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SMART PIEZO-ENABLED GLASS-FABRIC-REINFORCED COMPOSITE STRUCTURE: EXPERIMENTS AND FINITE-ELEMENT MODELING

PAMETNA KOMPOZITNA STRUKTURA S STEKLENIMI VLAKNI OJAČANE TKANINE S PIEZO EFEKTOM: PREIZKUSI IN MODELIRANJE NA OSNOVI METODE KONČNIH ELEMENTOV

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This paper deals with an experimental and finite-element investigation of smart polyvinylidene fluoride (PVDF) embedded with a glass-fabric-reinforced polymer (GFRP) beam structure under vibration. PVDFs are well known stretchy polymer that process the properties of both piezoelectric and pyroelectric materials. An LDT0-028K PVDF polymer film is proposed in the present paper. Glass-fiber-reinforced polymer is a lightweight composite material having a high specific strength and specific stiffness, due to which it has a wide range of applications in the field of smart composite structures. GFRP laminates and beam structures are fabricated in the present investigation through a vacuum-assisted resin-infusion process (VARIP). Mechanical characterization in accordance with ASTM standards were also carried out for the purpose of the estimation of uni-directional mechanical properties of GFRP, which are a pre-requisite for finite-element simulations. Both the experiments and the finite-element modelling were carried out for the smart piezo composite beam structure under forced vibration conditions. The finite-element computations were incorporated in the present study using ANSYS® 16.0 Mechanical APDL. The results of the experimental and FEM investigations show a deviation of around 6.2 %, with the experimental values validating the FEM analysis. Based on the harmonic response of the smart piezo-composite beam, a micro-energy harvesting study was established with reference to the varying frequency and voltage.

Keywords: piezoelectric, polyvinylidene fluoride, piezocomposite, glass-fiber-reinforced polymer, finite element method, ANSYS®

V članku avtorji opisujejo študijo o »pametnem« poliviniliden fluoridu (PVDF; $(C_2H_2F_2)_n$) obdanem s steklom ojačano »pametno« polimerno strukturo (GFRP; angl.: glass fabric reinforced polymer). Izdelano strukturo v obliki traku (nosilca) so analizirali eksperimentalno in modelirali z metodo končnih elelmentov (FEM; angl.: Finite Element Method). PVDFs so dobro znani prožni/raztegljivi (angl.: stretchy) polimerni materiali, ki imajo piezo- in piro- električne lastnosti. Avtorji so za pričujočo študijo porabili LDT0-028K PVDF polimerni film. S steklenimi vlakni ojačan polimer je lahek kompozitni material, ki ima veliko specifično trdnost in togost ter se zato pogosto uporablja na področju »pametnih« kompozitnih struktur. Za pričujočo raziskavo so GFRP laminate in nosilne strukture izdelali s pomočjo procesa vakumsko podprtega nalivanja polimerne smole (VARIP; angl.: vacuum assisted resin infusion process). Nato je sledila mehanska karakterizacija v skladu z ASTM standardom, zato da so lahko določili njihove mehanske lastnosti v različnih smereh. Njihovo poznavanje je predpogoj za modeliranje s pomočjo FEM. Avtorji so izvedli tako eksperimentalne preizkuse kot tudi FEM modeliranje nosilca pametne piezo kompozitne strukture v pogojih vsiljenih vibracij. Izvedli so kompletne računalniške simulacije in izračune s pomočjo programskega orodja ANSYS® 16.0 Mechanical APDL. Rezultati eksperimentalnih preizkusov in računalniškega FEM modeliranja so se med seboj razlikovali za približno 6,2 %. Pri različnih frekvencah in napetostih so na osnovi harmoničnega odgovora pametnega piezo kompozitnega nosilca izvedli mikro energijsko študijo.

Ključne besede: piezo električnost, poliviniliden fluorid, piezokompozit, s steklenimi vlakni ojačan polimer, metoda končnih elementov, programsko orodje ANSYS®

1 INTRODUCTION

During recent decades there has been an increasing interest in smart materials. The benefits of smart piezoelectric materials[1] include sensing, actuation, structural health monitoring, smart structures and energy-harvesting applications. The piezoelectric energy harvester has become more popular in a wide variety of applications. Micro-energy can be harvested from the natural resources i.e., mechanical vibration, mechanical stress and strain, thermal energy sources, solar energy, chemical energy sources, etc. Researchers have pointed out that the bidirectional woven glass-fabric-reinforced composites are pertinent to smart composite applications. VARIP is a better technique for the manufacture of composite structures with negligible voids and good strength. By varying the frequency response, the maximum voltage could be attained and thereby a suitable way of positioning the piezoelectric material also on the glass-fiber-reinforced polymer could be identified. Finite-element modelling

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and analysis are essential for the development of piezo-enabled composites.

Heywang et al. have addressed the experimental investigation on the direct and inverse piezoelectric effects.[2] Vatanserver et al. investigated the voltage response and the mechanical stimulus of PVDF in various temperature for the purpose of identifying the suitable type of PVDF material viz. LDT1-028K, LDT2-028K, LDT4-028K.[3] Vasanthanathan et al. developed a finite-element model of a non-circular shaft using ANSYS® with the smart finite-element modelling of piezo zirconate titanate embedded glass-fiber-reinforced polymer[4,5] cantilever beam under free and forced vibrations. Vinod et al. proposed the effect of positioning the piezo-fiber composite (PFC-W14) that is embedded along the multilayer glass-fiber-reinforced composites.[6]

Lee et al. developed a piezoelectric harvester[7] that was mounted inside the tire for implementing wireless sensor technology wherein the energy harvester technology transmits the residual energy from the environment and converts it into the electrical energy to observe the performance of the tire. The observation has been made by fixing the strain gauge (Y11-FA) by which the signal has been transmitted from the transducer which could consume the energy of 1.9 mJ every 8.3 s with a velocity of 60 km/h by applying the capacitor of 2000 μF. Viet et al. have suggested a model of floating mass spring-piezoelectric energy harvester[8] in order to extract energy from the intermediate and deep energy harvester. The mass spring system presented by Viet et al. observed the wave motion and converted it into the mechanical vibration that would lead the piezoelectric lever devices, which in turn could generate the electric power. Viet et al. have also found that the harvested electric source obtained was 103 W from the floating waves by varying the width, height, length and mass of the system. Chang et al. showed the enhancement of pyroelectric coefficient of lead zirconate titanate[9] and stainless-steel laminated composite for increasing the maximum power density. Broadhurst et al. described the molecular and bulk structure of PVDF[10] which is crystallized and melt into spherulitic structures of thickness 10–20 mm. Hwang studied the piezoelectric response[11] of unidirectional glass-fiber-epoxy composite. Kimi et al. investigated the mechanical property and failure mechanism of glass-fiber-reinforced polymer made by both hand lay-up and vacuum infusion[12] technique.

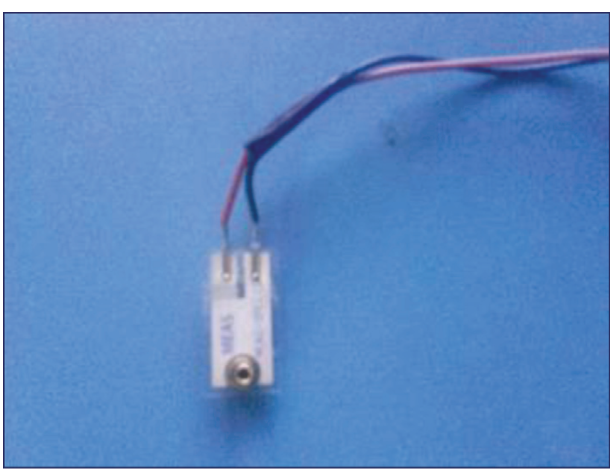

Figure 1: Polyvinylidene fluoride (LDT0-028K) sensor

The study in the present paper deals with two phases of work:

- In the first phase of the paper, a finite-element modelling of smart piezo-composite has been carried out using commercially available ANSYS® Mechanical APDL software. In the finite-element simulation, PVDF was embedded along with the GFRP laminate by providing necessary boundary conditions. The simulation results were observed for parameters, i.e., varying frequency, voltage and providing the harmonic response. This phase also deals with the mechanical characterization of GFRP material fabricated through VARIP in accordance with ASTM. The experimentally observed mechanical properties of GFRP were incorporated into the FE model.
- In the second phase of the paper, the experimental setup which accommodates GFRP cantilever piezocomposite, DC motor to induce forced vibration and a microcontroller was developed to experiment on the response of piezocomposite beam under forced vibration.

2 MATERIALS AND METHODS

2.1 Materials

2.1.1 Piezoelectric material

The present study emphasizes LDT0-028K, which is a stretchy PVDF polymer with printed Ag inkjet electrodes. The LDT0-028K is a piezoelectric sensor designed to convert mechanical vibrations or pressure changes into electrical signals commonly used for sensing, measuring and monitoring physical phenomena manufactured by Measurement Specialties, Inc. (MEAS), which is now a part of TE Connectivity. The sensor was designed compact and lightweight, with high sensitivity to detect even small changes in pressure, acceleration or force. The selection of LDT0-028K aligns with its specific functional properties, such as piezoelectric strain and stress coefficients.

Table 1: Material properties of PVDF[13]

Properties	PVDF
Young's Modulus (*E*)	2e9 GPa
Poisson's ratio (Y)	0.29
Piezoelectric strain coefficient (d_{31})	22e-12 m/V
Piezoelectric stress coefficient (g_{31})	216e-3 Vm/N
Density (ρ)	1.78e3 kg/m^3
Permittivity constant (ε)	106e-12 F/m
Permittivity constant ($\varepsilon/\varepsilon_o$)	12

Table 2: Physical properties of Glass fabric[14]

Weave type	Fabric width mm	Count (Along wrap & weft)	Filament diameter (μm)	Thickness (mm)	Weight per sq.meter. (g/m^2)	Tensile strength MPa
Plain	1000	3k	11	0.27	380	115/warp

Table 3: Physical properties of Matrix[15,16]

Matrix	Type	Curing Temperature	Flash point	Density (kg/m^3)	Tensile strength (MPa)
Epoxy	Araldite (LY556)	20 °C – 180 °C	–	1.06 e^3	33
Hardener	Aradur (HY951)	–	110 °C	1 e^3	–

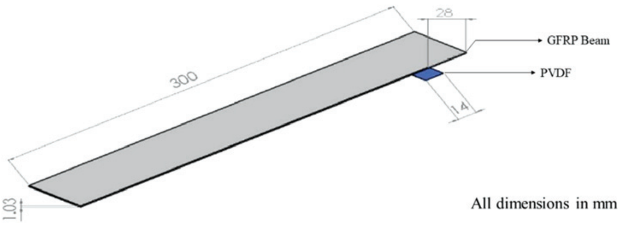

Figure 2: Structural geometry of piezo-enabled GFRP beam structure

LDT0-028K is fitted into two crimped contacts having the dimensions (25 × 13) mm, as shown in **Figure 1**. The PVDF features both piezoelectric and ferroelectric characteristics. The PVDF used in the present investigation was supplied by spark fun electronics (Pvt.) Ltd., US, and the properties of PVDF are represented in **Table 1**.

2.1.2 Composite materials

The reinforced material used in the study was glass woven fabric and the matrix medium selected was epoxy (LY556) with a compatible hardener (HY951). The mixing ratio of epoxy to hardener was 1:10, as per the methodology outlined in the fabrication process. The glass fabric was supplied by Urja products (Pvt.) Ltd. Ahmedabad and the epoxy resin with hardener was supplied by Huntsman Advance Materials, Switzerland. The preference for GFRP is that GFRP is commonly used in massive structures where structural health monitoring; micro energy harvesting can be implemented. GFRP is driven by its lightweight nature, high strength-to-weight ratio, corrosion resistance, durability, design flexibility, and other properties that collectively contribute to the efficient construction, reduced maintenance, and long-term structural integrity. The physical properties of the fabric and matrix are shown in **Table 2** and **Table 3** respectively.

2.1.3 Structural geometry

For performing the experimental and finite-element investigation, a piezo-enabled GFRP beam structure of size (300 × 28 × 1.03) mm was modelled, as represented in **Figure 2**. The PVDF of size (14 × 25) mm with thickness as 25 μm is bonded at a distance of 28 mm from the left. The structural geometry of the piezo-enabled GFRP beam structure was modelled using Solidworks® 2013.

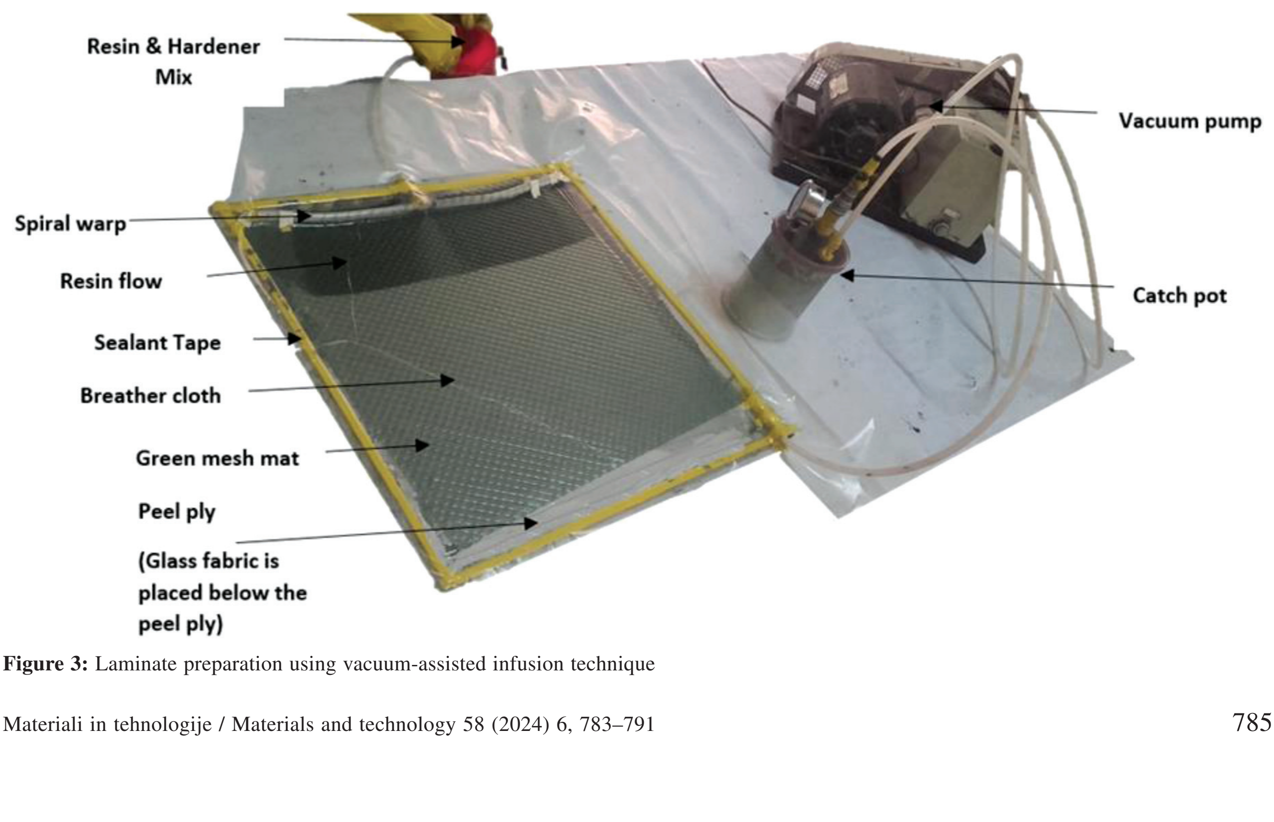

Figure 3: Laminate preparation using vacuum-assisted infusion technique

2.2 Fabrication of composite laminate

2.2.1 Vacuum-assisted resin infusion process

VARIP was used for the fabrication of the GFRP test coupons and the GFRP beam structure. VARIP is one of the advanced technique under close mould process for the fabricaiton of polymer matric composites (PMC), which uses the resin infusion-technique. VARIP provides larger ua ltimate strength, tensile modulus, shear strength, negilible void content while comparing with other fabricaiton techniques. VARIP[17,18] was designed to create void-free composite structures.

The vacuum pressure applied during the resin-infusion process helps remove air and other gases from the mold, minimizing the likelihood of voids in the final product. This is particularly important for applications where structural integrity and performance are critical. The glass fabric/epoxy laminate was prepared by using VARIP, as shown in **Figure 3**, to provide better strength. Initially, the polymer base plate is cleaned with acetone to remove the dust particles. A thin wax film was coated over the entire polymer base plate so as to remove the fabricated part easily. The glass fabric layer having orientation of 0°/90° is placed over the thin wax-coated polymer base plate. A green mesh mat was placed over the fabric, which would provide the uniform distribution of resin flow over the entire surface of the glass fabric and a peel ply was kept in between the glass fabric and green mesh mat to provide for easy removal of the fabricated glass fabric/epoxy laminate. The spiral warp was fixed at the one end of the setup for the purpose of suction. The whole setup was covered by breather cloth or vacuum bag (0.05-mm thick) and the bag was sealed using sealant tapes (AT90 AT140; 12 × 3 mm) so that the whole setup would be subject to vacuum. The end of the setup was connected to the vacuum pump (Model: F182, speed 1440 min^{-1}, 2.4 amp, 230 V, 50 Hz, 1 HP) through the catch pot. The catch pot plays a significant role in pressure control and also the excess resin would be collected in the catch pot. When the vacuum pump is switched on, suction was induced. At another end of the setup, the resin and hardener mixture of ratio 100:27 was taken in a container. The epoxy resin along with the hardener was drawn and it spreads uniformly over the glass fabric. Finally, the curing was carried out in vacuum at room temperature. Test specimens as per ASTM dimensions were cut from the composite laminate made and subjected to material testing.

2.3 Material characterization

The principal objective of the present material characterization is to extract the material properties of the glass-fabric-reinforced composite. The experimentally obtained material properties of GFRP are given input to the finite-element analysis procedure. The finite-element method (FEM) simulations rely on accurate material property data as the input. Material characterization provides essential information such as elastic modulus, Poisson's ratio and other material constants needed for the simulation. The information is crucial for defining the material behaviour within the FEM model under different types of forces or pressures applied. In the present experimental work, the material characterization of the GFRP was obtained in accordance to ASTM using a FIE make UTE-40 Universal Testing Machine.

The displacements were measured using an electronic extensometer of 50 mm standard gauge length. The uniaxial tensile testing was conducted and the unidirectional mechanical properties, i.e., Young's modulus,

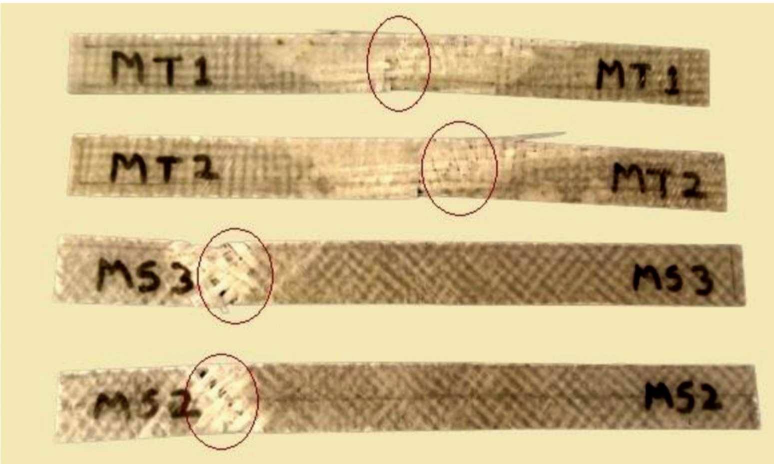

Figure 4: GFRP Test coupons after mechanical testing

Table 4: Test-coupon configuration

ASTM	Range of thickness (mm)	Quantity	Details
D3039	1.32 - 1.33	5	Tensile test to obtain Young's Modulus
D3518	1.33 - 1.29	5	Shear test to obtain Shear modulus

Table 5: GFRP Material characterization results

Sl. No.	ASTM	F_m (kN)	Displacement at F_m(mm)	Elongation %	Young's Modulus (MPa)	Load at break (kN)
1.	D3039	9.52	8.7	9	37850	9.52
2.		8.94	8.6	9.1	37594	9.1
3.		8.94	10.5	10.6	39407	10.6
4.		9.30	10	10.1	37537	10.1
5.		9.17	9.4	9.7	38097	9.83
Sl. No.	ASTM	F_m kN	Displacement at F_m (mm)	Elongation %	Shear Modulus (MPa)	Load at break (kN)
1.	D3518	2.84	6.7	10.1	2654	0.92
2.		2.42	8.2	11.4	2819	0.95
3.		2.92	12.5	14.4	3768	1.20
4.		2.73	9.13	11.97	3080	1.02
5.		2.56	7.86	13.3	3657	1.15

tensile strength, shear strength and shear modulus were experimentally estimated. **Figure 4** shows the tensile test coupon and the shear test coupons and **Table 4** shows the test-coupon configuration of GFRP for performing material characterization.

The load vs displacement plot for all the test coupon was extracted from the universal testing machine. The experimental results for the tensile (ASTM D3039) and the shear (ASTM D3518) were plotted, and it was noted that the load bearing capacity varies in the range of 9 kN to 10.6 kN. Similarly, for the shear test coupons, the load-bearing capacity varies in the range of 10.1kN to 14.4 kN.

The material characterizations of all the specimens are listed in **Table 5**. F_m is the maximum force withstand by the test coupon whereas the displacement at F_m shows that displacement value about the total length of the test coupon from both the ends of the grippers.

2.4. Finite-element method

The FEM can solve the complex material models with complex loading environment and boundary conditions. The FEM for piezo-enabled composite structures involves simulating the behaviour of materials and structures that incorporate piezoelectric elements. Piezoelectric materials generate an electrical charge in response to the mechanical stress The present analysis is predicted as a coupled field analysis that couples the structural procedure along with the electrical effects. The entire finite-element analysis was carried out using an ANSYS®16.0 Mechanical APDL.

2.4.1 Piezoelectric constitutive relation

The piezoelectric constitutive relation[19,20] was incorporated into the finite-element formulation. Piezo-enabled composite structures involve coupled fields, where the mechanical and electrical responses are interrelated. FEM models need to account for this coupling to accurately predict the behaviour of the structure. Piezoelectric materials act as an interaction between the electrical and mechanical behaviour of the material. The mathematical modelling of the piezoelectricity is shown in the Eqn (1)

$$\{T\}=[C]\{S\}-[e]\{E\} \quad (1)$$

$$\{D\}=[e]^{\mathrm{T}}\{S\}+[d]\{E\} \quad (2)$$

2.4.2 Finite-element modelling of piezo-enabled GFRP composite

Finite-element modelling of piezo-enabled GFRP beam structure was carried out using the software ANSYS® Mechanical APDL. Karthik Vinayaga et al. and Jerold John Britto et al. studied and simulated the finite-element model of composite materials embedded with piezoelectric structures.[21,22] A smart cantilever configuration has been proposed, which comprises a host structure and sensor in which the host structure is made up of glass-fabric-reinforced composite and the sensor is made up of polyvinylidene fluoride. Harmonic analysis is useful for studying the steady-state response of the structure under harmonic excitation, while transient analysis is suitable for capturing dynamic responses to time-varying inputs.

Table 6: Finite-element modelling details

Software Package used	ANSYS 16.0 Mechanical APDL	
Analysis Type	Harmonic analysis (Structural-electric)	
Mesh size (Element edge length)	1 mm	
Material	GFRP	PVDF
Element Type	Solid 185	Solid 5
Material model	Orthotropic	Isotropic
Maximum number of nodes	20992	780
Maximum number of elements	10200	350
Boundary conditions and Loading	One end of the beam: U_x, U_y, U_z = 0 Another end (Tip) of the beam: F_y = –0.196133 N Two sides of the beam: U_x, U_z = 0	

The assumptions considered for the analysis are shown in the **Table 6**. Solid 5 is the three-dimensional coupled solid having 8 nodes with 6 degrees of freedom such as U_x, U_y, U_z, Volt, Temp & Mag at each node. SOLID5 has a three-dimensional magnetic, thermal, electric, piezoelectric, and structural field capability with limited coupling between the fields. The element has eight nodes with up to six degrees of freedom at each node. Solid 185 is the layered structural solid element that includes layer thickness, number of plies and material orientation. SOLID185 is a three-dimensional, 20-node, higher-order hexahedral element. It supports eight nodes at the corners and additional mid-side nodes to improve the solution accuracy. In solid 185 degrees of freedom is represented as U_x, U_y and U_z. Both the solid 5 and solid 185 have been chosen for the modelling of polyvinylidene fluoride and glass-fabric-reinforced composite in the present analysis. The meshing view of the sensor and host structure and the finite-element model are shown in **Figure 5** respectively. The finite-element assumptions have been made on the basis of the experimental arrangements.

To consider the vibration along the mode 1 (bending), one end of the beam was fixed by arresting all the degrees of freedom and the load acting on the tip of the beam is considered as the weight of the DC motor, PVDF sensor and the tape attachments were assumed to be approximately 20 g, which in turn converted into an equivalent load of 0.196133 N. The vibration produced in the experimental setup was forced vibration, which induces under the harmonic response. For considering the mode 1 response, the two sides of the cantilever beam considering the degrees of freedom U_x, U_z were fixed and providing the movement only along U_y direction. To provide the forced vibration to the - enabled composite beam, a harmonic analysis was enabled.

2.5 Experiment

The experimental setup consists of a glass-fabric-reinforced polymer laminate that would act as cantilever beam and a PVDF sensor that is patched on the cantilever beam at a distance of 28 mm from the free end. A 5-V DC motor of 1000 rpm is fixed at the free end of the cantilever beam for producing the required vibrations. The glass-fabric-reinforced polymer beam was fixed in the aluminium stand. A schematic diagram of the piezo-enabled GFRP beam setup is shown in the Figure 6(a). The DC motor is being connected to the step-down transformer along with the rectifier and filter. The

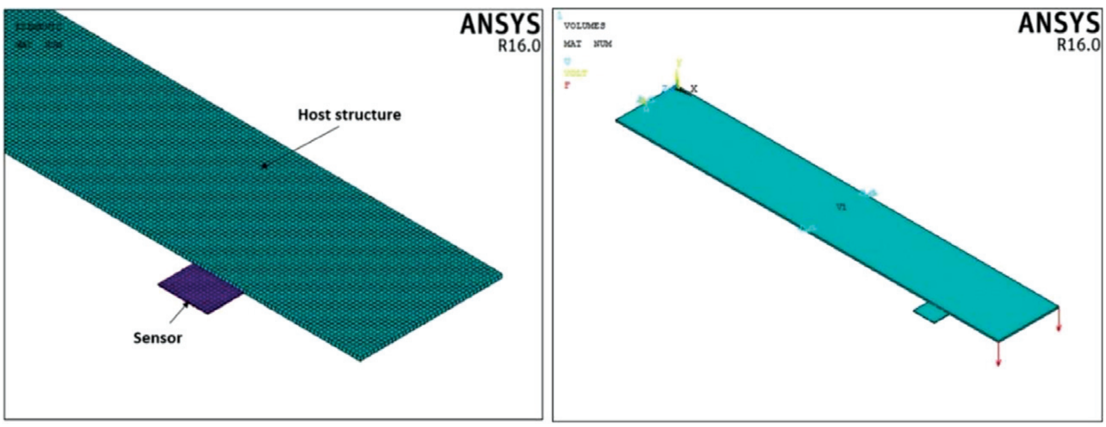

Figure 5: Meshed model and the applied boundary conditions

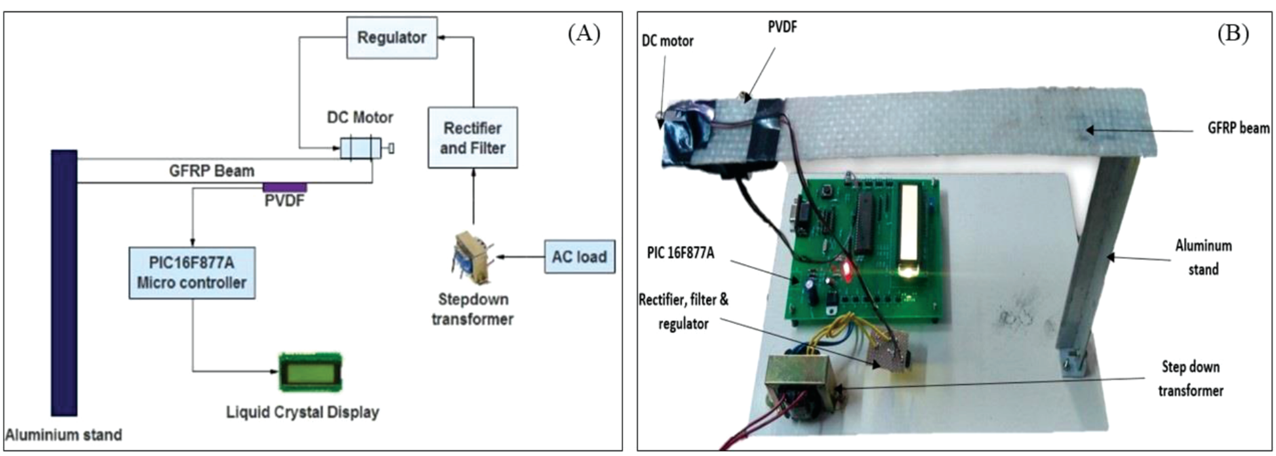

Figure 6: a) Schematic diagram of smart piezo-enabled GFRP beam, b) Experimental arrangement

step-down transformer is used to convert the high voltage input into the low voltage output. After reducing the noise level using the filter, the rectifier will convert the AC power to DC power and the regulator synchronize the required voltage to the DC motor. The motor was completely fixed at the tip of the GFRP beam. Then the beam starts to vibrate as a result of motor rotation.

The terminal point of PVDF sensor is fixed with the PIC16F877A microcontroller which has the total number of 40 pins out of which 33 pins are used as an input and output and the respective coding was dumped into the microcontroller. A liquid crystal display is connected along with the microcontroller to display the generated voltage and frequency. The experimental setup of piezo-enabled GFRP is shown in the **Figure 6b** When the motor rotates continuously, the glass-fibre-reinforced epoxy composite beam could vibrate. The forced vibration of the piezo-enabled beam leads to the mechanical straining of the beam which in turn generates voltage using PVDF. The generated voltage has been recorded from the different frequencies. While repeating the cycle during a certain point, it is noted that a constant voltage has been obtained at certain frequencies.

3 RESULTS AND DISCUSSION

The uni-directional elastic properties, i.e., Young's modulus, shear modulus and the strength parameters, i.e., tensile strength, shear strength of GFRP material, were experimentally estimated. The qualitative analysis of the fractured surfaces of the glass-fabric/epoxy composite under uni-axial tensile, shear and forced vibration was also conducted. The fractured surfaces of a glass-fabric/epoxy composite observed after a material testing provided valuable insights into the material's failure mechanisms, behaviour under loading and the overall integrity of the composite structure. The features observed on fractured surfaces indicated of the mode of failure and helped analyse response of material under applied stress. Observation of broken fibres suggested that the composite has reached a point where the fibres themselves have fractured. Cracks in the epoxy matrix were visible, indicating the initiation and propagation of fractures within the matrix. The extent and pattern of matrix cracking provided insights into the composite's overall toughness.

In harmonic analysis, structures are subjected to harmonic loading, and the material response can vary with frequency. Material characterization provided data on how the GFRP responded under harmonic excitation, allowing for the accurate representation of frequency-dependent material properties in the FEM model. Harmonic analysis identified the resonant frequencies at which the structure tends to vibrate with maximum amplitudes. Material characterization aided in understanding how the GFRP structures respond to different resonant frequencies and helps tp predict mode shapes, which represent the spatial distribution of vibration. It was found that the commercial FEM software package ANSYS® was compatible for the simulation of smart PVDF-enabled glass-fabric-reinforced beam structure under forced vibration. GFRP composite incorporated with piezoelectric elements, material characterization was crucial for understanding their behaviour under harmonic loading. Piezoelectric materials generated electrical charges in response to mechanical stress. **Figure 7** shows the voltage generation plot of PVDF embedded

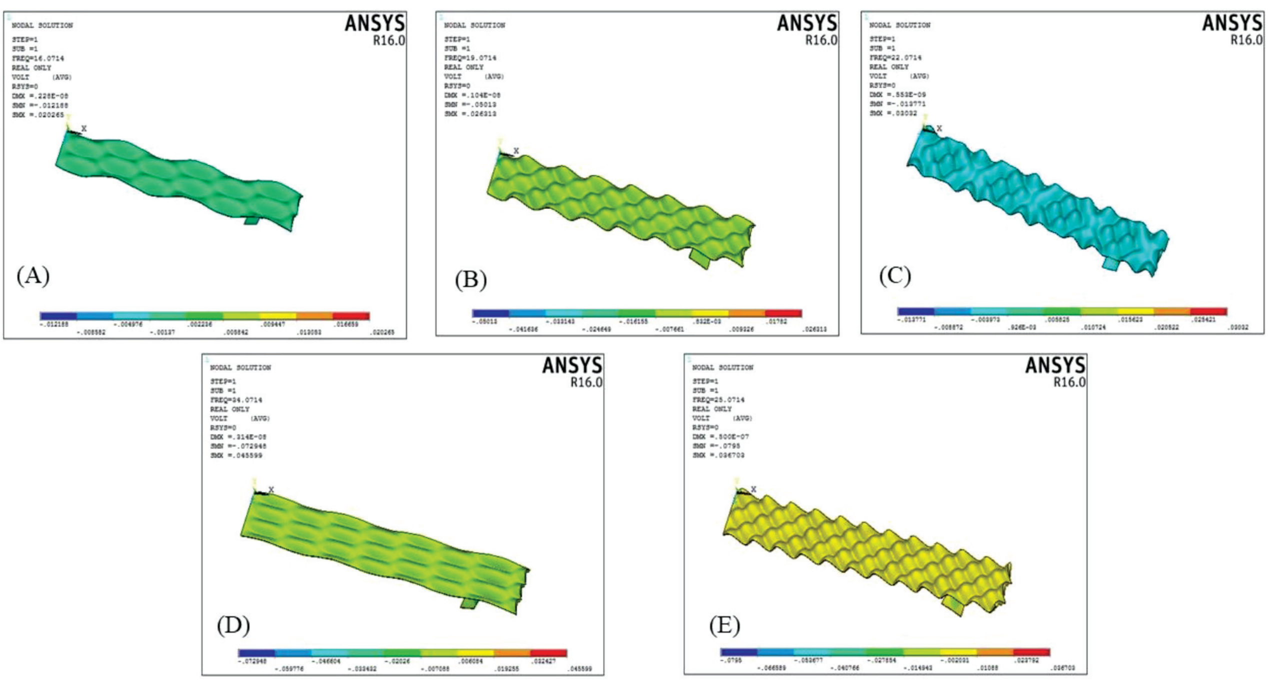

Figure 7: Simulation results: voltage generated for varied frequency input

GFRP beam at different frequencies for the ranges 16 Hz, 19 Hz, 22 Hz, 25 Hz and 34 Hz using ANSYS®. The voltage range was predicted under the harmonic response using Finite-element capabilities. A simple, cost-effective, smart piezo-enabled GFRP cantilever beam structure was developed for micro-energy harvesting. It was observed from experiments that for a 5-V DC motor, a maximum voltage of 43 mV at a frequency of 34 Hz was obtained, while FEM predicted a maximum voltage as 45.59 mV for the same frequency. It was seen an average of 6.2 % error while comparing the experimental and FEM results. Experimental validation helped confirm that the FEM model accurately represented the real behaviour of the structure. It verified that the assumptions, material properties and boundary conditions applied for the simulation aligned well with the physical system. The results shown in the present study would be useful in energy harvesting structure design applications. The present study also gave an ample suggestion for carrying out experiments and finite-element simulation for harmonic response of piezo-composites.

The finite-element results are in good agreement with the experimental results. The voltage response based on the constant voltage generation for the frequency viz. 16 Hz, 19 Hz, 22 Hz, 25 Hz, and 34 Hz is plotted in **Figure 8**. While comparing with the finite-element results, the error in the experimental results may be due to the uncertainties and also because of the presence of changes in external atmospheric factors such as intention of pressure, temperature etc. This may cause interrupt to the real time vibrational environment. Numerical simulation suggests that any ANSYS® composites and structural modules can be used for positioning and arranging the sensors over large-scale structures such as aerospace, automotive and civil engineering. However, challenges remain in scaling this technology for larger systems, as the complexity of integrating piezoelectric sensors into more extensive structures might require more advanced fabrication methods. Additionally, environmental factors, such as temperature and external vibrations, could affect the performance of the piezo-composite structures in real-world applications.

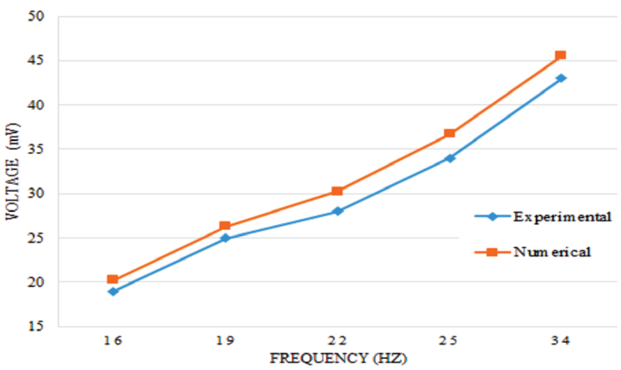

Figure 8: Experimental vs Numerical results

4 CONCLUSION

A simple fabrication technique using vacuum bagging method for the fabrication of void free GFRP laminates was presented in this paper with an emphasis on development of a smart piezo-enabled GFRP beam.

The study showed that GFRP composites embedded with PVDF sensors have applications in structural health monitoring and energy harvesting, achieving a maximum experimental voltage of 43 mV at 34 Hz.

The finite-element modelling using ANSYS® provided a maximum predicted voltage of 45.59 mV, with an error of 6.2 % compared to the experimental results.

The GFRP specimens exhibited Young's modulus of up to 39,407 MPa, indicating high material stiffness, while tensile strength reached up to 10.6 kN.

The piezoelectric characteristics of the composites allowed for micro-energy harvesting, demonstrating the material's practical utility in smart structures.

Disclosure statement

The authors declare that they have no relevant or material financial interests that relate to the research described in this paper.

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Nomenclature

$\{T\}$	Stress vector
$[C]$	Elasticity matrix
$\{S\}$	Strain vector
$[e]$	Piezoelectric matrix
$\{E\}$	Electric field vector
$\{D\}$	Electric field vector
$[d]$	Dielectric matrix
E	Young's modulus, GPa
γ	Poisson's ratio
d_{31}	Piezoelectric strain coefficient (m/V)
g_{31}	Piezoelectric stress constant (Vm/N)
ρ	Density, kg/m^3
ε	Permittivity constant, (F/m)
$\varepsilon/\varepsilon_0$	Relative permittivity
GFRP	Glass-fibre-reinforced polymer
PVDF	Polyvinylidene fluoride
ASTM	American Standard for Testing Materials
FEM	Finite-element method
PMC	Polymer-matrix composite
F_m	Maximum force withstood by the test coupon, kN