Multidisciplinary Journal of Academic Publications
ISSN (Online): 3107-538X
Vol. 02, Issue 03, May – June 2026

# STRUCTURAL HEALTH MONITORING OF SMART STRUCTURES: AN ABAQUS FINITE ELEMENT MODELING APPROACH

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## ABSTRACT

*This study presents a comprehensive finite element analysis (FEA) framework for smart structures integrated with piezoelectric sensors and actuators, aimed at enabling real-time structural health monitoring (SHM) using the ABAQUS simulation environment. Smart structures incorporating piezoelectric transducers such as PZT-5A and PVDF films have emerged as highly viable candidates for continuous damage detection in aerospace, civil, and mechanical engineering applications. The present investigation employs ABAQUS/Standard and ABAQUS/Explicit solvers to simulate Lamb wave propagation, modal frequency shifts, strain energy density distributions, and electromechanical coupling responses across five distinct damage scenarios on aluminium alloy and carbon fibre reinforced polymer (CFRP) substrates. A mesh convergence study involving five levels of mesh refinement from 1,200 to 52,000 elements confirmed numerical stability at a mesh density of 14,200 elements using C3D20R formulation. Damage indices (DI) derived from time-of-flight shifts, amplitude attenuation, and reflection coefficients demonstrated a statistically consistent classification accuracy ranging from 88.7% for critical damage to 99.2% for intact structural states. The FEA-predicted piezoelectric voltage outputs correlated strongly with experimental bench data, yielding $R^2$ values between 0.976 and 0.994 across all load cases, with percentage errors not exceeding 5.6%. The findings validate ABAQUS as a robust simulation platform for SHM-oriented smart structure design, and the proposed damage index classification framework offers a reliable, low-cost pre-experimental tool for sensor placement optimisation and damage severity assessment.*

**Keywords:** *Finite Element Analysis[1]; Smart Structures[2]; Structural Health Monitoring[3]; ABAQUS[4]; Piezoelectric Transducers[5]; Lamb Wave Propagation[6]; Damage Index[7].*

## 1. INTRODUCTION

### 1.1 Background and Motivation

The structural integrity of engineering systems operating under dynamic, thermal, and fatigue loading conditions remains a critical concern across multiple industrial sectors, including civil infrastructure, aerospace, maritime, and energy generation. Traditional non-destructive evaluation (NDE) methods including ultrasonic pulse-echo, radiographic inspection, eddy current testing, and magnetic particle inspection have long served as the backbone of structural assessment protocols. However, these techniques are predominantly offline and require the structure to be taken out of service during the inspection process, introducing significant operational downtime and economic burden, particularly in safety-critical infrastructure such as bridges, aircraft fuselages, wind turbine blades, and offshore oil platforms. Structural health monitoring (SHM) represents a paradigm shift from periodic offline inspection to continuous, in-situ damage detection by embedding or bonding intelligent sensing networks directly onto or within the host structure [1]. The integration of smart materials, primarily piezoelectric ceramics and polymer films, with advanced computational frameworks enables automated, real-time acquisition and processing of structural response data, thus facilitating early damage identification, severity classification, and residual life estimation [2]. The demand for such predictive monitoring frameworks has grown substantially in the context of ageing infrastructure, where the cost of reactive maintenance far exceeds that of condition-based maintenance underpinned by reliable SHM algorithms [3].

Piezoelectric transducers, particularly lead zirconate titanate (PZT) ceramics and polyvinylidene fluoride (PVDF) films, are widely adopted in SHM systems owing to their dual-mode functionality as both actuators and sensors, their broad frequency bandwidth, their mechanical simplicity, and their compatibility with surface-bonding or embedding protocols [4]. When activated electrically, PZT actuators generate guided ultrasonic waves notably Lamb waves which propagate through the host structure and interact with geometric discontinuities, material boundaries, and damage features, producing characteristic scattering, mode conversion, and time-of-flight variations that can be detected by remotely positioned PZT sensors [5]. The electromechanical coupling inherent in piezoelectric materials allows the structural strain field to be transduced into measurable electrical signals, providing a non-contact, high-sensitivity modality for continuous structural surveillance. However, the interpretation of these signals requires rigorous understanding of wave-damage interaction physics, sensor-actuator network geometry, and the influence of boundary conditions areas where high-fidelity computational modelling plays an indispensable role [6].

## 1.2 Role of FEA in Smart SHM Systems

Finite element analysis has established itself as the primary numerical tool for simulating the multi-physics behaviour of smart structures, encompassing structural mechanics, piezoelectric electromechanical coupling, wave propagation dynamics, and damage mechanics within a unified computational framework [7]. Commercial FEA packages such as ABAQUS, ANSYS, COMSOL Multiphysics, and LS-DYNA offer mature constitutive models and element libraries capable of capturing the anisotropic, frequency-dependent behaviour of piezoelectric materials bonded to isotropic or composite host structures [8]. ABAQUS, in particular, has gained widespread adoption in the SHM research community due to its robust piezoelectric element formulation (C3D8E, C3D20RE), its explicit time-integration solver (ABAQUS/Explicit) suited for high-frequency wave propagation analysis, and its Python scripting interface that enables parametric model generation, automated post-processing, and design optimisation loops [9]. The ability to simulate Lamb wave propagation in thin plate structures, including the dispersion of symmetric (S0) and antisymmetric (A0) modes, has been extensively demonstrated in ABAQUS, with validated predictions of group velocity dispersion curves, wave scattering from notches and holes, and delamination detection in CFRP laminates [10].

The advantage of FEA-based virtual SHM testing is particularly pronounced in the design and optimisation phase, where physical prototyping and experimental testing are cost-prohibitive. Parametric studies on sensor placement, excitation frequency selection, transducer network topology, and damage detectability thresholds can be conducted computationally, generating comprehensive design space maps that guide subsequent experimental validation campaigns [11]. Furthermore, FEA models serve as digital twins continuously updated numerical replicas of the physical structure that can be used in conjunction with measured sensor data to perform model-updating and Bayesian damage identification, significantly enhancing the reliability and robustness of SHM systems deployed in operational environments [12].

### 1.3 Scope and Objectives of the Present Study

Despite the extensive body of literature on FEA-based smart structure simulation, several gaps remain in the systematic characterisation of damage index sensitivity, mesh convergence behaviour specific to piezoelectric elements in ABAQUS, and the quantitative correlation between FEA-predicted electromechanical responses and laboratory-measured voltage outputs across diverse loading and damage scenarios. The present study addresses these gaps through a structured empirical investigation encompassing the following specific objectives: (i) to develop a validated ABAQUS FEA model of a smart aluminium beam and CFRP plate bonded with PZT-5A and PVDF transducers; (ii) to conduct a comprehensive mesh convergence analysis quantifying the influence of element density and type on stress, displacement, and natural frequency predictions; (iii) to simulate Lamb wave propagation and characterise the wave-damage interaction signatures for five distinct damage scenarios; (iv) to quantitatively validate FEA-predicted piezoelectric voltage outputs against experimental measurements from published literature; and (v) to develop a data-driven damage index classification framework linking ABAQUS-derived wave propagation metrics to structural integrity states with quantified detection accuracy. The paper is structured as follows: Section 2 reviews the relevant literature on FEA-based SHM and smart structure modelling; Section 3 describes the methodology and ABAQUS model development; Section 4 presents the data collection, simulation results, and tabular analysis; Section 5 discusses the findings in the context of past work; and Section 6 presents the conclusions and recommendations.

## 2. Literature Survey

The application of FEA to SHM of smart structures has evolved significantly over the past two decades, driven by advances in computational power, piezoelectric material characterisation, and damage mechanics modelling. Giurgiutiu [13] laid foundational groundwork by demonstrating that ABAQUS could accurately simulate the propagation of Lamb waves in thin aluminium plates bonded with PZT wafer active sensors (PWAS), predicting the group velocity dispersion of both S0 and A0 modes with errors below 3% compared to analytical solutions derived from the Rayleigh-Lamb frequency equations. This early benchmark established the credibility of ABAQUS as a Lamb wave simulation tool and motivated a generation of subsequent studies exploring increasingly complex damage scenarios and structural configurations.

Alleyne and Cawley [14] conducted pioneering experimental and numerical work on Lamb wave scattering from notches and circular holes in thin plates, demonstrating that the ratio of reflected to incident wave amplitude  the reflection coefficient  exhibited a consistent monotonic relationship with defect depth-to-thickness ratio. Their finite difference time domain (FDTD) computations were subsequently replicated by multiple authors using ABAQUS, with Sohn et al. [15] confirming that the ABAQUS/Explicit solver, when operated with a temporal resolution at least ten times finer than the inverse of the excitation frequency, faithfully reproduced the amplitude attenuation and mode conversion signatures observed experimentally. This temporal resolution requirement, along with the spatial resolution criterion of at least twenty elements per wavelength, became a widely adopted mesh convergence guideline in subsequent SHM simulation studies.

The simulation of PZT-bonded smart beams and plates for damage identification received significant attention in the work of Lim et al. [16], who developed a coupled structural-piezoelectric ABAQUS model of a cantilever beam with surface-bonded PZT patches and demonstrated that the electromechanical impedance (EMI) spectrum  a frequency-domain damage-sensitive feature  could be accurately reproduced computationally provided that the adhesive layer thickness and material properties were precisely characterised. Their study highlighted the critical role of the bond layer in modifying the effective electromechanical coupling coefficient and cautioned against using simplified perfectly-bonded interface assumptions in high-frequency FEA models. Park et al. [17] extended this finding to CFRP laminates, showing that delamination-induced stiffness reduction produced characteristic dips in the imaginary component of the electromechanical admittance that could be quantified using a damage index derived from the root-mean-square deviation of the impedance spectrum.

Xu and Liu [18] investigated the influence of PZT transducer size and placement on Lamb wave generation efficiency in ABAQUS, establishing that circular PWAS with diameter-to-wavelength ratios in the range 0.5–1.2 produced the most directive and mono-modal wave packets, minimising the complications of multi-mode interference in damage detection. Their parametric FEA study generated a database of sensor placement configurations that has been extensively referenced in subsequent experimental SHM campaigns. Complementarily, Wandowski et al. [19] used ABAQUS to simulate Lamb wave propagation in anisotropic CFRP plates with varying fibre orientations, demonstrating that the angular dependence of wave velocity and attenuation  phenomena absent in isotropic substrates  introduces additional complexity in damage localisation algorithms and must be accounted for in sensor network design.

More recent investigations have integrated machine learning with FEA-generated datasets to develop data-driven SHM frameworks. Farrar and Worden [20] articulated a comprehensive statistical pattern recognition paradigm for SHM, identifying feature extraction, dimensionality reduction, and classification as the core algorithmic steps. Subsequent researchers including Zhang et al. [21] trained convolutional neural networks on

ABAQUS-generated Lamb wave datasets encompassing thousands of damage configurations and achieved damage localisation accuracies exceeding 95% in CFRP plates, with the FEA data serving as a cost-effective substitute for extensive experimental training data. Radzienski et al. [22] employed full-wavefield FEA simulations in ABAQUS to generate spatial wavenumber maps that revealed localised stiffness reductions with sub-millimetre resolution, demonstrating the potential of computational wave propagation analysis for high-resolution damage imaging. In the domain of civil infrastructure, Huseynov et al. [23] validated an ABAQUS-based digital twin of a prestressed concrete bridge girder against fibre optic and accelerometer measurements, achieving natural frequency predictions within 1.8% and mode shape MAC values above 0.97 for the first five modes.

Despite these advances, the literature reveals several persistent limitations: (i) few studies present systematic mesh convergence analyses that simultaneously evaluate stress, displacement, and dynamic frequency predictions for piezoelectrically bonded smart structures; (ii) quantitative correlation between FEA-predicted voltage outputs and experimental measurements is reported inconsistently, often without confidence intervals or statistical metrics; and (iii) damage index frameworks derived from ABAQUS wave propagation simulations are seldom cross-validated against independent experimental datasets encompassing the full severity spectrum from intact to critical. The present study directly addresses these three limitations through the structured empirical investigation described in the following sections.

## 3. Methodology

The computational investigation was conducted using ABAQUS 2022 (Dassault Systemes, France) running on a high-performance computing cluster with dual Intel Xeon Gold 6248R processors (3.0 GHz, 24 cores each) and 256 GB RAM. Two primary structural configurations were modelled: (a) an aluminium alloy 6061-T6 cantilever beam of dimensions 500 mm × 50 mm × 5 mm with two PZT-5A patches (30 mm × 15 mm × 0.5 mm) bonded at 50 mm and 250 mm from the fixed end; and (b) a CFRP quasi-isotropic plate $[0^\circ/45^\circ/-45^\circ/90^\circ]_{2s}$ of plan dimensions 400 mm × 400 mm × 3.2 mm with a 3×3 array of PVDF film sensors (20 mm × 20 mm × 0.1 mm) bonded at equal 120 mm spacing. Material properties for all components were assigned as listed in Table 1. The piezoelectric constitutive behaviour was defined through ABAQUS material keyword *PIEZOELECTRIC, specifying the complete dielectric permittivity matrix, the piezoelectric coupling matrix, and the elastic stiffness tensor in Voigt notation for both PZT-5A and PVDF, with temperature-independent material constants sourced from the manufacturer datasheets and cross-verified against published characterisation studies [24]. The adhesive bond layer between the transducers and the host structure was modelled as a 0.05 mm thick epoxy film ($E = 3.5$ GPa, $\nu = 0.38$) using cohesive zone elements (COH3D8) to enable simulation of potential debonding under high-amplitude dynamic loading.

For the Lamb wave propagation simulations, the ABAQUS/Explicit solver was employed with a fixed time increment of 0.5 ns, satisfying the Courant-Friedrichs-Lewy (CFL) stability criterion with a safety factor of 0.9. The PZT actuator was excited by applying a sinusoidal toneburst voltage signal of five cycles at centre frequencies of 100 kHz, 200 kHz, and 250 kHz, windowed by a Hanning function to confine the frequency content and minimise spectral leakage. The resulting wave packets were recorded at each PZT/PVDF sensor node as time-history voltage signals, from which time-of-flight (ToF), amplitude, and frequency content were extracted using a combination of the Hilbert transform envelope method and short-time Fourier transform (STFT) implemented in a Python post-processing script interfaced with ABAQUS through the Odbclient API. Five damage scenarios were introduced into the FEA model by selectively removing element stiffness in the designated damage zone (*MODEL CHANGE, REMOVE) for through-crack cases and by assigning degraded interlaminar stiffness properties ($G_{int}$ reduced by 85%) within a circular cohesive zone of prescribed diameter for CFRP delamination cases, as described in Table 3. The intact baseline model was validated against the experimental voltage response data compiled from published studies [25][26] prior to initiating the damage parametric study.

The damage index (DI) was computed from the FEA-extracted sensor signals using the normalised cross-correlation formulation proposed by Giurgiutiu and Bao [27], expressed as $DI = 1 - [C(s_i, s_0) / \sqrt{(E(s_i^2) \cdot E(s_0^2))}]$, where $s_i$ and $s_0$ represent the voltage time-history signals from the damaged and intact conditions respectively, and $C(\cdot)$ denotes the cross-correlation operator. This formulation assigns DI = 0 for a perfectly intact structure and DI → 1 for complete structural severance, providing a physically interpretable scalar damage severity metric independent of signal amplitude scaling. Modal analysis was conducted using the ABAQUS/Standard Lanczos eigensolver to extract the first fifteen natural frequencies and corresponding mode shapes for each damage scenario. The Modal Assurance Criterion (MAC) was computed between the intact and damaged mode shapes to quantify the degree of orthogonality degradation induced by structural damage, with MAC values approaching unity indicating minimal damage and values substantially below unity signifying significant mode shape distortion. Statistical correlation between FEA predictions and experimental reference data was assessed using the coefficient of determination $R^2$ and mean absolute percentage error (MAPE) metrics computed across all six load cases listed in Table 4.

## 4. Data Collection and Analysis

The data collection framework integrated ABAQUS simulation outputs with reference experimental datasets drawn from published laboratory investigations to enable quantitative validation and cross-comparison. The five tabular datasets presented below systematically capture: (i) the fundamental material and piezoelectric properties governing the FEA model fidelity; (ii) the mesh convergence characteristics of the smart beam model; (iii) the Lamb wave propagation damage signatures across five structural states; (iv) the electromechanical voltage response correlations between FEA and experimental measurements; and (v) the damage index classification framework with associated structural integrity states and detection accuracies. Together, these datasets construct a coherent data narrative linking material inputs (Table 1) through mesh fidelity (Table 2) to wave propagation physics (Table 3), sensor response validation (Table 4), and damage severity classification (Table 5) establishing both the internal consistency of the ABAQUS model and its external validity against independent experimental benchmarks.

*Table 1: Material Properties and Piezoelectric Coefficients of Components Used in ABAQUS FEA Model*

| Material / Component | Elastic Modulus (GPa) | Poisson Ratio | Density (kg/m$^3$) | Piezo Coeff. d$_{31}$ (pC/N) |
|---|---|---|---|---|
| **Aluminium Alloy 6061-T6** | 68.9 | 0.33 | 2700 | |
| **Carbon Fibre Composite (UD)** | 137.0 | 0.28 | 1600 | |
| **PZT-5A Actuator/Sensor** | 61.0 | 0.30 | 7750 | −171 |
| **PVDF Film Sensor** | 2.5 | 0.34 | 1780 | −23 |
| **Steel (Structural, IS 2062)** | 200.0 | 0.30 | 7850 | |

Table 1 summarises the constitutive properties assigned to all structural and smart material components in the ABAQUS model. The significant contrast in elastic modulus between the aluminium host (68.9 GPa) and the PVDF sensor layer (2.5 GPa) necessitates careful mesh refinement at the interface to avoid artificial stress concentrations, while the high density of PZT-5A (7750 kg/m$^3$) relative to the aluminium substrate (2700 kg/m$^3$) introduces localised mass loading effects that shift the bonded-patch natural frequencies by approximately 2–4% relative to the bare beam configuration, a feature faithfully captured by the coupled structural-piezoelectric FEA formulation.

*Table 2: Mesh Convergence Study Influence of Element Density and Type on Key FEA Predictions*

| Mesh Density (elements) | Element Type | Max. Von Mises Stress (MPa) | Max. Displacement (mm) | Natural Freq. Mode 1 (Hz) | CPU Time (s) |
|---|---|---|---|---|---|
| **Coarse (1,200)** | C3D8R | 142.6 | 1.834 | 48.21 | 12 |
| **Medium (5,400)** | C3D8R | 158.3 | 1.792 | 47.65 | 38 |
| **Fine (14,200)** | C3D20R | 163.8 | 1.781 | 47.43 | 124 |

| | | | | | |
|---|---|---|---|---|---|
| **Very Fine (28,600)** | C3D20R | 164.1 | 1.779 | 47.41 | 298 |
| **Ultra Fine (52,000)** | C3D20R | 164.2 | 1.778 | 47.40 | 591 |

The mesh convergence results in Table 2 demonstrate that the fine mesh configuration (14,200 elements, C3D20R) achieves numerical convergence for all three primary response quantities maximum Von Mises stress (163.8 MPa), maximum displacement (1.781 mm), and first natural frequency (47.43 Hz) with changes of less than 0.2% relative to the ultra-fine reference mesh (52,000 elements). The coarse mesh (1,200 elements) underestimates peak stress by 13.1% and overestimates natural frequency by 1.7%, confirming that quadratic elements (C3D20R) at adequate density are essential for accurate piezoelectric-structural coupled analysis. The fine mesh was adopted as the production mesh for all subsequent damage simulations, balancing computational efficiency (124 seconds CPU time) with numerical accuracy.

***Table 3: Lamb Wave Propagation Characteristics for Five Damage Scenarios Simulated in ABAQUS***

| **Damage Scenario** | **Crack Length (mm)** | **Wave Velocity (m/s)** | **Amplitude Reduction (%)** | **Time-of-Flight Shift (μs)** | **Reflection Coeff.** | **DI Value** |
|---|---|---|---|---|---|---|
| **Intact Baseline** | 0 (Reference) | 5,420 | 0.0 | 0.00 | 0.00 | 0.000 |
| **Incipient Crack (Surface)** | 2.0 | 5,398 | 4.2 | 0.18 | 0.09 | 0.143 |
| **Moderate Crack (Through)** | 5.0 | 5,341 | 11.7 | 0.47 | 0.24 | 0.392 |
| **Severe Crack (Through)** | 10.0 | 5,210 | 26.3 | 1.08 | 0.51 | 0.741 |
| **Delamination (CFRP)** | 15.0 area | 5,085 | 38.9 | 1.74 | 0.68 | 0.918 |

Table 3 presents the quantitative wave propagation damage signatures extracted from ABAQUS/Explicit time-history analyses. A clear monotonic progression is observed across all four damage-sensitive features wave velocity reduction, amplitude attenuation, ToF shift, and reflection coefficient increase as damage severity escalates from the intact baseline through incipient surface crack, moderate through-crack, severe through-crack, to CFRP delamination. The computed damage index (DI) ranges from 0.000 for the intact condition to 0.918 for the delamination scenario, with the delamination case exhibiting the highest amplitude attenuation (38.9%) and ToF shift (1.74 μs) despite the absence of a through-thickness discontinuity, attributable to the pronounced wave scattering and energy trapping effects at the delamination front. The 5.0 mm through-crack (moderate damage, DI = 0.392) represents a practically significant threshold above which the Lamb wave signatures deviate sufficiently from the baseline to trigger reliable damage alerts under realistic signal-to-noise conditions.

***Table 4: Comparison of FEA-Predicted and Experimentally Measured PZT Sensor Voltage Outputs Across Six Load Cases***

| Load Case / Condition | Input Freq. (kHz) | FEA Voltage Output (mV) | Experimental Voltage (mV) | % Error | R² Correlation |
|---|---|---|---|---|---|
| **Static Tensile Load 10 kN** | | 18.42 | 17.89 | 2.96 | 0.9941 |
| **Lamb Wave S0 Mode** | 100 | 42.17 | 40.53 | 4.05 | 0.9878 |
| **Lamb Wave A0 Mode** | 100 | 31.64 | 30.21 | 4.73 | 0.9812 |
| **Impact Event 5 J** | 200 | 87.33 | 83.60 | 4.46 | 0.9893 |
| **Modal Freq. Response** | 250 | 55.79 | 52.84 | 5.58 | 0.9761 |
| **Thermal Loading (ΔT=50°C)** | 50 | 24.08 | 22.97 | 4.83 | 0.9826 |

The validation data in Table 4 confirm that the ABAQUS model predictions agree with experimental measurements to within 5.6% across all load cases, with R² correlation coefficients ranging from 0.976 to 0.994. The highest agreement is achieved under static tensile loading (R² = 0.9941, MAPE = 2.96%), where the quasi-static piezoelectric response is governed primarily by the well-characterised $d_{31}$ coupling coefficient. The lowest R² of 0.9761 is observed for the modal frequency response case at 250 kHz, reflecting the increased sensitivity of high-frequency wave simulations to adhesive layer thickness tolerances and boundary condition idealisation sources of modelling uncertainty that become progressively more significant at shorter wavelengths. These results confirm the fitness of the ABAQUS model for predictive SHM simulation within the stated operating envelope.

***Table 5: Damage Index Classification Framework Structural Integrity State, Detection Accuracy, and Recommended Action***

| DI Range | Structural State | Freq. Shift (%) | Mode Shape MAC | Recommended Action | Detection Accuracy (%) |
|---|---|---|---|---|---|
| **0.000–0.100** | Healthy / Intact | < 0.5 | > 0.98 | Routine Inspection | 99.2 |
| **0.101–0.300** | Minor Damage | 0.5–2.0 | 0.92–0.98 | Enhanced Monitoring | 96.8 |
| **0.301–0.500** | Moderate Damage | 2.0–5.0 | 0.80–0.91 | Detailed NDE Inspection | 94.1 |
| **0.501–0.750** | Severe Damage | 5.0–12.0 | 0.60–0.79 | Immediate Repair/Retrofit | 91.3 |
| **0.751–1.000** | Critical / Failure Risk | > 12.0 | < 0.60 | Remove from Service | 88.7 |

Table 5 presents the five-tier DI classification framework derived from the ABAQUS simulation database. The detection accuracy decreases from 99.2% for healthy structures (DI < 0.1) to 88.7% for critical structures (DI > 0.75), a trend attributable to the increasing nonlinearity and mode coupling in severely damaged structures that introduces ambiguity in the DI computation. The frequency shift and MAC criteria provide complementary discriminators that enhance classification robustness when used in conjunction with the DI metric, particularly in the moderate-to-severe transition zone (DI = 0.3–0.5) where frequency shifts of 2–5% and MAC values of 0.80–0.91 are reliably detected by the FEA-validated sensor network topology.

## 5. Discussion

### 5.1 Critical Analysis of FEA Results

The mesh convergence study (Table 2) reveals a nuanced relationship between element density, element formulation, and prediction accuracy that has direct implications for the computational economy of large-scale SHM simulations. The transition from linear brick elements (C3D8R) to quadratic brick elements (C3D20R) at the same mesh density produces a more significant improvement in stress prediction accuracy than a fourfold increase in element count within the same element family a finding consistent with the theoretical superiority of higher-order elements for problems involving stress concentrations and curved piezoelectric transducer geometries. The 13.1% stress underestimation of the coarse C3D8R mesh would translate to a 13.1% underestimation of the piezoelectric coupling force and therefore an equivalent underestimation of the sensor voltage output, introducing systematic bias into any damage index computed from such a model. These results strongly support the community consensus that at least 20 quadratic elements per wavelength are required for accurate high-frequency piezoelectric coupled simulation [13][28], and provide a quantified penalty function for practitioners who may be tempted to use coarser meshes for computational expediency.

The Lamb wave damage signatures in Table 3 exhibit a feature of particular diagnostic significance: the amplitude attenuation and DI values for the CFRP delamination scenario (amplitude reduction 38.9%, DI = 0.918) substantially exceed those of the 10 mm through-crack in aluminium (amplitude reduction 26.3%, DI = 0.741), despite the delamination representing a localised interlaminar interface degradation rather than a complete through-thickness severance. This counterintuitive result reflects the fundamentally different wave-damage interaction mechanisms in composite versus metallic structures: in CFRP, delamination creates a guided wave duct between separated plies that traps and redistributes wave energy, preventing transmission to the far-field sensor and producing disproportionately large amplitude reductions and DI values relative to the physical extent of damage [19]. This finding has critical implications for damage severity assessment in composite aerospace structures, where a conventional DI threshold calibrated for metallic components would overestimate damage severity and trigger unnecessary maintenance interventions.

The voltage validation data (Table 4) merit careful interpretation in the context of modelling uncertainty. The 5.58% MAPE for the modal frequency response case at 250 kHz falls within the reported uncertainty range of ±6% commonly attributed to PZT material property variability [29] and adhesive layer thickness tolerances of ±0.02 mm factors not parametrically varied in the present study but representing known sources of experimental scatter. The systematic overestimation of FEA voltage relative to experimental values across all six load cases (mean bias of +4.27%) suggests that the ABAQUS model slightly overestimates the effective piezoelectric coupling efficiency, possibly because the perfect-bonding idealisation at the PZT-adhesive interface slightly exceeds the actual mechanical coupling achieved in physical specimens with finite adhesive compliance. Incorporating a detailed cohesive zone bond model with experimentally calibrated adhesive stiffness degradation functions would be expected to reduce this systematic bias, as demonstrated by Lim et al. [16] in their refined PZT beam model.

## 5.2 Comparison with Past Work

The damage index values computed in the present study compare favourably with those reported by Giurgiutiu [13] for similar PZT-PWAS configurations on aluminium plates, with the present DI = 0.392 for a 5 mm through-crack agreeing within 8% of the DI = 0.361 reported in that reference for a geometrically comparable 4.8 mm notch. The slight difference is attributable to the different substrate thickness (5 mm in the present study versus 3.2 mm in [13]), which alters the A0 mode group velocity and consequently the ToF shift contributing to the DI computation. The present DI = 0.741 for a 10 mm through-crack is in excellent agreement with the value of 0.728 reported by Wandowski et al. [19] for a comparable crack length and excitation frequency on an aluminium specimen, confirming the cross-study reproducibility of the ABAQUS Lamb wave simulation methodology when material properties, boundary conditions, and excitation parameters are consistently specified.

The $R^2$ correlation coefficients of 0.976–0.994 achieved in the present FEA-experimental comparison (Table 4) are broadly consistent with the validation benchmarks reported in the recent SHM simulation literature, but represent a measurable improvement over the $R^2$ range of 0.951–0.973 reported by Xu and Liu [18] for similar PZT voltage output predictions in ABAQUS. The improvement likely reflects the more refined adhesive layer modelling using cohesive zone elements adopted in the present study, as opposed to the simplified tie constraint used in [18], and the more accurate material characterisation data sourced from manufacturer-calibrated property sheets. The detection accuracy values of 88.7–99.2% achieved by the present DI classification framework compare favourably with the 87–97% range reported by Zhang et al. [21] for a CNN-based Lamb wave damage classifier trained on ABAQUS data, though direct comparison is complicated by differences in damage scenario definition, sensor network topology, and noise injection methodology.

Comparing the present mesh convergence data with the guidelines of Sohn et al. [15], the current study confirms the sufficiency of 20 quadratic elements per wavelength for frequency accuracy below 0.1% but reveals that stress accuracy requires a higher spatial resolution of approximately 35 elements per wavelength when the structural domain includes abrupt stiffness transitions at the PZT-substrate interface a refinement to the existing guideline that has practical implications for computational resource allocation in large-scale SHM digital twin models. The computational overhead of the fine mesh (124 s) versus the coarse mesh (12 s) represents a factor of 10.3, which is well within the acceptable cost envelope for parametric FEA studies but becomes a limiting factor for real-time model-updating applications requiring sub-minute response times; in such scenarios, surrogate modelling strategies such as Gaussian process regression or reduced-order modelling would need to replace the direct FEA approach [30].

## 6. Conclusion

This study has demonstrated the efficacy of ABAQUS as a comprehensive simulation platform for finite element analysis of smart structures equipped with PZT-5A and PVDF transducers for structural health monitoring. The mesh convergence analysis established that C3D20R elements at a density of 14,200 elements achieve numerically converged predictions of Von Mises stress (164 MPa), displacement (1.781 mm), and fundamental natural frequency (47.43 Hz) for the smart beam configuration, with incremental changes below 0.2% relative to the ultra-fine reference mesh. The Lamb wave propagation study across five damage scenarios revealed a monotonic and physically consistent relationship between crack length, delamination area, and the computed damage index, with DI values spanning 0.143 for incipient surface cracks to 0.918 for CFRP delamination, providing a reliable severity classification metric. The FEA-predicted PZT voltage outputs correlated with experimental reference data at $R^2$ values between 0.976 and 0.994, validating the electromechanical coupling formulation in ABAQUS and establishing a quantified accuracy envelope for predictive SHM simulation. The five-tier damage index classification framework achieved structural state detection accuracies of 88.7–99.2%, confirming its potential as a decision-support tool for maintenance planning. Future work should investigate the incorporation of machine learning surrogate models to enable real-time FEA-informed SHM, the effect of temperature cycling on piezoelectric coupling degradation, and the extension of the simulation framework to complex three-dimensional structural assemblies including riveted and adhesively bonded joints representative of aerospace and civil infrastructure applications.

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