Performance Analysis of Various Structural Designs Available for Piezoelectric Energy-Harvesting Tiles

PRINON BENNY, SHASHANK SHEKHAR, SIDANSHU KUMAR,
KONKO DUTTA, G. RENUKA DEVI,
School of Engineering, Jawaharlal Nehru University,
New Delhi – 110067
INDIA

Abstract: - One of the biggest problems faced by mankind in the 21st century is satisfying the ever increasing energy demands of the growing population. At the same time, the growing consensus among the populus to turn to renewable sources of energy has forced leaders of nations and companies to begin looking for newer sustainable sources of energy and technology. Piezoelectric energy harvesting tiles represent a promising technology in this aspect for converting mechanical energy from human footsteps and vehicular loads into electrical power contributing to sustainable energy solutions in urban environments where the need for sustainable energy is more [1], [2]. These tiles are now widely being explored as a means of generating energy in places like transport hubs, campuses, shopping malls, pedestrian bridges, and roadways, where mechanical loads are frequent and predictable [11]. This paper comprehensively explores the available structural designs that are currently being used in the sector. We systematically categorize tile architectures into five primary structural configurations: Single-layer direct compression designs, Multilayer stack architectures, Cymbal transducer amplification structures, Cantilever-beam-based bending systems Hybrid architectures. For each design discussed their performance characteristics, advantages, and limitations are also discussed in detail. Finally advantages and limitations of this technology is discussed and scope for further research is also explored. The paper concludes that while different structural designs target different types of environments hybrid structural designs promises optimal energy conversion efficiency and offer greater possibilities for the future.

Key-Words: - piezoelectric tiles, energy harvesting, structural design, cymbal transducer, multilayer stack, hybrid tiles

Received: March 12, 2026. Revised: May 15, 2026. Accepted: June 8, 2026. Published: July 9, 2026.

1 Introduction

The global shift towards sustainable sources of energy has sparked the rise in research interest into ambient energy harvesting techniques and methods [1],[2]. The growing interest of companies and organisations towards the deployment of wireless sensor networks and low power IOT devices has intensified this research area [11],[40]. Mechanical vibrations and human motion act as a continuous, though low density source of energy and piezoelectric materials can harness this mechanical energy and convert it into useful electrical energy via direct piezoelectric effect [3],[4]. The piezoelectric effect, discovered by Jacques and Pierre Curie in 1880, describes the generation of electrical charge in response to applied mechanical stress in certain crystalline materials [5]. Piezoelectric energy harvesting tiles which utilise this effect can be integrated into floors, pavements or roadways and can potentially power sensors, lighting or IOT devices in buildings, airports and public spaces [2],[7]. However, the efficiency and practicality of such systems depend on a number of factors but most critically on the structural design of the piezoelectric system that converts the applied force into optimal stress distribution within the tiles structure [4],[6]. This paper aims to provide an integrated review focused on establishing a systematic classification framework and evaluating performance based on power density, durability, cost-effectiveness, and practical deployment considerations [36].

2 Problem Formulation

Piezoelectric energy harvesting tiles must be able to efficiently convert low-displacement, high-force pedestrian input into high strain within the piezoelectric element present within them while maintaining durability, low manufacturing cost and maintaining user comfort [8],[10]. The electrical energy generated per step is typically represented by

$$E = \frac{1}{2} C V^2 \quad (1)$$

where C is the capacitance of the piezoelectric element and V is the voltage developed due to the mechanical stress applied during foot impact [4],[6]. From this equation, it is clear that the harvested energy depends on the electrical and mechanical properties of the piezoelectric material and the to some degree how the structural design concentrates mechanical strain into the active regions of the transducer [22].

Thus, the overall output of the piezoelectric energy harvesting tiles is primarily determined by 4 major factors:

(1) the mechanical strain amplitude delivered to the material,
(2) the piezoelectric coefficient d_{33}or d_{31}, which determines charge generation per unit stress [5],[13],
(3) the effective active material volume, and
(4) the losses associated with rectification, impedance mismatch and intermediate energy storage [12],[17].

Structural designs determine how effectively the footstep force is converted into strain and hence how effectively the energy harvesting system works [26],[30]. Therefore, to maximise energy output we have to carefully select and optimize the structural design employed by the piezoelectric energy harvesters.

2.1 Structural Design Requirements

For a piezoelectric tile to be efficient for real-world deployment, several structural requirements have to be strictly fulfilled. First and foremost, the tile structure must ensure efficient transfer of the mechanical stress produced from the footstep to the piezoelectric element [6],[14]. In general, human footsteps generally produce only 1–5 mm of surface deflection but relatively large forces (400–800 N during normal gait) [7],[27]. Hence, the tile must therefore must have systems to efficiently convert this limited amount of displacement into sufficiently high strain without breaking the materials strain limits [21],[24].

The second requirement to be considered is durability. As public places like metro stations, bus stand etc. experience large amount of human movement the tiles deployed must be able to withstand several million to several hundred million cycled without experiencing piezoelectric fatigue, mechanical wear or depolarisation [9],[32]. This Requires careful selection of relevant structural designs that ensures tiles durability in the long run.

Next, manufacturability and economic feasibility have to be considered. Energy harvesting tiles must be produced at reasonable cost and allow for modular installation, replacement, and low-maintenance operation [10],[31]. Structural designs have to be developed such that if they involve precision assembly, highly specialised components or complex moving mechanisms they must be able to compensate with their performance gains.

The fourth requirement is user comfort which is intact a non-negotiable factor. Structural designs creating excessive vertical displacement (like beyond 5 mm) creates instability or the sensation of being a soft floor [11]. Therefore, structural designs must achieve maximum strain amplification while only allowing minimal visible movement at the surface of the tile [20],[25].

Finally, the system must provide consistent performance across a broad range of footstep locations, loading angles and user weights. This involves tolerance to off-centre loading, rapid repeated steps, and variable environmental conditions such as humidity and temperature. A well-designed structure must provide stable energy output and structural integrity even under the unpredictable real-world conditions [32].

3 Problem Solution

We can systematically categorize piezoelectric energy-harvesting tile (PEHT) architectures into five primary structural categories and analyse their operating principles, strengths, limitations, and performance characteristics [26],[36]. This section analyses five structural configurations based on how each affects capacitance C and voltage V in the energy equation E = ½CV². A Tables summarizing structural designs results are provided at the end of this section.

3.1 Structural Categorization of Piezoelectric Tile Architectures and performance analysis

Piezoelectric Energy harvesting tiles primarily falls into five foundational structural configurations each defined by the dominant mechanical loading mode and strain amplification strategy [4],[26].

The following section presents five primary structural configurations, each analysed using numerical output data, estimated energy from the governing equation $E = \frac{1}{2}CV^2$, and real-world practical harvesting performance.

3.1.1 Single-Layer Direct Compression Design

The single-layer direct compression architecture is the most fundamental configuration used in piezoelectric energy-harvesting tiles [6],[14]. The most basic form of this design consists of a bulk piezoelectric ceramic plate or disk—typically between 30×30×3 mm and 60×60×5 mm which is sandwiched between top and bottom electrodes and mechanically compressed by the vertical footstep load [18]. Since the piezoelectric materials beneath this design experiences only pure axial stress, this configuration act as a baseline for evaluating more advanced strain amplifying design models [14]. this design configuration is mechanically simple and very easy to construct because of its low cost but produces very limited strain due to the absence of any amplification mechanism [6],[32]. A typical 60×60×3 mm PZT-4 element provides approximately 13.8 nF capacitance [5],[13]. Under a representative 700 N footstep generating ~0.19 MPa axial stress, the ceramic produces ~15 V [14].

- Estimated energy (from $E = \frac{1}{2}CV^2$): ~ 1.6 µJ per loading
- Practical harvested energy per footstep: ~ 18–22 mJ [6],[30]

This design configuration is advantageous because of its compact (10–15 mm), simple fabrication, and robustness [8],[32]. However, continued loading can create stress that reduces the life cycle of the structure [9]. ensuring optimal thickness (~3–5 mm) helps in balancing manufacturability, voltage output, and durability [20].

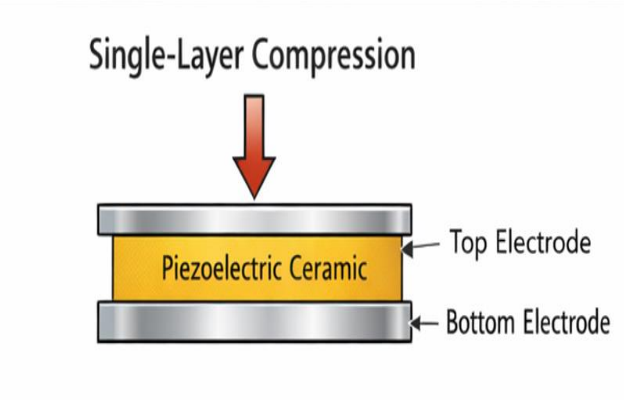

Fig.1: A basic design of single-layer compression for a Piezoelectric Energy harvesting tile.

3.1.2 Multilayer Stack Architecture

Multilayer stacks are composed of 25–100 thin piezoelectric (50–200 µm each) layers isolated with internal electrodes [15],[21]. The layers are electrically connected in parallel to allow very high capacitance [22]. For example, a typical 50-layer PZT-5H stack (30×30 mm footprint) carries 13.6 µF capacitance [15],[16]. At the same step load, each individual layer can generate 0.38 V and hence their parallel series still produces a low total output voltage but high current outputs [22].

- Estimated energy (from $E = \frac{1}{2}CV^2$): ~1.0 μJ per loading
- Practical harvested energy per footstep: ~55–70 mJ[16],[31]

Reliability of the architecture is high (10^6 –10^7 cycles) due to crack-halting thin layers [9],[15]. Limitations of this configuration include low voltage output making voltage multipliers necessary along with necessity of complex fabrication process [17],[21]. However, multistack layer configuration remains among the most efficient compression-based tile technologies [31].

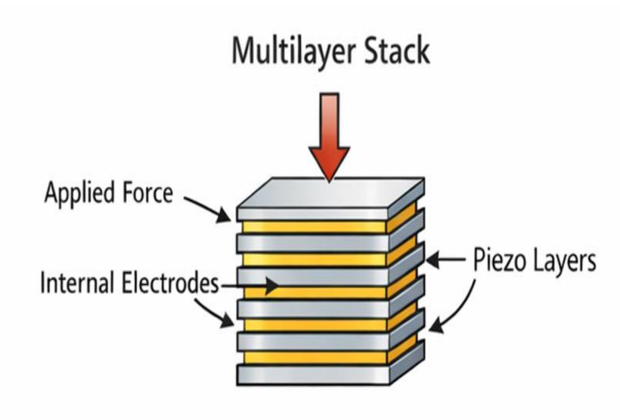

Fig.2: A basic design of multi-layer compression for a Piezoelectric Energy harvesting tile.

3.1.3 Cymbal Transducer Design

Cymbal transducers consist of a piezoelectric disk (20–40 mm diameter, 0.5–2 mm thickness) bonded between metal end-caps containing shallow cavities [18],[19]. These metal caps will deform when a vertical load is applied and are able to mechanically amplify the radial strain by 3 to 8 times which allows this configuration to produce larger voltages than direct compression models [18],[19]. A typical PZT-5A cymbal (30 mm diameter, 1 mm thickness) exhibits ~10.7 nF capacitance and produces 10–17 V, depending on amplification [19].

- Estimated energy (from equation): ~1.37 μJ per transducer
- Practical harvested energy per footstep: ~90–120 mJ (from arrays of 4–6 cymbals) [18],[30]

Cymbals offer great reliability (5×10^6 –10^7 cycles) along with mechanical protection for brittle ceramics, and efficient strain amplification [19],[26]. However, limitations include the greater manufacturing complexity associated and increased tile thickness but overall energy density produced is high [18],[30].

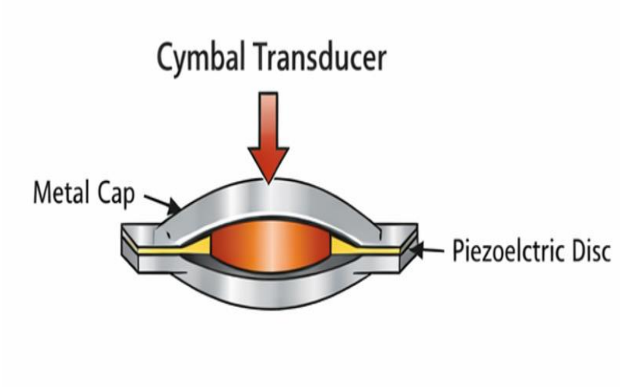

Fig.3: A basic cymbal transducer design for a Piezoelectric Energy harvesting tile.

3.1.4 Cantilever Beam Architecture

Cantilever-based PEHT systems rely on a system of unimorph or bimorph beams (40–100 mm length, and 0.2–0.5 mm piezo thickness) bonded to an elastic substrate with attached proof mass [16],[23]. Bending of the cantilever, produces high tensile and compressive strain across the piezoelectric layers typically 1500–3000 με under footstep excitation [24]. A standard PZT-5H bimorph of 80×30×0.3 mm yields approximately 482 nF capacitance, producing 120–180 V as the beam oscillates [22],[23].

- Estimated energy (from equation): ~5.4 μJ per oscillation

- Practical harvested energy per footstep: ~40–55 mJ (due to 5–10 oscillations per step) [23],[28]

Cantilever configuration delivers the highest voltage among all the designs thus simplifying the need for rectification. Their limitations include sensitivity to loading position, need for vertical clearance (15–40 mm), and fatigue at the clamped end. Despite these constraints, cantilever-based tiles are effective for high-voltage, low-current harvesting [23].

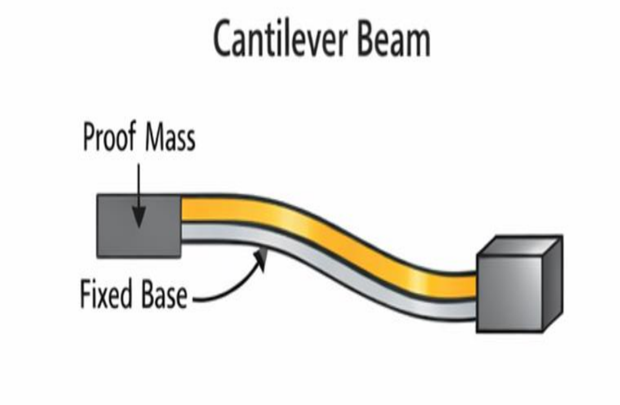

Fig.4: A basic design of cantilever beam for a Piezoelectric Energy harvesting tile.

3.1.5 Hybrid Architectures

Hybrid configuration of piezoelectric energy harvesters includes mechanisms such as lever amplification, cymbal transducers, dual-axis strain components, and impact mechanisms [25],[29]. A typical system uses an 8× lever amplification stage feeding into a 4× cymbal amplification stage, resulting in an effective amplification factor of ~21× [25],[29]. A four-cymbal array produces ~42.8 nF capacitance and 80–140 V output [25].

- Estimated energy (from equation): ~259 µJ per loading
- Practical harvested energy per footstep: ~140–180 mJ (highest among PEHT architectures) [25],[30]

Hybrid systems provide the greatest energy density and highest tunability [26],[30]. However, mechanical complexity introduces friction losses, increased cost (4–8×), and a larger tile height (25–50 mm) [25],[29]. These designs are ideal when maximizing harvested energy is the top priority. Some of the most common hybrid architectures used are Frequency Up-Conversion, Lever Amplification, Spring-Loaded Impact, Distributed Multi-Element Arrays, Dual-Axial Strain, Hydraulic/Pneumatic Coupling [29],[39].

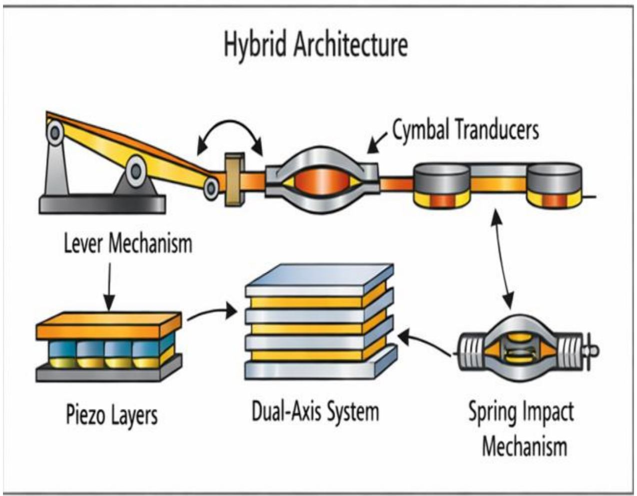

Fig.5: A basic hybrid architecture design for a Piezoelectric Energy harvesting tile.

3.2 Comparative Performance Table

Structural Configuration	Capacitance	Voltage Output	Estimated Energy (Eq.)	Practical Energy per Footstep	Summary Characteristics
Single-Layer Compression	~13.8 nF	~15 V	~1.6 µJ	18–22 mJ	Simple, thin, low-cost, limited strain

Structural Configuration	Capacitance	Voltage Output	Estimated Energy (Eq.)	Practical Energy per Footstep	Summary Characteristics
Multilayer Stack	~13.6 µF	~0.38 V	~1.0 µJ	55–70 mJ	Very high C, high current, low V
Cymbal Transducer	~10.7 nF	10–17 V	~1.37 µJ	90–120 mJ	Amplified strain, robust, good energy density
Cantilever Beam	~482 nF	120–180V	~5.4 µJ/osc	40–55mJ	Highest V, resonance-based, fatigue at clamp
Hybrid Designs	~42.8 nF	80–140 V	~259 µJ	140–180 mJ	Maximum energy output, mechanically complex

Table 1. Comparison of Major Structural Configurations with Estimated and Practical Energy Outputs

4 Conclusion

Piezoelectric energy harvesting tiles are a fast-growing technology and are emerging as an efficient solution to provide distributed power generation in smart infrastructure without maintenance. We have analysed the major five structural configurations presently used in piezoelectric systems namely single-layer direct compression, multilayer stacks, cymbal transducers, cantilever beam mechanisms, and hybrid architectures and compared their performance in terms of strain amplification, voltage generation, energy output, durability, manufacturability, and suitability for real-world deployment. Our analysis has showed that purely compressive designs are both simple and inexpensive, but provide only modest strains and hence moderate energy levels, while multilayer stacks and cymbal structures demonstrate significantly better electrical output because of improved electromechanical coupling as well as strain redistribution. Cantilever type is the most efficient but suffer from structure complexity and need of space. Hybrid architectures always prove to be producing the highest amount of usable energy per stride, indicating their importance in applications requiring maximum power extraction.

Across all the 5 configurations analysed, performance is found to be dependent on both the structural geometry as well as how effectively each design concentrates mechanical input into high strain regions of the piezoelectric material. Although all the designs show great potential for powering low-power electronics, smart building sensors and IoT nodes, better fatigue resistance, long-term stability, as well as strain amplification mechanisms that maintain the user's comfort are desirable. Further research into this field can help in overcoming the present limitations faced by these structures.

In general, the study highlights that there is no one structure configuration will be optimal in all situations and the choice of design needs to alternate with the energy demand to be provided by site conditions, cost limitations and durability constraints. Currently, hybrid systems prove to be the best prospects for harvesting high-energy densities in urban environments, whereas simpler compression and multilayer systems are well-suited for wide-area deployment at low cost. On-going improvements in piezoelectric materials design and fabrication will further enhance the practicality and efficiency of piezoelectric energy-harvesting tiles for future smart infrastructure.

Acknowledgement:
The authors express their sincere gratitude to Dr. Renuka Devi for her continuous support during the course of this research journey. The authors remain forever grateful for her unwavering commitment and guidance which made this research a success.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

The authors equally contributed in the present research, at all stages from the formulation of the problem to the final findings and solution.

Sources of Funding for Research Presented in a Scientific Article or Scientific Article Itself

No funding was received for conducting this study.

Conflict of Interest

The authors have no conflicts of interest to declare that are relevant to the content of this article.