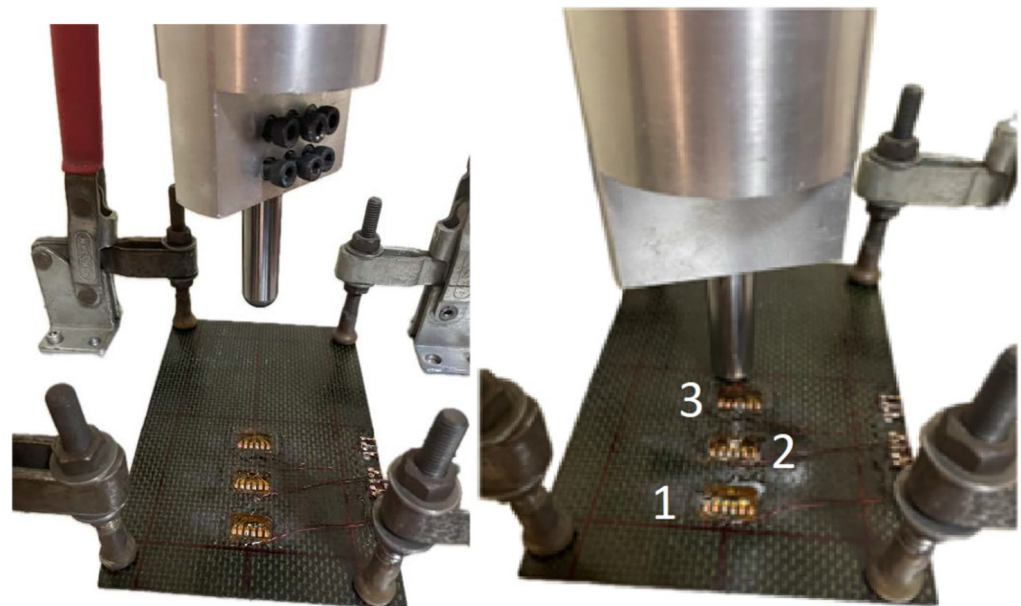


Figure 4. ASTM D7136/D7136M-20-Compliant drop-weight impact test apparatus, detailing the clamping fixture constraints and the alignment of the hemispherical impactor relative to the three-gauge instrumentation layout on the CFRP specimen. The labeled locations (1, 2, 3) correspond to specific strain gauge positions (1.25 mm, 32.5 mm, and 52.5 mm from the specimen edge, respectively).

The overall numerical approach (explicit time integration, hemispherical steel impactor, and fixture-consistent boundary conditions) is consistent with a broad body of standard-based low-velocity impact simulations of composite laminates. Prior studies performing drop-weight impact tests according to ASTM D7136/D7136M-20 commonly adopt explicit solvers (e.g., ABAQUS/Explicit or LS-DYNA) to capture contact, geometric nonlinearity, and progressive damage initiation/propagation while maintaining numerical robustness [50,51]. The present study deliberately utilizes an implicit solver (MSC Nastran) restricted to the linear elastic regime. This methodological choice allows for the clear identification of damage onset by systematically quantifying the experimental deviation from the idealized elastic prediction. From a modeling standpoint, the laminated shell idealization used here is widely accepted as an efficient representation for thin composite panels when the objective is to recover global impact response and strain fields at discrete locations (e.g., strain-gauge points), provided that the lay-up, thickness, boundary conditions, and contact definition match the experimental configuration [52]. The developed finite element model, including the discretized laminate and spherical impactor, is illustrated in Figure 5.

The finite element model was developed and solved using MSC Apex with an Implicit solver. Crucially, the numerical model was formulated to be strictly elastic, intentionally omitting progressive damage or delamination failure criteria. The primary objective of utilizing an implicit elastic solver was to establish a robust, theoretical ‘damage-free’ baseline under equivalent loading. By comparing the experimentally measured dynamic strains against this idealized implicit elastic prediction, it becomes possible to systematically quantify the deviation from linear elastic scaling at higher impact energies (e.g., the 400 mm case), thereby inferring the onset of damage-dominated energy dissipation. Mesh sensitivity was evaluated, confirming that a 2.5 mm shell element size adequately captured the localized strain gradients.

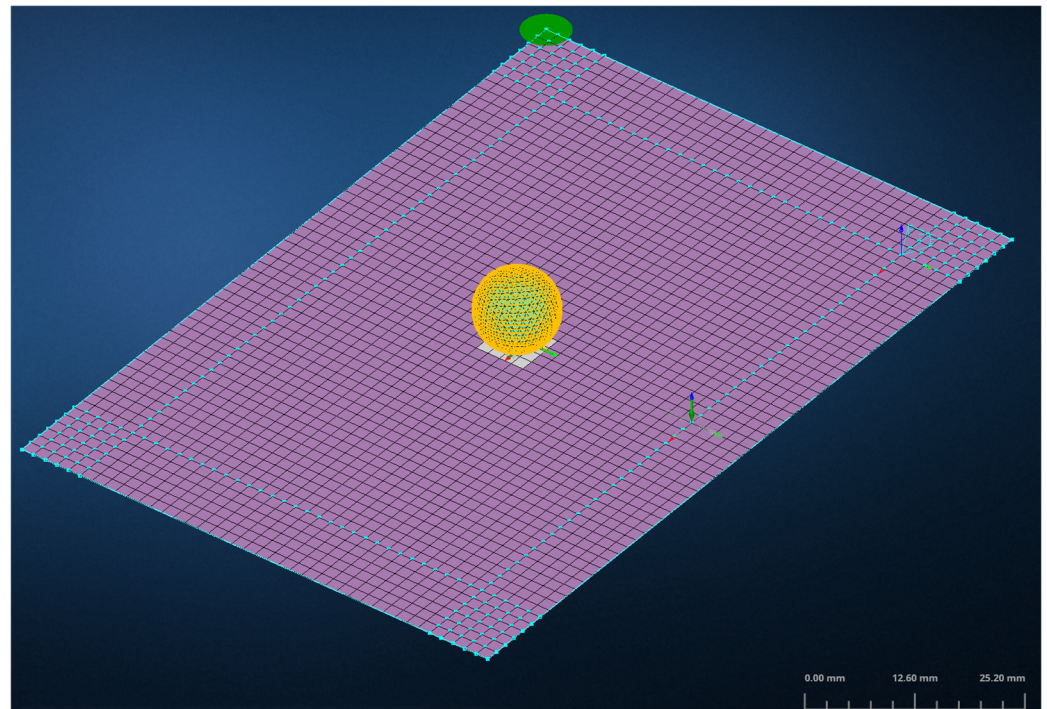


Figure 5. Discretized finite element model formulated in MSC Apex, illustrating the 2.5 mm quadrilateral shell element mesh for the composite laminate (purple plate) and the 3D tetrahedral mesh for the rigid spherical impactor (yellow/orange sphere).

4. Results

4.1. Results and Discussion Summary

Impact tests were conducted at drop heights of 250, 300, 350, and 400 mm, with three repetitions per level. The standard deviation from three strain measurement values of the corresponding test group is given in parentheses in Table 3. Strain gauges captured deformation response at different points. The strain measurements showed consistent trends with minor variation, indicating good repeatability.

Table 3. Comparative strain analysis between experimental tests and FEA at three-gauge locations measured from the impact point (12.5 mm, 32.5 mm, 52.5 mm).

Height (mm)	Metric	12.5 mm	32.5 mm	52.5 mm
250	Avg. Strain ($\mu\epsilon$)	720.00	1363.67	2026.33
	FEA ($\mu\epsilon$)	738.00	1330.00	2020.00
	Difference (%)	2.44	−2.53	−0.31
300	Avg. Strain ($\mu\epsilon$)	994.33	1669.67	2628.00
	FEA ($\mu\epsilon$)	981.00	1780.00	2770.00
	Difference (%)	−1.36	6.20	5.13
350	Avg. Strain ($\mu\epsilon$)	1029.00	1816.00	2949.00
	FEA ($\mu\epsilon$)	1040.00	1880.00	2940.00
	Difference (%)	1.03	3.42	−0.30
400	Avg. Strain ($\mu\epsilon$)	887.00	1918.67	2819.33
	FEA ($\mu\epsilon$)	1100.00	1990.00	3110.00
	Difference (%)	19.36	3.58	9.35

4.2. Analysis of Strain and Energy Levels

Gauges positioned closer to the impact center registered higher strain values, and the measured peak strain decayed with increasing distance from the impact point (12.5 mm,

32.5 mm, and 52.5 mm). This monotonic spatial decay is summarized in Figure 6 and forms the basis for correlating impact severity with the strain-field gradient.

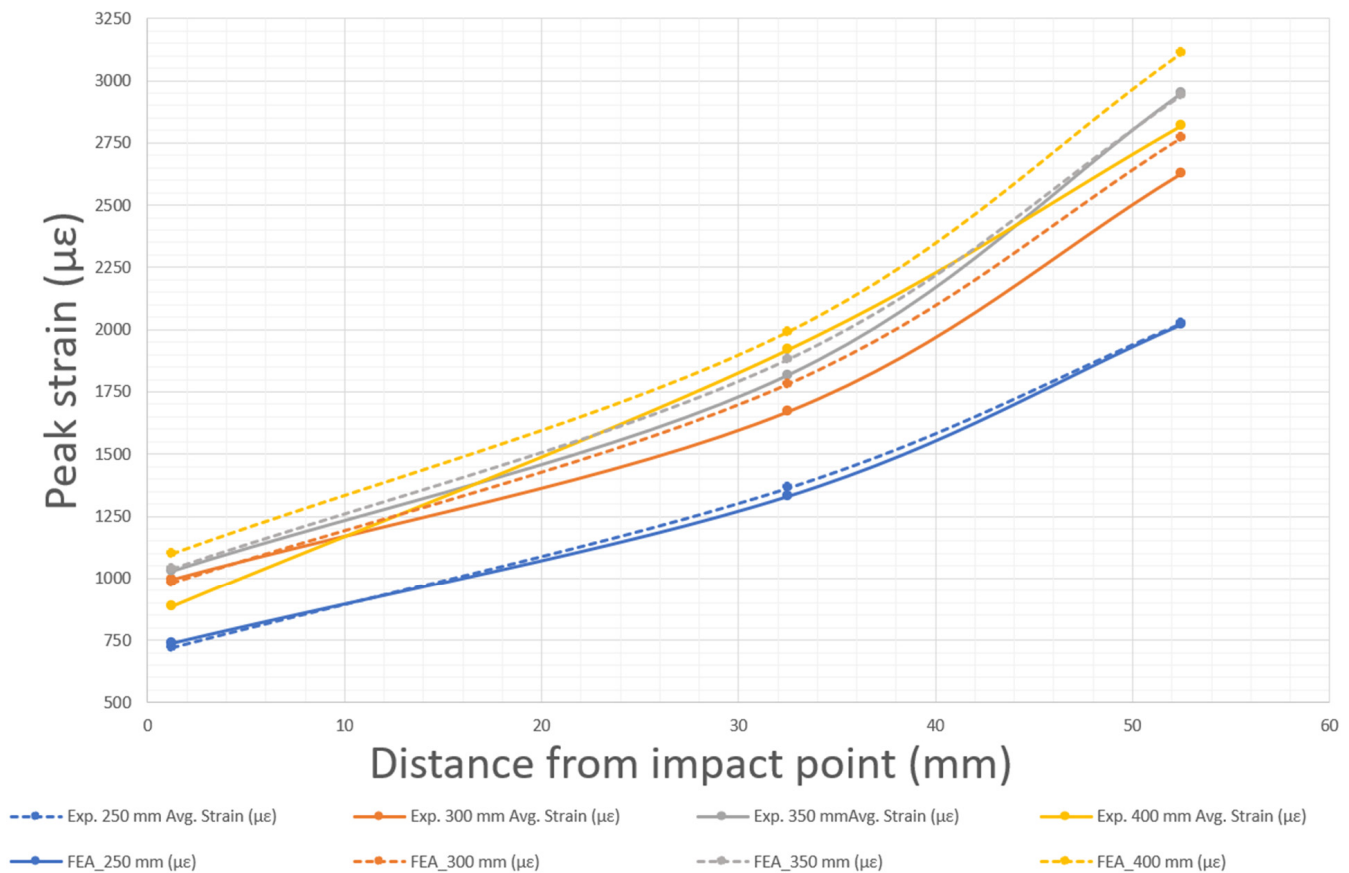


Figure 6. Peak strain as a function of distance from the impact point for four impact energy levels (represented by drop height).

- 250 mm: average strains from primary gauges ranged approximately from 720 $\mu\epsilon$ to 2026 $\mu\epsilon$.
- 300 mm: strains reached up to 2628 $\mu\epsilon$.
- 350 mm: strains reached up to 2949 $\mu\epsilon$.
- 400 mm: maximum strains exceeded 2800 $\mu\epsilon$ (Table 3).

Overall, peak strain decreased with increasing distance from the impact point, consistent with a strongly localized impact-induced strain field. For the 250–350 mm cases, strain magnitude increased with drop height at all three-gauge locations, reflecting the expected increase in input energy (Table 1).

At 400 mm, the strain response became non-monotonic across the three-gauge locations (Table 3). Specifically, the closest gauge (1.25 mm) and the farthest gauge (52.5 mm) decreased relative to the 350 mm case, whereas the intermediate gauge (32.5 mm) increased. Such mixed behavior is expected once the response transitions from predominantly elastic deformation to a damage-dominated regime: impact-induced damage (matrix cracking, delamination growth, and local fiber failure) redistributes load paths and consumes energy irreversibly, so peak strains may decrease at some locations and increase in others depending on the evolving local stiffness field.

To estimate the no-damage baseline at 400 mm, a simple elastic extrapolation was performed by fitting a linear relation between experimental peak strain and impact energy (Table 1) using the 250–350 mm data and predicting the corresponding 400 mm values. The resulting expected peak strains (Table 2) exceeded the measured values at all three-gauge

locations, with the largest deficit at 1.25 mm. This energy-normalized deviation provides a quantitative indicator that a substantial portion of the additional impact energy at 400 mm is dissipated through damage mechanisms rather than recovered as elastic strain.

For visualization of the spatial decay, a second-order polynomial in distance was used as a compact representation of the three-point strain field (Figure 7). Because only three-gauge locations are available, the quadratic curve interpolates the measured points and is used here for graphical interpretation rather than as a unique physical law.

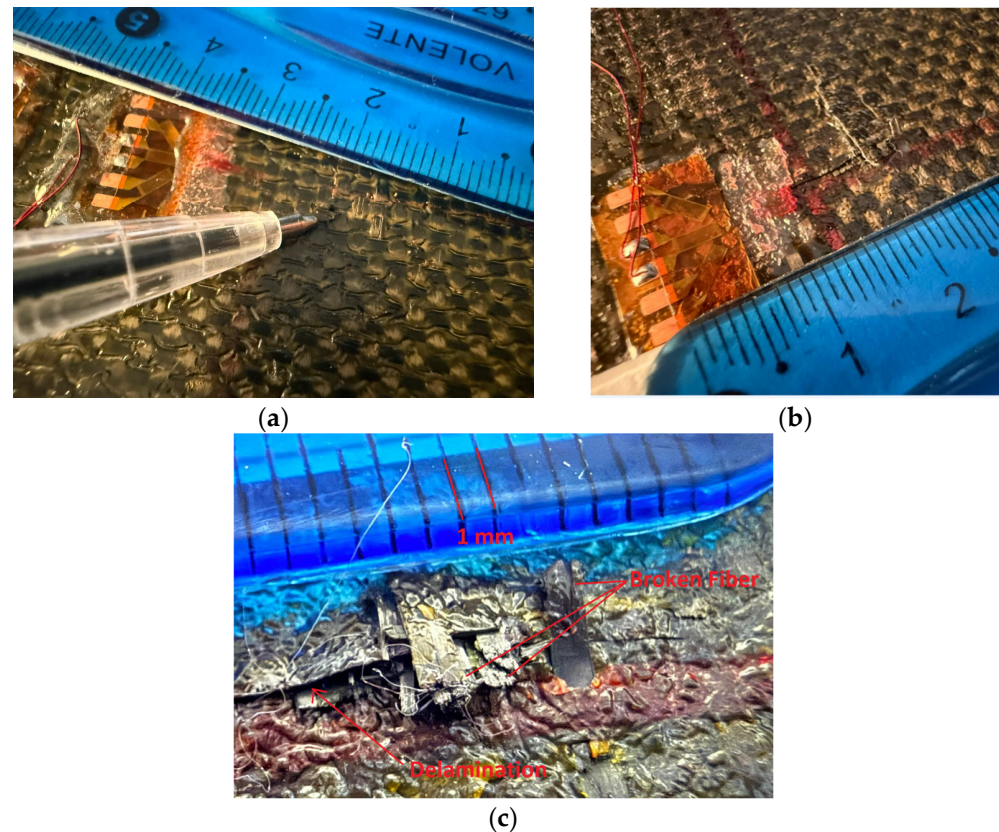


Figure 7. Detailed post-impact damage assessment on the rear surface of the CFRP specimen subjected to the 400 mm drop height. The magnified view explicitly identifies the critical damage mechanisms, including interlaminar delamination and localized fiber breakage, accompanied by a 1 mm reference scale to quantify the extent of the damage zone. (a) Top view and (b) underside delamination patterns. (c) Underside detail view.

The spatial decay shown in Figure 6 can be interpreted as an experimental signature of strain-field attenuation away from the impact center. In practice, this relationship provides a basis for estimating impact severity and potential damage state from multi-gauge measurements, which is directly aligned with the SHM motivation of this study.

To estimate the no-damage baseline at 400 mm, an elastic extrapolation was performed by fitting a linear relation between experimental peak strain and impact energy using the 250–350 mm data. This linear baseline exhibited a strong correlation with an R^2 value of approximately 0.96. The measured strains at 400 mm fell significantly below this expected elastic trend particularly at nearest 1.25 mm gauge location. While direct internal NDT (e.g., ultrasonic C-scan) cannot be performed, this pronounced deviation from the highly linear energy-normalized baseline, combined with the extreme statistical scatter (45.4% variance) observed at the central gauge, strongly infers a transition to a damage-dominated regime. It is hypothesized that a substantial portion of the impact energy is dissipated through irreversible damage mechanisms rather than being recovered as elastic strain.

To address potential concerns regarding the sensitivity of our conclusions to the chosen elastic baseline, it is crucial to examine the magnitude of the strain deviation. The measured peak strain at the 12.5 mm gauge for the 400 mm impact ($887.0 \mu\epsilon$) is nearly 28% lower than the linearly extrapolated elastic baseline value ($1223.4 \mu\epsilon$). Such a dramatic deficit cannot be mathematically reconciled by employing alternative elastic curve-fitting methods, as any purely elastic projection based on the 250–350 mm energy absorption trend would strictly predict a continued monotonic increase. Furthermore, the argument for damage initiation is not solely reliant on this empirical extrapolation. The abrupt onset of extreme statistical scatter (45.4% variance) at the central gauge exclusively during the 400 mm impacts serves as an independent, physical indicator of unpredictable material failure initiating directly beneath the impactor. This baseline-independent physical evidence renders the damage-regime conclusion highly robust and insensitive to the specific mathematical formulation of the baseline.

4.3. FEA Validation and Quantitative Comparison

The FEA results correlated well with the experimental data. Table 3 summarizes the comparative strain analysis.

4.4. Damage Assessment and SHM Feasibility

Low-velocity impact in CFRP laminates typically produces a combination of matrix cracking, delamination, and localized fiber failure, with the most critical damage often developing below the impacted surface (i.e., barely visible impact damage (BVID)). Consistent with these established observations, post-impact inspection of the tested panels in each height revealed damage on the rear surface (underside) at 400 mm height tests. Delamination patterns and local fiber breakage can be seen in Figure 7 at 400 mm drop heights. The delamination and fiber breakage with approximately 10 mm visible length damages observed on the underside of the specimens is clearly visible in Figure 7c.

From an SHM perspective, these damage mechanisms are relevant because they alter local stiffness and load paths, which in turn change the measured strain field. The present multi-gauge layout provides a practical way to capture this change: (i) the outer gauges (32.5 mm and 52.5 mm) track the global increase in deformation with increasing impact energy, whereas (ii) the closest gauge (1.25 mm) is more sensitive to local damage initiation and nonlinear energy dissipation.

A key observation is the non-monotonic response at 400 mm, where the measured strain at the closest gauge decreases relative to 350 mm (Table 3). Such a decrease is consistent with the onset of significant damage in the immediate vicinity of the impact point, where an increasing fraction of the impact energy is consumed by irreversible processes (matrix cracking, delamination growth, and fiber failure) rather than being stored elastically and recovered as strain at the gauge location. In operational terms, this behavior is valuable: it suggests that the combination of multi-point strain measurements and energy-normalized interpretation (Table 1) can provide not only an impact-detected flag, but also an indicator of whether the structure has transitioned into a damage-dominated response regime.

The close agreement between experiment and FEA (Table 3) further supports the use of simulation as a physics-based interpreter for strain signatures, enabling the strain-gauge data to be mapped to likely damage states and regions. This hybrid experimental-numerical approach aligns with broader SHM practice in aerospace composites, where sensor data are increasingly combined with calibrated models to improve diagnostic confidence and reduce uncertainty in maintenance decisions.

5. Discussion

5.1. Interpretation and Implications for SHM

The results indicate that sparse, surface-mounted strain gauges can provide actionable information for post-impact assessment of composite aircraft panels when the measurements are interpreted through (i) spatial attenuation trends and (ii) an energy-normalized baseline. The monotonic decay of peak strain with distance for 250–350 mm drop heights (Figure 7) supports the use of multi-point strain gradients as a compact signature of impact severity.

The 400 mm case shows a clear departure from elastic scaling: measured peak strains fall below the expected elastic trend (Table 2) and become non-monotonic across gauge locations, consistent with a shift toward damage-dominated energy dissipation and stiffness redistribution. From an operational perspective, such deviations can be used to trigger targeted NDT or repair actions, while lower-energy impacts that follow the elastic baseline may be handled with reduced inspection burden.

Although damage initiation in the low-velocity impact (LVI) literature and the ASTM D7136 standard is generally characterized by the ‘load drop’ phenomenon in force–time curves, the dynamic strain signatures obtained in this study were evaluated as a direct physical surrogate. Notably, the peak strain measured at the location nearest to the impact center (1.25 mm) showed a -27.5% deviation from the linear elastic extrapolation baseline (Table 2), serving as quantitative evidence that the impact energy surpassed the elastic deformation limit and was consumed by permanent damage formation (surface creation/fracture energy). This strain deficit indicates that the local stiffness of the material was reduced due to delamination and matrix cracking, leading to a redistribution of load paths. Moreover, the significant 45.4% statistical variance observed at the same point confirms the stochastic nature of the damage and verifies the transition of the material from an ‘elastic scaling’ regime to a ‘damage-dominated’ response.

5.2. Agreement Between Experiment and Simulation

Across the sub-critical impact levels (250–350 mm), the experimentally measured strains and MSC Nastran Implicit elastic predictions exhibit good agreement (Table 3), supporting the use of the simulation as a physics-based baseline for interpreting dynamic strain signatures. Rather than directly simulating complex failure modes, this approach establishes an idealized, damage-free structural response. This methodology is particularly useful for isolating damage-induced non-linearities; impact energy levels or specific sensor regions where the experimental data significantly diverges from the implicit elastic model (e.g., the 400 mm case) can be systematically and reliably identified as probable damage zones.

5.3. Limitations and Recommendations

The present study is limited by the sparse gauge layout and by the lack of direct internal damage quantification (e.g., ultrasonic C-scan) to corroborate the inferred damage modes. While the localized statistical scatter analysis provided strong physical evidence for damage initiation at the 400 mm impact height, future work should (i) expand sensing layouts in multiple radial directions to capture more complex two-dimensional strain contours, (ii) couple the dynamic strain signatures and statistical variance directly to independent NDT damage metrics (e.g., mapping internal delamination areas), and (iii) build upon the purely elastic baseline approach utilized here by incorporating advanced progressive damage models (e.g., cohesive-zone or continuum damage mechanics) to directly simulate and predict delamination initiation and growth under increasing impact energies. Furthermore, no additional non-destructive testing (NDT) methods (e.g., ultrasonic

C-scan or thermography) were employed to directly verify the internal damage distribution, which should be considered a limitation of the present work. In addition, the present study focuses on strain-based measurements obtained from surface-mounted strain gauges. Therefore, detailed impact response histories such as force–time or displacement–time curves were not directly measured, which should be considered a limitation of the current experimental setup.

6. Conclusions

6.1. Conclusion and Future Work

This study developed and validated a combined experimental–numerical framework for low-velocity impact assessment of CFRP panels by integrating surface-mounted strain gauges with implicit finite element simulations in elastic region. Although the finite element model does not incorporate damage mechanisms, the close agreement between measured and simulated peak strains supports the use of the FEA as a ‘Baseline Digital Twin’. This approach enables the interpretation of strain signatures by extrapolating likely damage states based on deviations from the idealized elastic baseline, offering a robust pathway for post-impact assessment beyond visual inspection alone. Future studies may incorporate advanced non-destructive testing techniques and force-based impact measurements to further characterize the internal damage mechanisms in composite panels.

6.2. Key Findings and Insights

- Energy-consistent spatial attenuation: For the 250–350 mm cases, peak strain increases with impact energy (Table 1) and exhibits a clear monotonic decay with distance from the impact point (Figure 7), consistent with a localized impact-induced strain field.
- Model validation for SHM interpretation: The validated FEA captures the measured strain levels at three-gauge distances (Table 3), indicating that the adopted mesh resolution, laminate definition, and ASTM D7136-consistent boundary conditions provide an adequate representation of the test configuration.
- Damage-regime transition at 400 mm: At 400 mm, the strain field becomes non-monotonic across gauge locations and deviates from an elastic energy-scaling baseline (Table 2). This behavior is consistent with a transition to a damage-dominated response in which part of the input energy is dissipated irreversibly through matrix cracking, delamination growth, and local fiber failure, which redistributes the load paths and alters strain signatures.
- Practical SHM implication: The combined use of (i) multipoint strain measurements, (ii) energy normalization based on drop height and impactor mass, and (iii) a validated numerical model provides a pathway to assess both the presence and severity of maintenance-relevant impacts (e.g., tool drops) in composite aircraft structures.

6.3. Limitations and Future Research

While the present results demonstrate feasibility, several limitations should be addressed before operational deployment:

- Damage quantification and uncertainty: The current study correlates strain signatures with impact severity and visible damage features; future work should quantify internal damage using complementary NDT (e.g., ultrasonic C-scan) and report uncertainty bounds for strain-based diagnostics.
- Expanded sensor layouts: Only three primary gauge distances were used; denser layouts and multiple radial directions would improve impact localization and reduce sensitivity to unknown impact location.

- Enhanced damage modeling: Incorporating cohesive-zone or continuum damage mechanics models would allow for delamination initiation/growth and stiffness degradation to be predicted more directly and compared with post-impact inspections.
- In-service realism: Future experiments should include realistic boundary conditions, environmental effects, and repeated impacts to assess long-term sensor reliability and the robustness of the proposed energy-normalized interpretation.

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