Smart Piezo-bonded carbon fibre/epoxy composite structure: experiments and finite element simulation

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Abstract
Smart sensors patched to composite structures assist in the prediction of the mechanical behaviour of the structures. The present paper used finite element modelling and experimental procedures to conduct a detailed study on the response of composite laminate bonded with smart piezoelectric material. Fibre reinforced epoxy composite laminate was fabricated using the vacuum assisted resin transfer method. Test coupons in accordance with ASTM standards were prepared using high-speed and high-pressure abrasive water jet cutting. The mechanical properties of the composites were obtained through material characterization and the material properties were incorporated into the Finite element model. The layer-wise strain rate was computed with the ANSYS® Composite Prep Post module. A finite element model of a composite with piezoelectric sensor patch was created in ANSYS® APDL and harmonic analysis was conducted to determine the optimal frequency range for the applied load. An attempt was made to measure the strain by affixing lead zirconate titanate to a carbon fibre reinforced polymer laminate for cantilever configuration, and the LabVIEW® VI software module was integrated with the NI myDAQ system to detect the corresponding voltage for the excited frequency. The values of the generated voltage through numerical simulations were verified and validated using experimental counterparts.

Nomenclature and Units

| Symbol | Description |
|--------|-------------|
| E      | Electric field components (N/C) |
| D      | Electric charge density displacement components (c/m²) |
| d      | Piezoelectric coupling for strain charge form |
| I      | Area moment of inertia of the cross section (m³) |
| L      | Length of the beam (m) |
| M      | Moment (N.m) |
| P      | External load (N) |
| S      | Compliance coefficients (m²/N) |
| T_avg | Average thickness (mm) |
| V      | Voltage (v) |
| X      | Longitudinal tensile strength (N/m²) |
| Y      | Transverse tensile strength N/m² |
| σ      | Stress (N/m²) |
| C      | Mechanical material matrix (N/m²) |
| ε      | Electric permittivity (F/m) |

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1. Introduction

The use of sophisticated fibre-reinforced composite materials in military, missile, and aerospace applications [1] has increased as a result of recent advances in materials and design. Changes in vibration modes [2] owing to stiffness and damping have an impact on structural performance. Several researchers have recently shown the effectiveness of the integrated [2, 3] concept. Resin impregnated carbon fibre components may decrease weight while maintaining a high level of strength in high-performance applications and Carbon Fibre Reinforced polymers (CFRP) proves to exhibit high-performance for structural applications. Hand lay-up and autoclave curing carbon/epoxy prepregs systems [4] are used to design body panels and chassis components for some high-end vehicles, for example, Murcielago imposes the use of woven fabrics for durability, environmental resistance and aesthetical considerations. Multidirectional tape materials were preferred for strength and stiffness. In real time applications, composite materials are bonded to other engineering materials using adhesives. To examine the effects of bond-line thickness, composite adherent thickness, fibre type, processing and environment deteriorations, Single-lap shear testing [3] was utilised.

The intrinsic mechanical and electrical couple field characteristics have garnered a lot of interest due to the usage of sensors for monitoring and actuators for control structures [5–7]. The research community is interested in developing a self-controlled and self-monitoring [5] ‘smart’ system for advanced structural design. The piezoelectric fibre composite sensors [6] are extremely flexible, easy to embed, have a high level of compatibility with composite structures and provide manufacturing flexibility. Higher piezoelectric sensitivity [8, 9] was achieved in polymers with a low volume fraction. Computer Simulations of polymer composites with piezoelectric components supports researchers in developing efficient transducers [7]. Two flexible patch types and a non-flexible patch containing solid piezo ceramic material integrated with piezoelectric carbon fibres were investigated by Duffy et al. [10]. The inference of the work was used to determine the effects caused by embedding.

The electromechanical characteristics of piezoelectric composites with passive and active polymer matrix were investigated by the researchers [2, 4, 5] using a computational simulation model. In contrast to the passive Araldite-D polymer matrix, an active PolyVinylidene Fluoride (PVDF) polymer matrix was utilised to alter piezoelectric charge coefficient d31, hydrostatic coefficient d33, voltage coefficient g31 and hydrophone figure of merit g31. Maxwell Homogenization [11] technique was used to homogenize the solution. Piezoelectric Active Fibre Composites (AFC) have provided a variety of sensor functions using a non-destructive approach. The first level consists of structures with an integrated health monitoring system. The introduction of AFC [12] overcomes the existing restrictions. Under the influence of mechanical and electrical loads, the static and dynamic behaviour of laminated composites was investigated by Detwiler et al. [5] using finite element modelling of eight-noded three-dimensional composite brick element.

Before implementation of a piezoelectric composite for an application, it is required to fabricate it with the necessary strength [13]. The Vacuum Assisted Resin Transfer method (VARTM) has proven to be a popular approach for producing void-free, high-strength composite laminates. The mechanical characteristics of CFRP composite structures like tensile strength, Young’s modulus, shear strength, shear modulus, elongation and Poisson’s ratio were investigated by the authors [10]. The effects of fibre orientation, resin types and laminate number on the mechanical characteristics of laminated composites [14] were studied by Rahmani et al. For structural health monitoring and monitoring the performance of advanced carbon/epoxy composites, a polymeric film [15] was employed as a sensor/actuator carrier by Ben Q et al.

ANSYS® was used to perform finite element simulation by Taşdelen et al. [16]. Laird G et al. [17] studied the micromechanical modelling of composite materials. Using the finite element method, Kim J et al. modelled a plate structure [18] enabled with a piezoelectric active device. Due to anisotropy, three-dimensional components were employed to describe piezoelectric devices, which link electric and elastic fields to fulfil boundary constraints on both fields independently. As brick elements [19] cause unnatural plane stiffening and high natural frequencies, shell elements were chosen by the authors.
Though there are numerous research articles showcasing material characterization for polymer matrix composites, comparatively few researchers showcase piezoelectric patched polymer matrix composites \[5–7,20\]. Early researchers have used the ANSYS® software \[2,16,17,20,21\] tool to forecast the performance of sensor-based polymer matrix composites based on the direct piezoelectric principle. However, the placement of piezo patches for optimal voltage generation is rarely addressed. In this paper, layer wise strain rate was determined using the ANSYS® Composite PrepPost® (ACP) module for identifying the surface for patching the piezo sensors. In addition, the current study created a new experimental test setup for determining the strain in composite structures. A data acquisition system with a strain component integrator, myDAQ hardware and LabVIEW® simulation software was used in this method for real-time monitoring. The output was graphically presented, the necessary data was extracted and the outcomes of the experimental and simulation work were compared. This paper details the step-by-step approach for modelling and analysing CFRP using the advanced module ANSYS® ACP to extract layer-wise strain. The Tsai-Hill Failure Criterion mathematical model was employed and the layer-by-layer data acquired was used to calculate the stress and strain components. The ANSYS® APDL module to model the piezo patched CFRP specimens and the output voltage was validated with the experimental values. The pictorial representation of the entire work process is given in figure 1.

In the present study, CFRP laminates were fabricated using the Vacuum Assisted Resin Transfer Method (VARTM). The anisotropic nature of the composite and its elastic constants were determined by material characterisation using the prepared test coupon in accordance with ASTM standards. Due to the laminate’s layered nature, it is difficult to anticipate the layer at which the laminate \[1\] will fail. A finite element simulation technique was chosen for layer-wise examination. The ANSYS® composite prepost tool is primarily used to simulate layer-by-layer stress and strain. Carbon reinforcing \[1,4\] will significantly boost the strength and stiffness of the structure. CFRP \[22\] is employed in the majority of applications requiring lightweight, high-strength materials. Monitoring failures \[23\] is critical in today’s industrial environment. The piezoelectric sensor’s direct and indirect impact principles enable monitoring of material breakdown. The ANSYS® APDL module enables the investigation of the harmonic response of piezo-bonded CFRP composites using Finite Element modelling. To verify the ANSYS® APDL harmonic response, a customised experimental setup based on National Instruments myDAG equipment and LabVIEW® software was employed. The results of the study were found to be in line with the results of the simulation.

2. Materials and methods

2.1. Composites
In this research, plain weave carbon fibre was used as a reinforcing material and epoxy resin was the matrix material (commercial codes: LY556, HY951). Table 1 shows the physical characteristics of the woven carbon
 fibre and the properties of the epoxy resin and hardener combination utilised in this research. With 12 layers of carbon fibre, a CFRP laminate of 1.86 mm was achieved using VARTM.

### 2.2. Lead–zirconate–titanate

As per the piezoelectric direct effect principle, if the film changes its shape, a small AC and a large voltage (up to $\pm 90$ V) are induced. A resistor utilising a simple direct current blocking technique was used to reduce the voltage to analogue-to-digital converter levels. Table 2 shows the physicochemical properties of lead-zirconate-titanate (PZT) purchased from the commercial vendor. The photographic view of the PZT material is shown in figure 2.

The sensor model and actuator model presented in this paper are governed by the piezoelectric constitutive laws [28].

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**Table 1. Typical properties of carbon fibre [24–26].**

| Material          | Physical properties       | Specifications |
|-------------------|----------------------------|----------------|
| Carbon Fibre      | Fill Yarn                 | 3K Carbon      |
|                   | Density                   | 1.76 g/cc      |
|                   | Specific Surface Area     | 0.450 m$^2$ g$^{-1}$ |
|                   | Elongation at Break       | 1.40%          |
|                   | Electrical Resistivity    | 0.00180 ohm-cm |
|                   | Fabric Thickness (mm)     | 0.22 (mm)      |
|                   | Thermal Conductivity      | 8.50 W m$^{-1}$K$^{-1}$ |
| Epoxy Resin       | Viscosity at 25 °C (ISO 12058-1) (mPa s) | 10000–12000 |
|                   | Density at 25 °C (ISO 1675) (g cm$^{-3}$) | 1.15–1.20 |
|                   | Flash Point [°C]          | >200 (ISO 2719) |
|                   | Vapor Pressure            | —              |
|                   | Epoxy Content (ISO 3000) [eq/kg] | 5.3–5.45 |
| Hardener          | Viscosity at 25 °C (ISO 12058-1) (mPa s) | 10 to 20 mPa s |
|                   | Density at 25 °C (ISO 1675) (g/cm$^3$) | 1 g cm$^{-3}$ [20 °C (68°)] |
|                   | Flash Point [°C]          | Closed cup: 110 °C (230 °F) [DIN 51758 EN 22719 (Pensky-Martens Closed Cup)] |
|                   | Vapor Pressure            | 0.0003 kPa (0.00225 mm Hg) [20 °C] |
|                   | Epoxy Content (ISO 3000) [eq/kg] | — |

**Table 2. Technical specifications of PZT-5H [27].**

| S. no | Property                                | Symbol | Unit | Values       |
|-------|----------------------------------------|--------|------|--------------|
| 1.    | Dielectric constant (1 kHz)            | $K_1^f$ |       | 3800         |
| 2.    | Dielectric loss factor (1 kHz)         | $\tan \delta$ | %   | 2.0          |
| 3.    | Coercive field (Measured <1 Hz)        | $E_c$   | kV/cm | 8.0          |
| 4.    | Resonant Thickness                      | $N_0$   | kH cm  | 202          |
| 5.    | Remanent polarization                   | $P_r$   | $\mu$ Coul/cm$^2$ | 39.0        |
| 6.    | Curie Point                             | $T_c$   | °C    | 225          |
| 7.    | Coupling coefficients                   | $k_p$   |       | 0.75         |
|       |                                        | $C_{33}$ |       | 0.75         |
|       |                                        | $C_{11}$ |       | 0.44         |
|       |                                        | $C_{14}$ |       | 0.55         |
|       |                                        | $C_{15}$ |       | 0.78         |
| 8.    | Piezoelectric Charge (Displacement Coefficient) | $d_{11}$ | Coul/N $\times 10^{-12}$ | -320     |
|       |                                        | $d_{33}$ |       | 650          |
|       |                                        | $d_{33}$ |       | 1000         |
| 9.    | Mechanical quality factor               | $Q_m$   |       | 32           |
| 10.   | Density                                | $\rho$  | g/cm$^3$ | 7.87         |
| 11.   | Specific heat                           | $C_p$   | J/kg C | 420          |
| 12.   | Thermal conductivity                    | $K_d$   | W/m K  | 1.2          |
| 13.   | Thermal expansion (Perpendicular to poling) | $\alpha$ | ppm/C | 3.5          |
| 14.   | Anti-resonant thickness                 | $N_{at}$ | ppm/C | 236          |
Equation (1) represents the actuation law,
\[
\{\sigma\}_{3 \times 1} = [C]_{3 \times 3} \{e\}_{3 \times 1} - \{E\}_{2 \times 1}
\]  
(1)

The sensing law is represented in (2),
\[
\{D\}_{2 \times 1} = [e]_{2 \times 3} \{e\}_{3 \times 1} + [\mu]_{2 \times 2} \{E\}_{2 \times 1}
\]  
(2)

The simplified constitutive law is given in equation (3),
\[
\{\varepsilon\} = [S] \{\sigma\} + [d] \{E\}
\]  
(3)

The constitutive equations for the piezoelectric material (equation (4)) define the stress tensor and electric displacement vector in terms of the strain tensor and electric field. For a 2D analysis of an orthotropic piezoelectric material under plane stress conditions,
\[
\begin{bmatrix}
\sigma_{11} \\
\sigma_{22} \\
\sigma_{33} \\
\tau_{23} \\
\tau_{13} \\
\tau_{12} \\
D_1 \\
D_2 \\
D_3
\end{bmatrix} =
\begin{bmatrix}
C_{11} & C_{12} & C_{13} \\
C_{21} & C_{22} & C_{23} \\
C_{31} & C_{32} & C_{33} \\
C_{44} & C_{45} & C_{46} \\
C_{54} & C_{55} & C_{56} \\
C_{64} & C_{65} & C_{66}
\end{bmatrix}
\begin{bmatrix}
\varepsilon_{11} \\
\varepsilon_{22} \\
\varepsilon_{33} \\
\varepsilon_{12} \\
\varepsilon_{13} \\
\varepsilon_{23}
\end{bmatrix} -
\begin{bmatrix}
\varepsilon_{31} \\
\varepsilon_{32} \\
\varepsilon_{33} \\
\varepsilon_{24} \\
\varepsilon_{15} \\
\varepsilon_{25} \\
\varepsilon_{35}
\end{bmatrix} \\
\begin{bmatrix}
\mu_{11} \\
\mu_{22} \\
\mu_{33}
\end{bmatrix}
\]  
(4)

2.2.1. Sensor model
Piezoelectric materials deform in response to an applied voltage when pressure is applied. When deformed, piezoelectric materials generate a voltage. The Young’s modulus E and the appropriate piezoelectric coefficient \(e_{31}\) are the sole physical properties involved in this sensor module [28].

The constitutive law, for piezoelectric sensor model is represented in equation (5)
\[
\sigma_{xx} = -e_{31}E_z = -e_{31}V/t
\]  
(5)

The elementary beam theory is given in equation (6)
\[
\frac{M}{I} = \frac{\sigma_{xx}}{Z}
\]  
(6)

The moment developed due to electrical excitation is shown in equation (7)
\[
M = -\frac{2e_{31}VI}{t^2}
\]  
(7)

The configuration of the sensor model is schematically represented in figure 3.

2.2.2. Actuator model
The deflection for a cantilever beam subjected to tip concentrated load F is given equation (8)
\[
w(x) = \frac{P}{EI} \left(\frac{x^2}{6} - \frac{x^2L}{2}\right)
\]  
(8)
The tip deflection due to mechanical and electrical load at \( x = L \) is represented in equation (9),

\[
w(L)_{\text{total}} = \frac{PL^3}{3EI} + \frac{c_{31} V}{E} \left( \frac{L}{t} \right)
\]  

(9)

The schematic representation of the piezoelectric actuator model is shown in figure 4.

2.3. Preparation of CFRP test coupons

2.3.1. VARTM

To begin with the fabrication process, 12 layers of woven carbon fibre of the required dimensions (300 × 300 mm) are cut and stacked (figure 5(a)) and having the spiral pipes, with their ports for the vacuum and resin, arranged around the stacked layers of carbon fibre. To prevent air leakage, the entire setup was sealed with sealant tape, and a peel-ply was used to prevent the vacuum bag from sticking to the fabric.

The VARTM is a composite manufacturing method wherein the resin medium is pulled into a laminate under vacuum pressure. A woven carbon fibre is placed over the dry mould and a vacuum is created before the introduction of resin. The whole arrangement is protected by a plastic vacuum bag that serves as a flexible top mould. Once the desired vacuum pressure is achieved, the resin hardener mixture is impregnated into the fibre arrangement through precisely arranged tubes [29]. The impregnation time taken for wetting the entire layers was about 198 s. A typical VARTM process [30] involves resin (matrix phase), seeping through the empty space before the gel time is reached. The curing time took about 16 h at room temperature. Figure 5(b) depicts the VARTM experimental setup used in the present study. An aerospace-grade sealant tape is used to seal the whole system. The principal components involved in grafting the VARTM setup are listed in table 3 along with their respective technical specifications.

2.3.2. Water jet machining process

The abrasive water jet (AWJ) provides a fine cut without any composite failure and thus the mechanical properties [31] of the fabricated composite are unaltered. The finely focused water jet cuts consistently and precisely in any direction, revealing incredible details of the finished products. The CFRP test coupons are sized from the CFRP laminate using the AWJ process. The surface quality of the composite specimen is determined by AWJ parameters (table 4). As a result, it has a significant impact on how surfaces are machined.
Maximum abrasive jet pressure increases material removal rate, while minimum standoff distance (SOD) reduces kerf angle in woven carbon fibre composites [32]. Figure 5(c) also shows a picture of the CFRP test coupons that were cut from the CFRP laminate with a water jet.

2.3.3. Test coupon geometry
The material testing under uni-axial loading of the developed coupons is conducted as per ASTM D3039 and ASTM D3518 standards to extract the physical properties. The specimen cross section was 43.5 mm².

Table 3. VARTM specifications.

| S. no. | Components                  | Technical specifications |
|--------|-----------------------------|--------------------------|
| 1.     | Catch pot system            | End-pressure vacuum (%)  |
| 2.     | Peel ply                    | Thickness: 105 GSM       |
|        |                             | Usage temperature: Up to 190 °C |
| 3.     | Breather/Bleeder cloth      | Operating temperature: 204 °C |
| 4.     | Pressure gauge              | Vacuum Pressure: −30 bar |
| 5.     | Sealant Tap                 | Commercial Name: Flex Tape |

Table 4. AWJ process parameters.

| S.no. | Parameter                  | Value     |
|-------|----------------------------|-----------|
| 1.    | Nozzle diameter (mm)       | 0.76      |
| 2.    | Water Pressure (MPa)       | 375       |
| 3.    | Stand-off distance (mm)    | 3         |
| 4.    | Abrasive flow rate (kg/min)| 0.5       |
Table 5 shows the composite test sample configurations used in the present material characterization work. The Mitutoyo 500-197-20 digital vernier caliper was used to determine the thickness of a specimen at different places and the measurements of the specimens were recorded.

| Sample code | ASTM | Coupon configuration | Range of $T_{avg}$ mm | Qty |
|-------------|------|----------------------|------------------------|-----|
| CFRP1       | D3039| Without End Tab      | 1.74–1.76              | 3   |
| CFRP2       | D3039| With End Tab         | 1.72–1.76              | 3   |
| CFRP3       | D3518| $\pm 45^\circ$ With End Tab | 1.82–1.87              | 3   |
| CFRP4       | D3518| $\pm 45^\circ$ With End Tab | 1.86–1.9              | 3   |

2.4. Material characterisation
The CFRP composite test coupons prepared in accordance with ASTM standards were subjected to uniaxial tensile testing using a 50 kN INSTRON universal testing machine. The cross-head speed was set at 2 mm min$^{-1}$ and the gauge length was 150 mm for the testing. An extensometer is used to measure the strain during the test. The length of the extensometer gauge was 25 mm. Tensile tests were performed on CFRP materials to determine mechanical characteristics, such as tensile strength, tensile modulus, shear strength, and shear modulus.

2.4.1. Uniaxial tensile test results
Both experimental and numerical data were used to evaluate the material characterization of CFRP composite materials. In the tensile testing, a maximum extension of up to 0.4012 mm was recorded. The elastic modulus was determined from the experimental study (figure 5d). Other mechanical parameters, such as tensile strength and elongation percentage, were also determined. The applied load was divided by the nominal cross-sectional area of 43.75 mm$^2$ of the test specimens, which is the nominal thickness of 12 CFRP composites layers [33] multiplied by the width of the specimen. Figure 5(d) depicts experimentally observed stress-strain plots for CFRP samples, demonstrating that all test specimens break in brittle mode with a precipitous decline after reaching maximum tensile strength. Moreover, the VARTM fabrication [34, 35] method enhances the tensile strength of CFRP composites, as well as their ultimate strain, through experimental demonstration. According to the experiment results, there are stress values of 480 MPa, 520 MPa, 530 MPa, and 528 MPa, as well as strain values of 0.0125, 0.0165, 0.017, and 0.0175.

3. Finite element analysis using ANSYS®

The CFRP beam structure and the piezo-bonded CFRP beam (Sensor Model) structure were analysed using the Finite Element Method in the ANSYS® Parametric Design Language.

3.1. Tsai-hill failure criterion
The Tsai-Hill failure criteria were utilised to determine the ply-failure laminate. It is one of the most frequently used failure criteria for composite materials. It has been successfully integrated into ACP®.

Tsai-Hill equation for failure theory is stated in equations (10) and (11)

\[
\left(\frac{\sigma_1}{X}\right)^2 + \left(\frac{\sigma_2}{Y}\right)^2 + \left(\frac{\tau_{xy}}{S}\right)^2 - \left(\frac{\sigma_1\sigma_2}{X}\right) > 1
\]  

Where X and Y are

\[
\sigma_1 \geq 0 \rightarrow X = X_i, \quad \sigma_1 < 0 \rightarrow X = X_o, \quad \sigma_2 \geq 0 \rightarrow Y = Y_i
\]

\[
\sigma_2 < 0 \rightarrow Y = Y_c. \quad \text{If } \sigma_1 = 0 \text{ and } \tau_{xy} = \gamma \sigma_1, \text{ then the local stress can be written as } \sigma_1 = (c^2 - 2\gamma c)\sigma_1, \sigma_2 = (s^2 - 2\gamma sc)\sigma_2, \text{ and } \tau_{12} = (sc + \gamma (c^2 - s^2))\sigma_1. \text{ Applying this condition into the Tsai-Hill failure theory, the Tsai-Hill equation will possess only the global stress in the x direction.}
\]

3.2. Layer-wise strain calculation using ANSYS® ACP
ACP is a new module in the ANSYS® Workbench environment for the modelling of composite parts. Figure 6 schematically indicates the ANSYS® Workbench layout for composite modelling.

The CFRP test coupons under uni-axial tension are simulated using ANSYS® ACP modelling begins with the selection of a material as carbon/epoxy from engineering data (experimental data). To begin with the
simulation, the ANSYS® ACP (Pre) component system was selected and the process steps started with engineering data that describes the experimental CFRP test coupon properties. These were defined in this module, then a 3D model was created using Solidworks® software and imported into ACP (Pre) in Parasolid file format. For measuring the strain rate, the Rosette properties were defined in this module. The modelling ply was created for 12 ply materials and the ply material was chosen as epoxy-carbon. The Ply angle is 0° because the

Table 6. Material characterization results.

| Test no. | ASTM | $F_m$ (kN) | Max. extension (mm) | $S_0$ ($\text{mm}^2$) | Tensile strength (MPa) | % Elongation | $E_1$ (MPa) | Load at break, (kN) |
|----------|------|------------|---------------------|----------------------|-----------------------|--------------|------------|-------------------|
| 1        |      | 22.246     | 0.278               | 43.75                | 503.4                 | 1.11         | 45728      | 16.725            |
| 2        |      | 22.782     | 0.3586              | 43.75                | 501.2                 | 1.23         | 33562      | 15.762            |
| 3        | D3039| 21.469     | 0.4012              | 43.75                | 498.3                 | 0.98         | 46278      | 16.264            |
| 4        |      | 22.589     | 0.2812              | 43.75                | 492.3                 | 0.97         | 33622      | 16.758            |
| 5        |      | 21.894     | 0.2381              | 43.75                | 496.8                 | 1.13         | 42356      | 14.758            |

Test No. | ASTM | $F_m$ (kN) | Max. Extension (mm) | $S_0$ ($\text{mm}^2$) | $G_{12}$ (MPa) | % Elongation | Shear Strength (MPa) | Load at Break (kN) |
|----------|------|------------|---------------------|----------------------|---------------|--------------|---------------------|-------------------|
| 1        |      | 11.356     | 1.256               | 22.246               | 156.8         | 3.56         | 85                  | 5.36              |
| 2        |      | 12.856     | 1.785               | 22.782               | 144.2         | 3.78         | 68                  | 4.65              |
| 3        | D3518| 11.489     | 1.569               | 21.469               | 150.7         | 4.01         | 79                  | 5.88              |
| 4        |      | 11.358     | 1.784               | 22.589               | 152.6         | 3.88         | 78                  | 5.01              |
| 5        |      | 10.658     | 1.698               | 21.894               | 158.7         | 4.09         | 82                  | 4.09              |
The material chosen is bidirectional woven. The mechanical model module in workbench was chosen to create the end tab part in the specimen. The output of the ACP (Pre) and mechanical model is connected with the Static Structural component system in ANSYS® Workbench and the connections were defined between test coupon and the end tab model.

The mesh refinement size of 2 mm was considered for the entire model. The boundary conditions (table 7) were defined with one end fixed and another with remote displacement with a maximum displacement value of 0.45 mm along the X component, while the Y and Z components were zero in linear direction. The rotation X, Y and Z were also defined as zero for the CFRP test coupon. Three-time steps were defined with an initial sub step of 40, a minimum sub steps of 40, and a maximum sub step of 1000. The output of the ply wise equivalent elastic strain value was simulated based on the named selection mode. The maximum strain value was predicted in the top layer of the CFRP specimen. In the ACP (Post) module, a ply wise solid model was imported and the results were plotted. The entire simulation output represents the prediction of exact ply failure on the composite. The overall deformation is found to be 0.20299 mm and is shown in figure 7(a).

It is essential to analyze the composite layer-by-layer for piezo-enabled composite structures. Layer-by-layer finite element failure analysis on composite models and post-process results using failure criteria [36, 37] specific to composites have been assessed. A parametric design analysis was performed to determine how certain factors, such as the number of layers and fibre orientation, affected the design of the structure.

All composite material definitions are created and mapped to the finite element grid in the pre-processing module [38]. The layer-wise equivalent stress data was plotted in the post-processing stage. According to simulation results, the maximum strain was reached at the top layer of 12 (figure 7(b)). Based on the numerical results, the piezo sensor was patched on the top of the CFRP specimen as the maximum strain value was achieved at layer 12. The strain values that occurred in each layer are indicated in figure 8.

### Table 7. Finite element assumption.

| Sl.no. | Details                      | Layer wise strain calculation | Voltage generation on piezo patched CFRP |
|-------|------------------------------|------------------------------|------------------------------------------|
| 1.    | Software Module              | ANSYS® Composite Prepost      | ANSYS® APDL                              |
| 2.    | Analysis Type                | Static Structural            | Harmonic response                        |
| 3.    | Load details                 | Uniaxial tensile load on CFRP specimen | Piezo patched cantilever CFRP structure subjected to end point load |
| 4.    | Element Type                 | Shell 181 & Solid 186        | CFRP: shell 181 & Solid 186               |
|       |                              |                              | PZT: circuit 94                           |
| 5.    | Mesh resolution              | 2 mm                         | 2 mm                                     |
| 6.    | Number of fabric layers (CFRP) | 12                           | 12                                       |
| 7.    | Number of elements           | 1,74,044                     | 1,74,044                                 |
| 8.    | Material Properties          | CFRP                         | PZT                                      |

- Density $\rho = 1.54e-6$ kg mm$^{-3}$
- Young’s Modulus $E_1 = 46278$ MPa
- Poisson’s Ratio $\gamma = 0.2718324$
- Shear Modulus $G_{12} = 158.7$ MPa
- As listed in table 2

![Figure 8. Layer wise Equivalent elastic strain from Ply 1–12.](image-url)
3.3. Piezo-bonded CFRP beam structure

The element type was chosen as coupled field shell 181 and solid 186. The analysis type was electroelast/piezoelectric and circuit 94. The piezoelectric material property (constitution matrix) was fed into the material models. The CFRP specimen was defined using Solid186, a higher-order 3D 20-node solid element with quadratic displacement behaviour.

Each node in the element has three degrees of freedom: translations in the x, y, and z dimensions. In this simulation, the boundary conditions were defined for the model as a cantilever support. One end of the beam is fixed so that linear displacement of Ux, Uy, and Uz rotational displacement of Rx, Ry, and Rz are defined as zero. The other end of the beam is subjected to a point load in the y direction, which has a negative sign due to the downward direction (figure 9(a)). The piezoelectric sensor was patched on top of the free end portion of the beam. The circuit element CIRCU94 was used to analyse piezoelectric circuits. Two or three nodes identify the circuit component, while one or two degrees of freedom model the circuit response. The CFRP laminate and PZT–5H sensor were patched using the glue operation in the software module.

CFRP and PZT–5H materials are bonded using the glue operation in ANSYS®. For better mesh quality, the 4-to-6-sided option was chosen. The total number of generated elements considered in the FEA study was 1,74,044. PZT–5H is bonded with CFRP material. A cantilever structure loaded with end point load is defined in this simulation. The load varied from 492 N to 9800 N. The analysis type was chosen as harmonic with the stepped mode option.

The present study deals with finite element simulation of CFRP embedded with PZT–5H material with a harmonic frequency range of 0 to 1000 Hz with 1000 steps. The study was conducted using the CFRP and

Figure 9. (a) Finite element model with boundary condition (b) maximum Voltage developed at 162 Hz frequency.

Figure 10. Frequency versus amplitude graphical plot for nodal solution.
PZT-5H material parameters listed in tables 6 and 2 respectively. The graphical plot represents the output results of the Piezo-bonded CFRP composite material (figure 10). Electric potential is extracted from piezoelectric patches simulated across the surface of the cantilever beam based on the input load provided at its end. A maximum output voltage of 4.396 V (amplified at 1000X) was obtained from a numerical simulation at 162.5 Hz (figure 9(b)). The static load value was applied at different intervals in the range from 490 N to 9800 N and a similar procedure was carried out experimentally.

4. Experimentation

4.1. Strain measurement using Piezo enabled beam structure

Using Lab VIEW® software, Virtual Instrumentation (VI) was used to collect and display real-time output signals for the piezoelectric sensor. A real-time data collection hardware system is represented in figure 11. Piezoelectric fibre composite sensors were prepared using lead zirconate titanate. For a piezo sensor, the mV will be converted into volts by an amplification factor [37] of 1000X. The piezoelectric efficiency of piezoelectric sensors is assessed using a two-mode system. The load is proportional to the voltage supplied, which depends on the geometrical parameters. After measuring the capacitance and resistance, the PZT element’s integrity was qualitatively evaluated. Embedding PZT sensor/actuator in thicker composites was also studied with the goal of developing in situ condition monitoring methods to increase the operating safety of the composite structure using PZT sensors. The piezoelectric sensor was patched with the fabricated CFRP specimen. While curing, insulating coatings were utilised to keep the PZT’s anode and cathode from coming into contact with carbon fibre [39].

The specimen was initially rigidly clamped at one end and free at the other. Based on the findings of the ANSYS®, the PZT-5H sensor was patched over the specimen at the free end. An arrangement was developed at the end of the specimen to apply a quasi-static physical load to it. The myDAQ instrumentation kit has been used to connect the terminals. This myDAQ data acquisition device feature contains a digital multimeter, an oscilloscope, and a function generator, which are all plug-and-play computer-based lab instruments based on LabVIEW®. It’s a portable gadget that replaces the various instrumentation clusters with a single device. Through the piezo sensor terminal, it detects the external excitation induced by the load applied to the specimen. Based on our demand to examine the harmonic response of the CFRP structure, a graphical user interface software simulation module has been built in LabVIEW®. External stimulation has a proportionate effect on the output wave.

The voltage was converted from the output wave. The readings were taken for varied physical loads. Based on the experimental data, the values are obtained at a frequency range of 162 Hz (figure 12) for the external excitation load of 490 N, 1490 N, 2450 N, 4905 N and 9800 N with their corresponding emf values of 1.4V, 2.65V, 4.25V, 5.56V and 5.7V (table 8).
This indicates that the piezoceramic composite generates an increase in emf value for external load applications. Piezoelectric smart materials integrated into the laminated framework act as the sensing elements. Embedded piezoelectric materials connected with the myDAQ and LabVIEW® spectrum monitoring systems were used to detect active deterioration in composite constructions. The piezoelectric smart structure technology is also useful for active and online structural damage detection. Any complex planner mechanical loading was achieved by combining tensile and bending forces, and the findings gained in this research were used to further investigate the suggested interaction issue in more difficult loading scenarios.

The numerical findings may also be utilised as a reference for selecting the material characteristics and thickness of the coating layers. A method for integrating piezoceramic sensor and actuator patches over CFRP laminate composite structures to create active composite panels with simultaneous precision positioning was developed, and the performance of the smart CFRP laminate was determined experimentally.

### 5. Conclusion

This study shows that the following conclusions can be drawn from the test results and numerical simulations:

Sensors patched to the CFRP composites can be applied for condition monitoring of aircraft and aerospace structures that are subjected to impact and high-pressure applications. The piezo-bonded CFRP beam module also gives us a lot of ideas for composite materials that can be used to make micro power harvesting systems.

The composite module ANSYS® ACP is a promising tool for analysing composite design layer-by-layer properties. Predicting the strain along each layer will give us an idea of where to position the sensors where there is maximum equivalent elastic strain. A FEA simulation was carried out, and an equivalent elastic strain for each layer was predicted. Based on the results from ACP®, an FE model of a CFRP specimen with a Piezo sensor patch

### Table 8. Correlation of results @ 162.5 Hz.

| External excitation | Sensor reading (V) | Percentage of deviation (%) |
|---------------------|--------------------|-----------------------------|
| g N                 | Experimental solution | Numerical solution |                           |
| 50 490             | 1.21               | 1.32                        | 8.3                        |
| 100 980            | 1.61               | 1.54                        | 4.3                        |
| 150 1470           | 2.65               | 2.93                        | 9.5                        |
| 200 1960           | 3.93               | 4.11                        | 4.3                        |
| 250 2450           | 3.95               | 4.39                        | 10.0                       |
| 300 2940           | 2.14               | 2.42                        | 11.57                      |
| 500 4905           | 5.56               | 5.84                        | 4.79                       |
| 1000 9800          | 5.72               | 5.14                        | 10.13                      |

Figure 12. Graphical representation of frequency versus output voltage.
was developed. The output of the maximum deformation is 0.20299 mm and equivalent elastic strain at ply 12 is 0.0072582 mm mm⁻¹.

From FE simulation of a Piezo patched CFRP specimen, it is observed that maximum voltage generation is observed when the Piezo sensor is fixed at the topmost layer of the specimen and at the free end. FE simulation trails were also carried out for varied load values and frequencies. An output voltage of 4.396 V (amplified at 1000X) was achieved at 162.5 Hz.

Using Lab VIEW software, virtual instrumentation can be used to collect and display real-time output signals for the piezoelectric sensor. The experimental arrangement and procedure discussed in this paper can be implemented by future researchers to predict voltage from external excitation on sensor patched composites. The correlation between numerical simulation and experimental results was achieved with a minimum error percentage. This suggests that any ANSYS® composites and structural modules can be used for positioning and arranging sensors over large-scale structures.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

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This research paper has not been published in whole or in part elsewhere. The manuscript is not currently being considered for publication in another journal. All of the authors have been personally and actively involved in the work that led to the manuscript, and they will be jointly and individually responsible for its content.

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