

Experimental investigation of piezoelectric energy harvesting in a thin composite shell under dynamic effects

Edwin Sudhagar P¹, Grzegorz Litak^{2*} , Mohamed Dhia Ayadi³, Olfa Kanoun³,
Maiarutselvan Vasudevan¹, Mateusz Waskowicz², Marcin Fronc⁴

¹ School of Mechanical Engineering, Vellore Institute of Technology, Vellore, Tamil Nadu, 632014, India

² Department of Automation, Faculty of Mechanical Engineering and Computer Science, Lublin University of Technology, 20-618 Lublin, Poland

³ Laboratory of Measurement and Sensor Technology (MST), Chemnitz University of Technology, Chemnitz, 09126, Germany

⁴ Department of Electric Drives and Machinery, Faculty of Electrical Engineering and Computer Science, Lublin University of Technology, 20-618 Lublin, Poland

* Corresponding author's e-mail: g.litak@pollub.pl

ABSTRACT

This experimental study investigated the piezoelectric energy-harvesting performance of composite laminated shell structures for energy-harvesting applications. Thin-walled composite shells were fabricated using hand layup with glass fibre reinforced polymer (GFRP) composites, and PZT patches were placed on the shell surface. The effective orthotropic material properties of the laminated shell were initially estimated using the Rule of Mixtures to predict the modal characteristics of the GFRP shell. Experimental tests were conducted using an electrodynamic shaker under sinusoidal base excitation at 30 Hz, with the thin composite shell structure mounted at its centre. The electromechanical response was characterised by simultaneously measuring the central transverse displacement of the shell and the voltage outputs from the two surface-bonded macro fiber composite (MFC) transducers. Results demonstrated bounded oscillations of the composite laminated shell, with a peak-to-peak central displacement of approximately 1.60 mm and corresponding voltage outputs of 3.68 and 3.44 V from the two MFC transducers. The composite shell configuration achieved a wideband frequency response with superior broadband harvesting characteristics. The experimental validation confirms that composite laminated shell piezoelectric energy harvesters offer broadband performance suitable for powering wireless sensor networks, IoT devices, and structural health monitoring systems in large vibrating structures operating at low frequencies.

Keywords: GFRP composite shell, energy harvesting system, PZT patches, macro fibre composite.

INTRODUCTION

The growing adoption of composite structures across various engineering sectors is primarily attributed to their superior strength-to-weight and stiffness-to-weight characteristics. As their use continues to expand, developing testing models becomes essential to reliably estimate structural responses. In recent years, considerable attention has focused on developing advanced engineering structures capable of performing multiple functions simultaneously. Multifunctionality

has emerged as an important design objective, extending beyond conventional load-bearing requirements to incorporate additional functions. Alongside structural performance, the integration of non-structural functionalities has become increasingly significant in the design of next-generation smart materials and systems (Ferreira et al., 2016; Gibson, 2010).

Researchers have explored several multifunctional attributes, including electrical and thermal conductivity, sensing and actuation, energy harvesting and storage, self-repair mechanisms,

electromagnetic interference shielding, and environmentally sustainable features such as recyclability and biodegradability. These capabilities enhance the overall efficiency and adaptability of engineering structures while reducing system complexity and weight. Smart structures are a major class of multifunctional systems because they can respond to external stimuli and adapt to changing operating conditions. Among the available smart materials, piezoelectric materials have attracted significant interest because they directly couple the mechanical and electrical domains. Through the piezoelectric effect, these materials can convert mechanical deformation into electrical energy and vice versa over a broad range of operating frequencies. The unique electromechanical characteristics of piezoelectric materials have enabled their application in numerous fields, including structural health monitoring, active vibration suppression, adaptive shape control, and energy harvesting technologies (Zhang et al., 2017). However, designing and fabricating piezoelectric-integrated smart structures often involves complex material interactions and coupled physical phenomena. Recent investigations have therefore focused on improving the understanding of these coupled electromechanical systems and enhancing their overall performance (Akbar and Curiel-Sosa, 2019; Banerjee and Roy, 2018).

The conversion of ambient vibrational energy into usable electrical power has attracted significant research interest over the past several decades because it can power low-power electronic systems (Rodriguez et al., 2019). From early developments in vibration-based energy harvesting to recent advances addressing emerging challenges, efforts have focused on improving the efficiency and applicability of these systems. The growing demand for self-powered devices has further accelerated the adoption of energy harvesting solutions, particularly in the applications where battery replacement is impractical, maintenance is costly, or long-term autonomous operation is required (Li et al., 2021). Among these materials, fibre-reinforced polymer laminates can exhibit biostability, enabling them to maintain multiple stable configurations without continuous external loading. Early investigations showed that thermal residual stresses generated during the curing of unsymmetrical laminates produce stable curved shapes, laying the foundation for morphing and energy-harvesting composite structures (Kamal et al., 2022; Lee and Inman, 2019; Mukherjee et al., 2021).

Harris et al. (2015) developed a bistable piezoelectric energy harvester using an asymmetric CFRP cantilever laminate coupled with a ferroelectric piezoelectric material. Experimental studies were conducted at different excitation frequencies, vibration levels, and electrical load resistances to evaluate the energy-harvesting performance. The study showed that low vibration amplitudes produced linear single-well oscillations with a narrow operating bandwidth, while higher amplitudes triggered snap-through behaviour, leading to nonlinear softening and a wider frequency response. Syta et al. (2016) investigated a bistable piezoelectric energy harvester composed of a piezoelectric transducer bonded to a bistable CFRP laminate. Experimental responses under harmonic excitation were analysed using the Fourier spectrum and recurrence quantification analysis (RQA). The findings showed that RQA successfully identified distinct dynamic behaviours, and that chaotic snap-through motions yielded higher energy-harvesting efficiency. The study concluded that nonlinear bistable dynamics can improve the energy harvesting performance of piezoelectric systems. Khazaei et al. (2020) developed a broadband piezoelectric energy harvester incorporating macro fiber composite (MFC) active layers and a composite laminate substrate to enhance energy conversion under wideband vibrations. The results showed that optimising the piezoelectric fibre orientation and taper geometry significantly increased power output and power density while broadening the operational frequency range. An asymmetric four-corner simply-supported bistable piezoelectric composite laminate was developed by Guo et al. (2025) and evaluated for vibration-based energy harvesting applications. The authors examined its dynamic characteristics through nonlinear response analyses, including bifurcation behaviour, phase-space trajectories, and experimental voltage measurements under varying excitation conditions. The investigation showed that snap-through oscillations expanded the effective operating bandwidth and enhanced electrical output. Plagianakos et al. (2024) proposed a post-buckled piezoelectric composite beam for harvesting energy from low-frequency wind turbine blade vibrations. Finite element analysis and experimental testing were performed to assess the bistable response and power generation capability. The harvester achieved effective energy conversion at sub-resonant frequencies, producing measurable

electrical output. The findings demonstrated the feasibility of bistability-based harvesters for self-powered monitoring applications in large structural systems.

Bradai et al. (2025) explored vibration-driven energy generation using a piezoelectric patch bonded to a bistable composite laminate. The authors fabricated the harvester with different glass-fibre layups and experimentally evaluated it under cyclic excitation. Electrical output was measured for various mass configurations to examine dynamic performance. The results highlighted the strong influence of laminate design on kinetic-energy conversion efficiency. Daraji et al. (2021) examined energy harvesting from beam-stiffened composite shells for structural health monitoring applications. An optimisation framework was developed to determine the most effective locations for piezoelectric sensors to maximise power output. The methodology was validated using a composite wing model subjected to flight-frequency vibrations. The results confirmed that optimal sensor placement could provide sufficient energy for wireless structural health monitoring devices. Akbar and Curiel-Sosa, (2018) developed a hybrid framework to assess the energy harvesting performance of piezoelectric composite plates under dynamic bending. The approach combined NURBS-based iso-geometric analysis with voltage-governing equations to predict the electromechanical response and harvested energy. The study demonstrated that the proposed method achieved improved accuracy for thin structures while reducing computational effort, making it effective for preliminary design and optimisation applications. Kloda (2026) explored the energy harvesting potential of a pentastable composite shell possessing five stable equilibrium configurations. Finite element simulations and experimental investigations were performed to determine optimal MFC placement, evaluate dynamic behaviour, and quantify electrical output under broadband excitation. The results showed that multi-stable snap-through motions enhanced vibration bandwidth and power generation, demonstrating the suitability of pentastable structures for broadband energy harvesting applications. Elsheikh, (2022) studied the use of bistable morphing composite structures for vibration-based energy harvesting applications. The study examined shape-transition mechanisms, dynamic modelling approaches, and the

integration of artificial intelligence techniques for design optimisation and response prediction.

Despite extensive research on beam and plate-based piezoelectric energy harvesters, the coupled electromechanical response of glass fibre reinforced polymer (GFRP) shells incorporating multiple bonded transducers remains insufficiently investigated. In particular, experimental information on the relationship between global shell displacement and the local voltage generated at different transducer locations remains limited. To bridge this gap, the present study experimentally investigated a centrally excited GFRP shell equipped with two diagonally positioned MFC transducers. The transverse displacement and voltage outputs were measured simultaneously to assess the structural response, strain-transfer effectiveness, and spatial variation in voltage generation. The findings provide an experimental baseline for the subsequent characterisation of snap-through dynamics, frequency response, and electrical power generation.

MANUFACTURING AND PROPERTY ESTIMATION OF THIN COMPOSITE SHELL

The thin Glass Fibre Reinforced Polymer cylindrical shell specimens were fabricated using a combination of hand lay-up and vacuum bagging techniques. Unidirectional *E*-glass fibre was used as the reinforcing material, while LY556 epoxy resin and HY951 hardener formed the matrix system. The epoxy resin provides excellent mechanical properties and adhesion, whereas the hardener acts as the curing agent, facilitating cross-linking within the matrix. Initially, a cylindrical mould matching the desired shell geometry was thoroughly cleaned to remove dust, moisture, and surface contaminants. A release wax coating was subsequently applied to the mould surface to facilitate easy demoulding after curing. The *E*-glass fibre sheets were then cut according to the required dimensions of the cylindrical shell, as shown in Figure 1. The fibre-to-resin weight ratio was maintained at approximately 50:50 to achieve optimum reinforcement and matrix distribution throughout the laminate. Following standard composite fabrication practices, the epoxy resin and hardener were mixed at a 9:1 weight ratio and stirred

continuously until a homogeneous mixture was obtained. The laminate was fabricated using the hand lay-up process, in which each fibre layer was carefully impregnated with the prepared resin mixture and sequentially placed on the mould surface, as shown in Figure 2. Two unidirectional glass fibre layers were arranged in an $[0^\circ/90^\circ]$ cross-ply configuration to provide balanced stiffness and improved structural stability in multiple directions. After laminate preparation, a peel-ply layer was placed over the composite surface, and a breather cloth was applied to distribute pressure uniformly and absorb excess resin during vacuum consolidation. The entire assembly was then enclosed in a vacuum bag and subjected to a vacuum of approximately 750 mm Hg for 2 hours at room temperature. This process removed entrapped air, reduced void formation, and improved fibre-matrix bonding, thereby enhancing the overall quality of the laminate. After vacuum bagging, the laminate was allowed to cure under ambient conditions for 24–48 hours while maintaining its cylindrical shape. After complete curing, the composite shell was carefully removed from the mould and trimmed to the required dimensions. The fabricated shell had a uniform thickness of approximately 0.5 mm, ensuring consistent structural

characteristics and suitability for subsequent dynamic excitation and piezoelectric energy-harvesting experiments.

Further, the thin composite shell material properties were also determined using the rule of mixture approach with the following Equations 1–5 for material property evaluation, and the fibre volume fraction is considered as $V_f = 0.40$. Here, the fibre (f) and matrix (m) properties are described in terms of their Young's modulus, Poisson's ratio, shear modulus, and density, denoted as E_f , ν_f , G_f and ρ_f and E_m , ν_m , G_m and ρ_m .

- Axial Young's modulus (E_{11}^f):

$$E_{11}^f = E_f V_f + E_m V_m \quad (1)$$

- Transverse Young's modulus (E_{22}^f):

$$\frac{1}{E_{22}^f} = \left[\frac{V_f}{E_f} + \frac{V_m}{E_m} \right] \quad (2)$$

- Major Poisson's ratio (ν_{12}^f):

$$\nu_{xy} = V_f \nu_f + V_m \nu_m \quad (3)$$

- In-plane shear modulus (G_{12}^f):

$$\frac{1}{G_{12}^f} = \left[\frac{V_f}{G_f} + \frac{V_m}{G_m} \right] \quad (4)$$

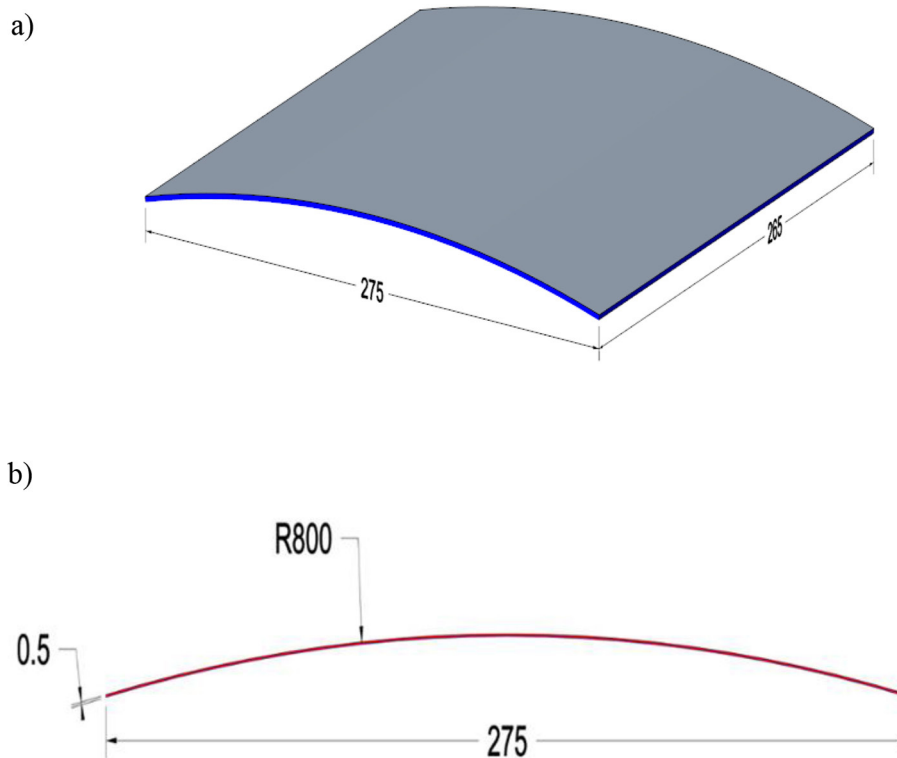


Figure 1. (a) 3D model for the cylindrical shell structure, (b) Geometry for the cylindrical shell structure



Figure 2. Fabricated GFRP cylindrical shell structure

The density of the composite (ρ^f):

$$\rho^f = \rho_f V_f + \rho_m V_m \quad (5)$$

As presented in Table 1, the effective orthotropic material properties of the face sheets, including the elastic moduli, Poisson's ratio, shear modulus, and density, were estimated using the rule-of-mixtures approach based on the constituent material properties.

EXPERIMENTAL METHODOLOGY

The experimental investigation examined the dynamic behaviour of the GFRP cylindrical shell and its capability to harvest energy under vibration excitation. This section describes the test setup, measurement instruments, data acquisition procedures, and testing methodology used to evaluate the electromechanical response of the energy harvesting system.

Description of the composite shell GFRP/MFC energy harvester

The developed energy harvesting system comprised a GFRP Shell integrated with two Macro Fiber Composite piezoelectric transducers. The shallow cylindrical GFRP shell had a square planform of 275×275 mm, a radius of curvature of 800 mm, and an overall thickness of approximately 0.5 mm. The experimental arrangement employed for dynamic characterisation is illustrated in Figure 3a. The GFRP shell was attached to an electrodynamic shaker using a centrally located magnetic fixture. This mounting strategy ensured secure attachment while allowing unrestricted deformation during vibration. A laser displacement sensor positioned above the specimen monitored the transverse displacement response at the shell's centre. Simultaneously, the piezoelectric transducers generated an electrical response, which was acquired under harmonic base excitation at a representative frequency of

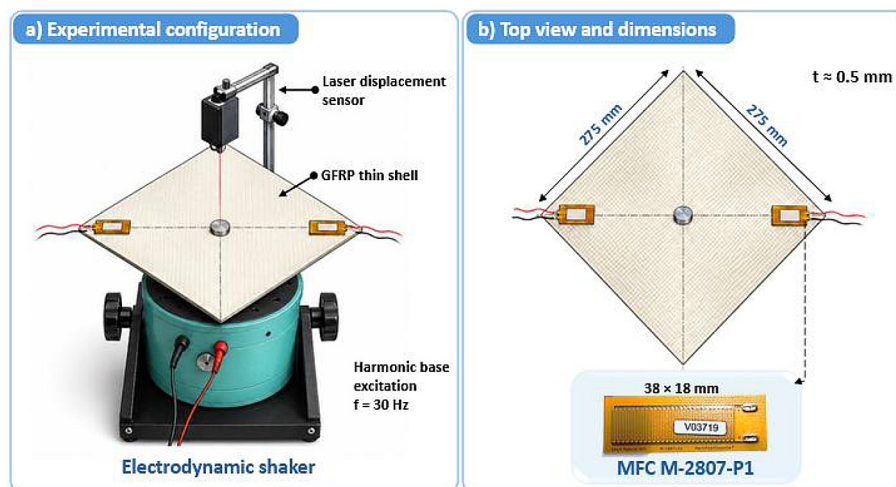


Figure 3. GFRP Composite shell with MFC energy harvester: (a) experimental configuration; (b) top view and dimensions

Table 1. Estimated material properties of face sheets

Estimation method	(GPa)	E_{22} (GPa)	ν_{12}	G_{12} (GPa)	ρ (kg/m ³)
Rule of mixture	27.1	5.102	0.27	1.966	1676.1

30 Hz. Two commercially available Smart Material MFC M-2807-P1 transducers, each measuring approximately 38 mm × 18 mm, were bonded to the outer surface of the composite shell. As shown in Figure 3b, the transducers were installed symmetrically on opposite sides along a diagonal direction of the structure. This diagonal placement was selected to locate the piezoelectric transducers in regions expected to experience substantial flexural deformation during shell oscillations, thereby promoting effective strain transfer to MFCs. Owing to their flexible architecture, in which aligned piezoceramic fibres are embedded within a polymer matrix and encapsulated by polyimide layers, MFC transducers are well suited for integration with curved composite structures subjected to flexural deformation (Guo et al., 2025; Harris et al., 2015; Syta et al., 2016). The energy-conversion mechanism is governed by the strain induced in the MFC transducers during the curved shell's dynamic deformation. Under harmonic excitation, the shell's out-of-plane

oscillation produces local bending and curvature variations at the transducer locations, which convert into alternating electrical voltage through the direct piezoelectric effect. Under the excitation conditions investigated in this study, the shell remained within a bounded oscillatory regime around its initial equilibrium configuration, with no evidence of complete snap-through. Nevertheless, the resulting flexural deformation generated measurable voltage outputs from both MFC transducers (Akbar et al., 2018, 2019; Banerjee et al., 2018; Bradai, 2025)

Experimental setup and instrumentation

The electromechanical response of the GFRP/MFC shell was experimentally evaluated using a laboratory-scale electrodynamic excitation system. Harmonic excitation was applied through an electrodynamic shaker (Veb Robotron Type 11077), driven by a sinusoidal signal generated

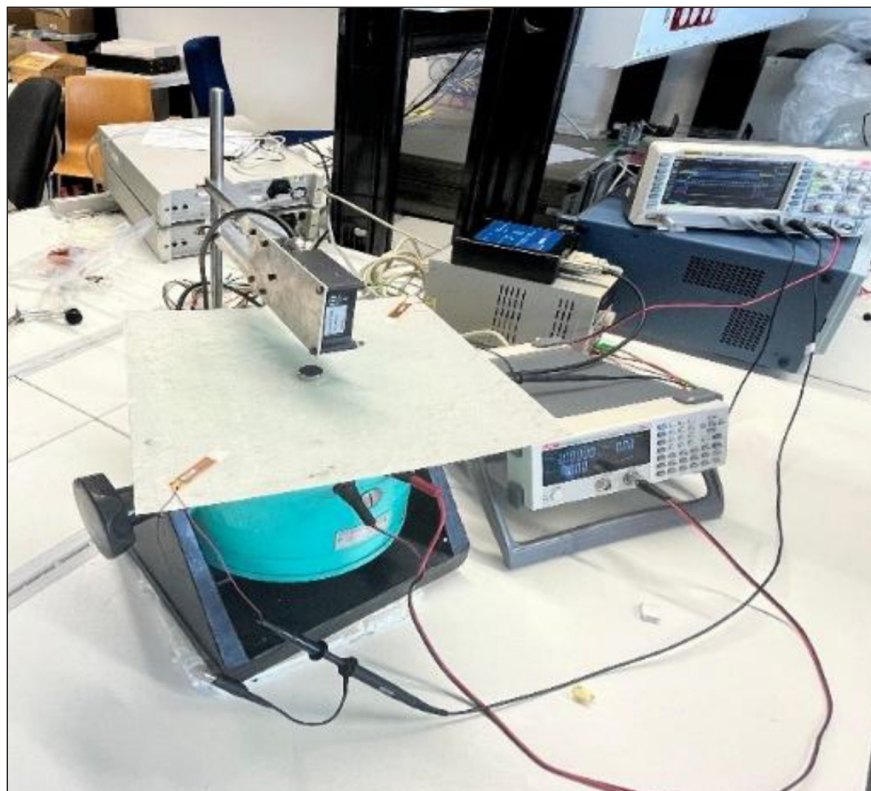


Figure 4. GFRP composite shell structure attached to the shaker system

using a waveform generator (UNI-T UTG9005C-II). The power amplifier amplified the signal before it was transmitted to the shaker. During the experiments reported in this study, the excitation frequency was maintained at 30 Hz, while the amplifier input voltage was set to 7 V. The composite shell, integrated with MFC transducers, was mounted on the shaker head at its centre using a magnetic fixture. This mounting arrangement allowed the shell boundaries to remain unconstrained, thereby facilitating large out-of-plane oscillations and snap-through behaviour under dynamic loading. A laser displacement sensor was positioned above the specimen to continuously monitor the transverse displacement response at the central region of the shell.

To evaluate the electrical energy-harvesting response, the voltage outputs of the two surface-bonded MFC patches were measured simultaneously. The signals generated by the transducers, designated as MFC 1 and MFC 2, were acquired using a data acquisition/oscilloscope system. Concurrent acquisition of displacement and voltage data enabled direct assessment of the relationship between the structural dynamics of the composite shell and the corresponding piezoelectric energy generation. Figure 4 shows the experimental setup, including the shaker-mounted shell and displacement-measurement system.

RESULTS AND DISCUSSION

Time-domain electromechanical response

The time-domain electromechanical response of the GFRP/MFC shell was evaluated under sinusoidal excitation at 30 Hz. The central transverse displacement and voltage outputs from MFC 1 and MFC 2 were recorded simultaneously to examine the relationship between the global shell motion and the local piezoelectric responses.

As shown in Figure 5, the central displacement remained bounded between approximately -0.72 and 0.88 mm, corresponding to a peak-to-peak displacement of about 1.60 mm. The displacement remained bounded between approximately -0.72 and 0.88 mm, corresponding to a peak-to-peak value of approximately 1.60 mm. No abrupt displacement transition was observed, indicating that the shell oscillated around its initial equilibrium configuration under the investigated excitation condition. Unlike a bistable plate, which has two stable shapes, a monostable plate only has one stable shape. However, it can still snap to an inverted, temporary shape when enough force is applied. The key difference is that once the force is removed, a monostable plate snaps back to its original shape on its own (see Figure 6). Accordingly, the present response is

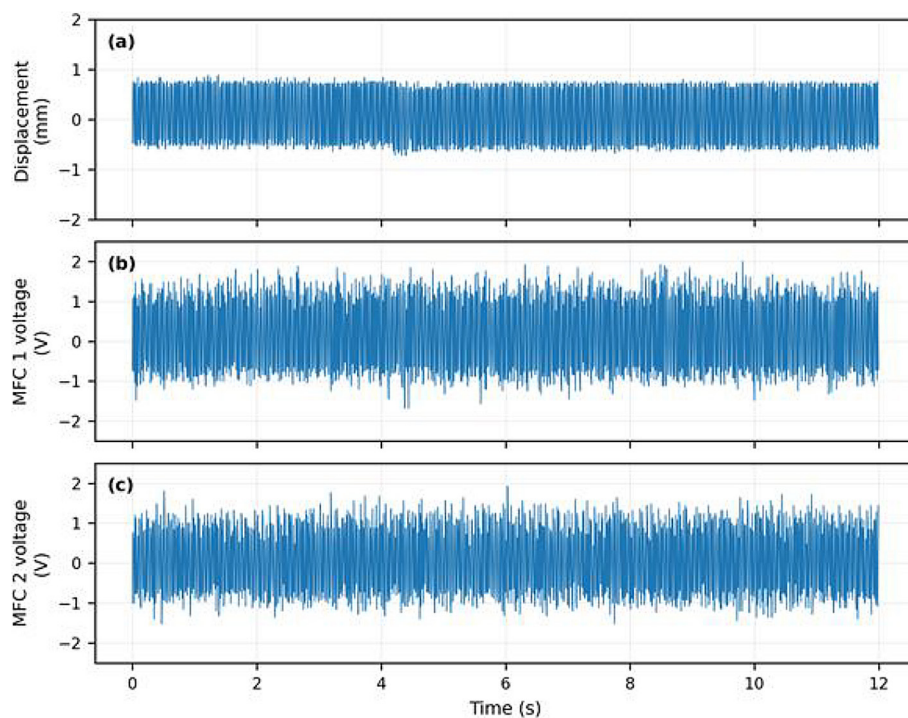


Figure 5. Time-domain response of the GFRP composite shell with MFC energy harvester under 30 Hz harmonic shaker excitation: (a) central displacement, (b) voltage output of MFC 1, and (c) voltage output of MFC 2

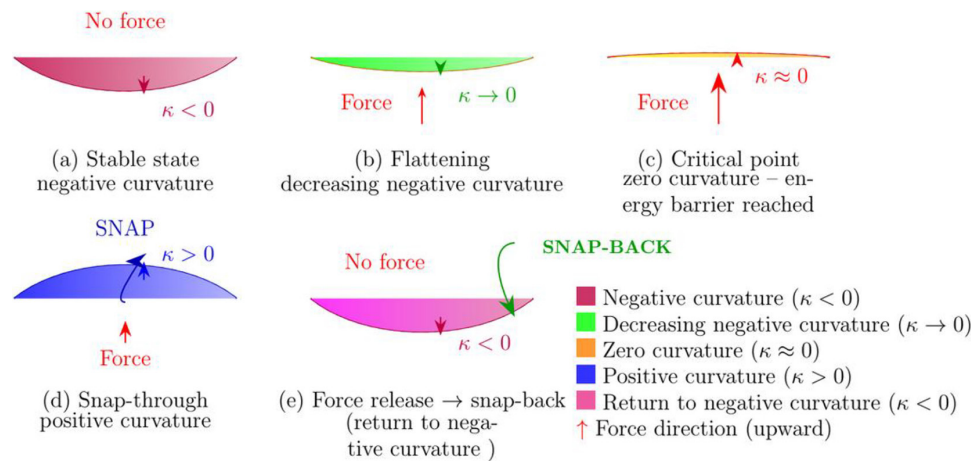


Figure 6. Snap-through sequence of the shell structure with an applied force

best interpreted as a pre-snap-through, dynamic regime rather than a complete transition between the two stable configurations.

A two-dimensional snap-through sequence of a monostable shell structure with force applied from below (upward direction) and inverted curvature (κ) direction is shown in Figure 6. Figure 6(a) stable state - negative curvature ($\kappa < 0$), plate curved downward; (b) flattening under upward force - negative curvature decreases ($\kappa \rightarrow 0$); (c) Critical point - zero curvature ($\kappa \approx 0$), energy barrier reached, maximum force before instability; (d) snap-through - positive curvature ($\kappa > 0$), temporary inverted shape with sudden force drop; (e) force release leads to spontaneous snap-back - curvature returns to negative ($\kappa < 0$), which is the original stable configuration. The upward force direction represents loading from below. The colour gradient from red-purple (negative) through orange (zero) to blue (positive) visually tracks the evolution of plate curvature during the snap-through cycle.

Voltage generation and channel comparison

Despite the limited global displacement, both MFC patches produced clear alternating

voltage signals. The extracted peak-to-peak voltages were 3.68 V for MFC 1 and 3.44 V for MFC 2, as shown in Figure 7. This confirms that the curved composite shell transfers dynamic bending strain to the bonded piezoelectric patches and that the selected diagonal locations are mechanically active during vibration. The result is particularly relevant because the electrical output of surface-bonded MFCs is governed by local strain and curvature variations at the patch location, not only by the central displacement amplitude of the shell. Table 2 summarizes the operating conditions and the electromechanical responses obtained. The two voltage channels were comparable, with MFC 2 reaching approximately 93.5% of the MFC 1 peak-to-peak voltage. This close agreement supports the effectiveness of the diagonal patch configuration. The remaining difference between the two channels should not be treated only as measurement scatter. It may also reflect spatially non-uniform bending strain, local curvature asymmetry, bonding-layer thickness variations, patch alignment errors, and the influence of the central magnetic fixation. Such effects are expected in thin composite shells, where small changes in boundary conditions or residual stress may strongly modify the local strain field.

Table 2. Summary of the operating conditions and extracted electromechanical responses at 30 Hz

Quantity	Measured value	Interpretation
Excitation condition	30 Hz, 7 V amplifier input	Representative harmonic shaker test
Central displacement	-0.72 to 0.88 mm (1.60 mm p-p)	Bounded oscillation around one stable state
MFC 1 voltage	3.68 V _{pp}	Effective local strain transfer
MFC 2 voltage	3.44 V _{pp}	93.5% of the MFC 1 response
Dynamic regime	Bounded/pre-snap-through oscillation	No complete snap-through observed in this test

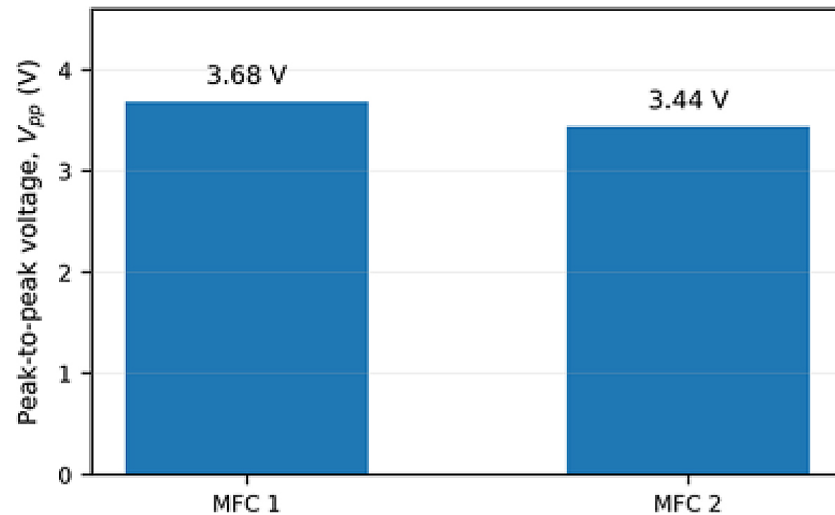


Figure 7. Peak-to-peak voltage comparison of the two diagonally bonded MFC transducers under the same harmonic excitation condition

Implications for energy harvesting in thin shell structures

The present results provide initial experimental validation of the GFRP/MFC shell configuration for vibration-induced piezoelectric voltage generation. At the tested excitation level, the device generated volt-level outputs while remaining in a bounded oscillatory regime. This means that measurable voltage can be produced before full snap-through activation, owing to local bending and curvature changes in the shell. However, the data should not be overinterpreted as proof of broadband bistable harvesting. A complete bistable response would require repeated inter-well transitions, which should appear as larger displacement jumps and sharper voltage peaks caused by rapid strain redistribution in the MFC regions.

Therefore, the 30 Hz result should be considered a baseline validation point for the harvester. To quantify the nonlinear advantage of the bistable configuration, the next manuscript results should include frequency sweeps, excitation-amplitude sweeps, and load-resistance tests. The frequency sweep would identify the resonance region and possible softening behaviour, the amplitude sweep would define the snap-through threshold, and the resistance sweep would allow the harvested power to be calculated. Only after these measurements can the contribution to bandwidth enlargement and power enhancement be separated from the conventional bending response of the shell.

CONCLUSIONS

The present study investigated the energy-harvesting potential of piezoelectric patches bonded to a GFRP laminated shell under low-level vibration. The hand layup technique was used to fabricate the thin composite shell structure. The Macro Fibre Composite piezoelectric transducers were mounted at the extreme locations of the thin shell structure. A shaker-based experimental setup was used, and the base excitation frequency was maintained at 30 Hz. The peak-to-peak voltage comparison of the two diagonally bonded MFC transducers under the same harmonic excitation condition was determined. The extracted peak-to-peak voltages were 3.68 V for MFC 1 and 3.44 V for MFC 2. This study systematically explained the effect of the thin composite shell structure on strain distribution and harvested power output. These findings aimed to guide the design of lightweight, thin composite shell structures, structurally integrated energy harvesters for automotive and aerospace applications, as well as structural health monitoring applications.

Acknowledgements

The work was supported by the National Science Centre, Poland, under the OPUS Call in the Weave program under project No. 2023/51/I/ST8/02739. The author ESP work is supported by the Polish National Agency for Academic Exchange (NAWA ULAM fellowship program) through Grant No. BPN/ULM/2025/1/00099.

REFERENCES

1. Akbar, M., Curiel-Sosa, J. L. (2018). Evaluation of piezoelectric energy harvester under dynamic bending by means of hybrid mathematical/isogeometric analysis. *International Journal of Mechanics and Materials in Design*, 14(4), 647–667. <https://doi.org/10.1007/s10999-017-9395-0>
2. Akbar, M., Curiel-Sosa, J. L. (2019). An iterative finite element method for piezoelectric energy harvesting composite with implementation to lifting structures under Gust Load Conditions. *Composite Structures*, 219, 97–110. <https://doi.org/10.1016/j.compstruct.2019.03.070>
3. Banerjee, S., Roy, S. (2018). A Timoshenko like model for piezoelectric energy harvester with shear mode. *Composite Structures*, 204, 677–688. <https://doi.org/10.1016/j.compstruct.2018.07.117>
4. Bradai, S., Naifar, S., Wolszczak, P., Bienias, J., Jakubczak, P., Rysak, A., Litak, G., Kanoun, O. (2025). Kinetic energy harvesting with a piezoelectric patch using a bistable laminate. *Micro-machines*, 16(4), 410. <https://doi.org/10.3390/mi16040410>
5. Daraji, A. H., Hale, J. M., Ye, J. (2021). Optimisation of energy harvesting for stiffened composite shells with application to the aircraft wing at structural flight frequency. *Thin-Walled Structures*, 161, 107392. <https://doi.org/10.1016/j.tws.2020.107392>
6. Elsheikh, A. (2022). Bistable morphing composites for energy-harvesting applications. *Polymers*, 14(9), 1893. <https://doi.org/10.3390/polym14091893>
7. Ferreira, A. D. B. L., Nóvoa, P. R. O., Marques, A. T. (2016). Multifunctional material systems: A state-of-the-art review. *Composite Structures*, 151, 3–35. <https://doi.org/10.1016/j.compstruct.2016.01.028>
8. Gibson, R. F. (2010). A review of recent research on mechanics of multifunctional composite materials and structures. *Composite Structures*, 92(12), 2793–2810. <https://doi.org/10.1016/j.compstruct.2010.05.003>
9. Guo, X. T., Zhang, Y. F., Zhang, W., Amer, A. (2025). Nonlinear snap-through vibrations and energy harvesting for bistable piezoelectric composite laminated plate supported at four corners. *Thin-Walled Structures*, 210, 112991. <https://doi.org/10.1016/j.tws.2025.112991>
10. Harris, P., Skinner, W., Bowen, C. R., Kim, H. A. (2015). Manufacture and characterisation of piezoelectric broadband energy harvesters based on asymmetric bistable cantilever laminates. *Ferroelectrics*, 480(1), 67–76. <https://doi.org/10.1080/00150193.2015.1012447>
11. Kamal, A., Ashmawy, M., S, S., Algazzar, A. M., Elsheikh, A. H. (2022). Fabrication techniques of polymeric nanocomposites: A comprehensive review. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 236(9), 4843–4861. <https://doi.org/10.1177/09544062211055662>
12. Khazaei, M., Rezaniakolaie, A., Rosendahl, L. (2020). A broadband macro-fiber-composite piezoelectric energy harvester for higher energy conversion from practical wideband vibrations. *Nano Energy*, 76, 104978. <https://doi.org/10.1016/j.nanoen.2020.104978>
13. Kloda, L. (2026). Pentastable composite shell for energy harvesting. *Mechanical Systems and Signal Processing*, 244, 113825. <https://doi.org/10.1016/j.ymssp.2025.113825>
14. Lee, A. J., Inman, D. J. (2019). Electromechanical modelling of a bistable plate with macro fiber composites under nonlinear vibrations. *Journal of Sound and Vibration*, 446, 326–342. <https://doi.org/10.1016/j.jsv.2019.01.045>
15. Li, Y., Tao, K., George, B., Tan, Z. (2021). Harvesting vibration energy: Technologies and challenges. *IEEE Industrial Electronics Magazine*, 15(1), 30–39. <https://doi.org/10.1109/MIE.2020.2978219>
16. Mukherjee, A., Ali, S. F., Arockiarajan, A. (2021). Hybrid bistable composite laminates for structural assemblies: A numerical and experimental study. *Composite Structures*, 260, 113467. <https://doi.org/10.1016/j.compstruct.2020.113467>
17. Plagianakos, T. S., Leventakis, N., Chrysochoidis, N. A., Kardarakos, G.-C., Margelis, N., Bolanakis, G., Papadopoulos, E. G., Saravanos, D. A. (2024). Piezoelectric energy harvester for wind turbine blades based on bistable response of a composite beam in post-buckling. *Smart Materials and Structures*, 33(7), 075033. <https://doi.org/10.1088/1361-665X/ad5890>
18. Rodriguez, J. C., Nico, V., Punch, J. (2019). A vibration energy harvester and power management solution for battery-free operation of wireless sensor nodes. *Sensors*, 19(17), 3776. <https://doi.org/10.3390/s19173776>
19. Syta, A., Bowen, C. R., Kim, H. A., Rysak, A., Litak, G. (2016). Responses of bistable piezoelectric-composite energy harvester by means of recurrences. *Mechanical Systems and Signal Processing*, 76–77, 823–832. <https://doi.org/10.1016/j.ymssp.2016.01.021>
20. Zhang, Z., Xiang, H., Shi, Z. (2017). Mechanism exploration of piezoelectric energy harvesting from vibration in beams subjected to moving harmonic loads. *Composite Structures*, 179, 368–376. <https://doi.org/10.1016/j.compstruct.2017.07.013>