# Finite Element Analysis of Piezoelectric Energy Harvesters In Pavements

By


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|---|---|
| SGT M. Kashif Mehmoodzai (Syn Ldr) | (358967) |
| GC Hamza Jawed | (358956) |
| SGT Ali Bin Shahid | (358961) |
| GC Alamzaib | (358948) |

Department of Transportation and Geotech

Military College of Engineering, Risalpur

National University of Sciences & Technology (NUST)

Islamabad, Pakistan


(2024)

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SGT M. Kashif Mehmoodzai (Syn Ldr) (Registration No:00000358967)

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SGT Ali Bin Shahid (Registration No:00000358961)

GC Alamzaib (Registration No:00000358948)


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Bachelor of Engineering in
Civil Engineering


Supervisor: Maj Dr. Munum Masood

Military College of Engineering, Risalpur

National University of Sciences & Technology (NUST)

Islamabad, Pakistan


(2024)

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Certified that final copy of BECE Thesis written by

SGT M. Kashif Mehmoodzai (Syn Ldr) (Registration No:00000358967)

GC Hamza Jawed (Registration No:00000358956)

SGT Ali Bin Shahid (Registration No:00000358961)

GC Alamzaib (Registration No:00000358948)

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Signature: ____________________

Name of Supervisor: Maj Dr. Munum Masud

Date: 15/5/24

Signature (HOD): ____________________

Date: 15/5/24

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| | |
|---|---|
| SGT M. Kashif Mehmoodzai (Syn Ldr) | (Registration No:00000358967) |
| GC Hamza Jawed | (Registration No:00000358956) |
| SGT Ali Bin Shahid | (Registration No:00000358961) |
| GC Alamzaib | (Registration No:00000358948) |

under the supervision of Maj Dr. Munum Masood. No part of this thesis has been submitted anywhere else for any other degree. This thesis is submitted to the Military College of Engineering in partial fulfillment of the requirements for the degree of Batchelor of Engineering in Field of Civil Engineering. Department of Transportation and Geotech National University of Sciences and Technology, Islamabad.

Student Name: M. Kashif Mehmoodzai Signature: ____________

Student Name: Hamza Jawed Signature: ____________

Student Name: Ali Bin Shahid Signature: ____________

Student Name: Alamzaib Signature: ____________

Supervisor Name: Maj Dr Munum Masud Signature: ____________

Name of Dean/HOD: Maj Dr Munum Masud Signature: ____________

## AUTHOR'S DECLARATION

We

SGT M. Kashif Mehmoodzai (Syn Ldr) (Registration No:00000358967)

GC Hamza Jawed (Registration No:00000358956)

SGT Ali Bin Shahid (Registration No:00000358961)

GC Alamzaib (Registration No:00000358948)

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Student Name: M. Kashif Mehmoodzai Signature: [signature]

Student Name: Hamza Jawed Signature: [signature]

Student Name: Ali Bin Shahid Signature: [signature]

Student Name: Alamzaib Signature: [signature]

Date: 15th May 2024

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Student Signature: ____________________

Name: GC Hamza Jawed

Student Signature: ____________________

Name: SGT Ali Bin Shahid

Student Signature: ____________________

Name: GC Alamzaib

# DEDICATION

To Almighty Allah for giving us the strength to undertake this project. And to our parents, whose dedication and teachings have been a beacon of light all our life.

# ACKNOWLEDGEMENTS

We are thankful to our creator أَللّٰهُ عَزَّ وَ جَلَّ who has guided us throughout this work every step of the way and for every new thought which He set up in our minds. Nothing would have been possible except by his will and command. All praises are for Him who has been our help the entire way.

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# ABSTRACT

This study examines the shape betterment of piezoelectric energy harvesters under mechanical stress, producing vibrations, using ABAQUS software. Six piezoelectric devices with varying dimensions but equal areas were constructed to investigate if model size affect the output voltage. These models underwent testing under different loading conditions mirroring real-time pavement scenarios to generate an output voltage through finite element modelling. The resulting output voltages were then compared to assess the impact of shape optimization on piezoelectric energy harvesters in order to obtain energy from mechanical vibrations. In addition, different cross-sections and materials were compared to find the optimum one yielding maximum values.

**Keywords:** Exploring Material Properties, Structural Dynamics, Piezoelectrics, Energy Harvesting and Finite Element Modelling.

# CHAPTER 1: INTRODUCTION

## 1.1 Background

A piezoelectric energy harvester (PEH) is a remarkable technology that serves as a self-power source for any network system containing sensors. The unique feature of piezoelectric materials is their ability to transform mechanical vibrations into electrical energy, thereby generating renewable and clean energy from these movements. This energy harvesting technique can be integrated into pavements, where it captures the mechanical vibrations from passing vehicles and converts them into usable energy. The potential applications for this energy are vast, ranging from powering a structure health indicator to illuminating lights or even heating snow-melting devices installed in the road. While PEHs rely on outer stress to generate electricity, the optimization of the PEH plays a crucial role in maximizing the energy harvested. Factors such as length, area, depth, and other dimensions can significantly impact energy generation by PEH

In Figure 1, we see a basic representation of a molecular model. This model demonstrates how an electric current is generated when a force is applied to the material. Initially, the centers of the negative and positive charges within every molecule align, resulting in neutralization of their outer effects. This creates a neutral molecule. However, when force is applied to the material, its structure is distorted. This distortion causes the different positive and negative parts of the molecules, leading to the formation of tiny dipoles. The dipoles within the material then cancel each other out, resulting in a distribution of linked charges on the material's surfaces. This process is known as polarization, where the material becomes polarized due to the separation of charges. The polarization creates an electric charge, which can be harnessed to convert the energy used in deforming the material into electrical charge.

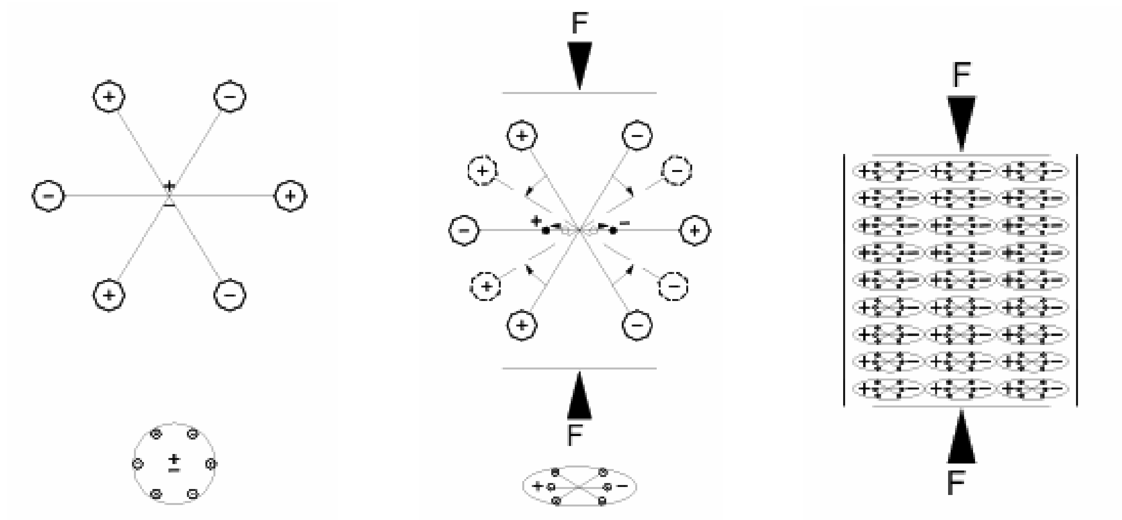



**Figure 1. Left: Normal molecule. Center: Molecule under force. Right: Molecule's surfaces polarized.**

Imagine if we could turn the vibrations from cars driving on roads into electricity. This innovative idea is made possible by a phenomenon called piezoelectricity, which converts mechanical stress into electrical energy. This concept has been around since 1880, when two French brothers, Pierre and Jacques Curie, first discovered it. Today, piezoelectricity is becoming a game-changer in the quest for sustainable energy. One exciting application is in road infrastructure, where it can be used to harness energy from the vibrations caused by vehicular traffic. This paper explores the potential of using piezoelectricity in pavements to generate renewable energy, which could have a significant impact on our environment and energy needs.

### 1.2 Problem Statement

Currently, fossil fuels are the most widely used energy source, and since pavements make up a significant portion of transportation infrastructure, energy-harvesting technologies like solar panels have been integrated into them to generate electricity. However, these systems have a major drawback: they rely on favorable weather conditions.

Transportation accounts for a staggering 63.8% of global oil consumption, according to the International Energy Agency's Key World Energy Statics 2015 report.

With the increasing demand for automobiles and significant alterations in highway systems, the total amount of available vibration energy has grown.

As the future is moving towards sustainability different energy harvesting methods are being tested to conserve lost energies and reduce the harmful impact of fossil fuels and other industrial processes in the environment. Piezoelectrics in this scenario pose a very viable solution being eco-friendly and embedded in the roads. Not only do they conserve lost mechanical energy from ongoing vehicular traffic but also weather independent energy harvesting devices. Though promising, they are in the nascent stages of development and there is a need for assessing their efficiency and effect of changing different parameters on their performance.

## 1.3 Research Objective

As we look towards building a more sustainable future, it is essential to develop advanced technologies like PEH to create cleaner energy sources. By harnessing the energy generated by vehicle vibrations, PEHs offer a promising alternative to address the environmental issues associated with harmful gases. This innovation is already in progress and has been found to be effective. In this study, we aim to utilize previous data on PEH models to design an optimal shape through finite element modelling that can collect acceptable amounts of electricity from vehicle movements. Our goal is to enhance our understanding of how PEHs work and to know about the environmental benefits of these energy harvesters. Further research will focus on investigating methods for amplifying the output of piezoelectric materials and improving the efficiency of associated circuits. We plan to explore innovative approaches such as material enhancements, geometric optimizations, and circuit design improvements to maximize the energy harvesting capabilities of piezoelectric systems. Our ultimate objective is to create a more sustainable and eco-friendly future by harnessing the power of PEH technology.

## 1.4 Objectives

The objectives are:

a. To test energy harvesting capabilities of Piezoelectrics.
b. To find the optimum cross-section.
c. To find material, yielding a maximum voltage and undergoing lower stresses.
d. To find factors resulting in maximum output in the field.

## 1.5 Scope of Work

In this research, we have used the ABAQUS software to design an optimal PE device. ABAQUS is commonly used for finite element modeling (FEM), which enables the modeling and analysis of mechanical components and assemblies, as well as visualizing different parameters. ABAQUS follows a number of steps to make a model, and it gives option to users to change the procedure, by their own will. This feature makes ABAQUS a flexible tool for modeling and analysis, as model is continuously modified through all steps, and the effects of steps performed before are always transferred to every new step created. The paper consists a literature review conducted on foundation of concept of PEH, piezoelectric materials, their principles, shape and finite element analysis. Additionally, an overview of Finite Element Modelling and some projects created in ABAQUS were studied. Our primary focus is to assess the effectiveness of PEHs across various design variables.

## 1.6 Summary

This chapter gives an insight into brief description and importance of the project. It explores the energy generation of piezoelectric energy harvesters (PEH) in road infrastructure, specifically pavements, to harness energy from vehicular traffic. Problem statement, objectives, scope, and the research methodology for the completion of the research is also discussed.

# CHAPTER 2: LITERATURE REVIEW

## 2.1 Introduction

The chapter is about the study of history, materials & their properties. Moreover, the shape optimization of piezoelectric materials (PEHs) over time is also studied in this. Significant events such as piezoelectric effect's discovery, creation of PEH ceramics, and the evolution of PEH shapes to absorb maximum energy are highlighted in this chapter. Although the piezoelectric effect was not known until 1880, it has already had a major impact on society, with watches and clocks becoming some of the most popular devices. Other common devices include converters, sensors, pumps and motors. This chapter also discusses the evolution of PEH forms over time and highlights the importance of understanding the piezoelectric effect in today's technology

### *2.1.1 Overview of research of PEH*

**In 1969**, pioneering application of energy harvesting from vibrations utilizing PZT materials was introduced by Wen H. Ko. Ko authored an official US document titled "Piezoelectric Energy Converter for Electronic Implants" (Ko.W.H., 1969), outlining the utilization of a cantilever beam of PZT with a less mass for extracting energy from heartbeats, which was subsequently employed to power implanted medical pacemakers.

**In 1983**, Taylor and Burns (Taylor, 1983) told about the use of a group of polyvinylidene fluoride (PVDF) piezoelectric films to capture hydro-dynamic energy from waves of ocean. At that time no practical system was constructed, their theoretical model suggested the potential for a 100 MW plant using PVDF to supply power to a grid at a costing 2.5 cents per kWh on the shore.

A practical application of piezoelectric materials for energy harvesting was initiated in **1984** by Hausler et al. (Hausler, 1984). They advocated for PVDF film as a power source which is implantable within biological systems. In order to gain energy from the rib's relative motion a prototype device was used in the ribcage of a dog during breathing, demonstrating the generation of a highest volt of eighteen V, equating to approximately seventeen W of power.

**In 1987**, Hausler and Stein (Hausler E. a., 1987) proposed another application of energy harvesting film of PVDF, this time from ocean waves. Their theoretical system involved tethering first end to the sea floor of a PVDF rope and the second at the sea surface end to float. Relative motion between float and the river floor would stretch PVDF rope, generating electrical energy. This system was envisioned to give measurement of buoys, with twenty kg of PVDF which is able of producing around 100W.

**In 1992**, Schmidt (Schmidt, 1992) discovered the use of PVDF film for power harvesting in windmill applications, designing 3 independent piezoelectric windmills vibrating small amplitude with high frequency. While these prototypes demonstrated energy generation in the microwatt to mill watt range, challenges remained in achieving practical windmill designs due to less power generation and more expenditures of PVDF film.

M**id-1990s** witnessed research into energy harvesting from human body motion. Antaki et al. (Antaki, 1995) integrated piezoceramic stacks in the shoe which would capture wasted energy during motion, leveraging mass of body and the rate of movement.

**In 1996**, Starner (Starner, 1996) detailed & explored harvesting energy from body heat and blood pressure. Following this, Kymissis (Kymissis, 132-139) experimentally tested piezoelectric and electromagnetic harvester designs integrated into shoes, with piezoelectric prototypes capable of gaining about 1-2 mW of power.

**In 1998**, Umeda et al. (Shenck, 1999) focused on developing a circuit model to study the reaction of a piezoelectric vibrator plate as struck by a steel ball. Experimental results demonstrated ability of piezoelectric vibrator to charge a storage capacitor once abrupt energy is applied, achieving an efficiency of 35%.

Continuing into **2001**, research efforts expanded to develop electromechanical models of piezoelectric harvesters, marking a decade of significant advancements in energy production by the use PEMs.

**In 2004**, Sodano et al. (Sodana, 2004) published a comprehensive review of piezoelectric vibration harvesting literature. This was followed by Beeby et al. (Beeby S. P., 2006) in 2006, who reviewed works on piezoelectric harvesting in applications of small-scale.

Subsequent years saw further reviews and overviews, including those by Priya (Priya, 2007), Anton and Sodano (Anton, 2007), and Cook-Chennault et al. (Cook-Chennault, 2008), which provided insights into the various energy harvesting sources for MEMS applications.

**In 2010**, a breakthrough in green energy technology emerged from the Israeli Institute of Technology in collaboration with the Technion. Innowattech scientists devised a system to harvest mechanical energy from vehicles imparted to roads, converting it into electrical energy for storage and various applications. By embedding small piezoelectric generators beneath road surfaces, energy typically lost as heat from asphalt deformation was converted into electricity. This energy conversion process enabled the storage of electrical energy in batteries or direct connection to the grid.

## 2.2 Background

The word piezoelectric is derived from Greek. "Piezoelectric" means "thrust". Hence, combining it with word "electricity", means electricity produced by five types of pressure. The piezoelectric effect was discovered the French Academy of Sciences on August 2, 1880 by the brothers Jacques and Pierre Curie (Arnau & Soares, Duck, Francis, 2009; Katzir, 2006). Curie brothers discovered that when an asymmetric crystal is compressed along its half-symmetry axis, positive and negative charges appear on opposite sides of the crystal and disappear when the pressure stops. Materials that the Curies considered at the time to exhibit electrically charged surfaces under mechanical stress included Rochelle salt, quartz, sucrose, and tourmaline.

This discovery was credited to the Curie brothers, Figure 3. But they found no inverse piezoelectric effect. In 1881 the scientist Gabriel Lippmann proved the existence of inverse piezoelectric effect. According to Lippmann, an electric field if applied to crystal would cause the material to deform according to the fundamental laws of thermodynamics (Uchino, 2017). New theory by Lippmann attracted the attention of the Curie brothers; the brothers confirmed the correctness of the inverse effect theory, as shown in Figure 4. Additionally, Curie brothers developed piezoelectric quartz electrometer; an instrument able of measuring weak electrical currents. This device was later used by Pierre and Marie Curie to estimate the radio-activity of Radium (Duck, F. A. & Thomas, 2022).

Although PE was an immense innovation in the field of science, still it was not noticed for decades. The piezoelectric effect was considered a credible scientific activity until World War I in 1914 (Moheimani & Fleming, 2006). As a result of the catastrophic events of the time, there was real investment in accelerated ultrasonic technology to locate German submarines under the water. In Feb 1917, Dr. Paul Langevin believed, approximately 6 quarts of properties of piezoelectric would initially be efficiently used to receive and transmit ultrasound waves, and a few experiments later it concluded that his theory was correct (Duck & Thomas, 2022). This discovery builds ultrasonic submarine detectors; causing sonar transmitters vibrations; then the vibrations of the sonar can deliver ultrasonic waves into the water and measure the time required for these waves to reflect back from objects. time to detect the distance of the object.

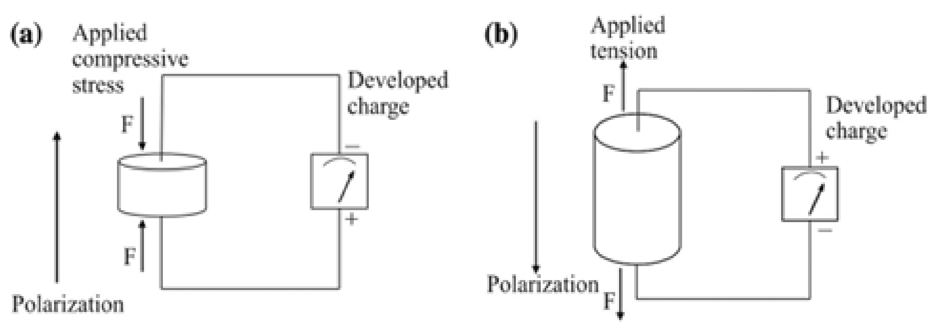



**Figure 2. Relation of direction of force with polarization.**

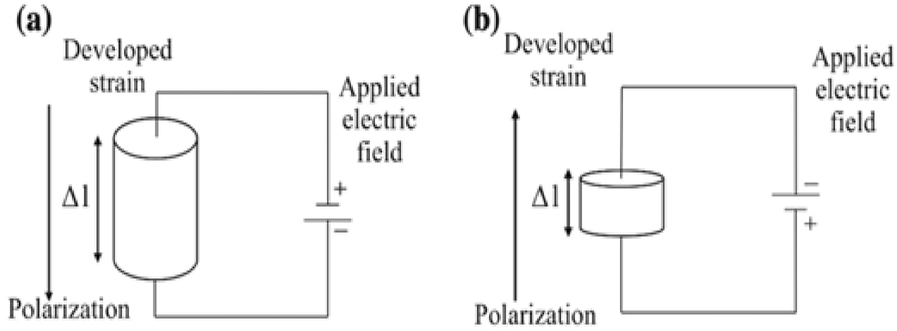



**Figure 3. Relation of strain developed with polarization.**

More research on PM's were carried in that era. The discovery of ferroelectricity by Joseph Valasek (Valasek, 1921) was one that had immense impact on PMs investigations. Ferroelectricity on a material is a polar 7 dielectric with two or more phases and domain structures in which an applied electric field can change the polarization (Whatmore, 2017). The first ferroelectric material was Rochelle salt; but it lost its ferroelectric properties when its composition was changed. The discovery of synthetic materials that are 100 times more piezoelectric and dielectric than natural piezoelectric materials led to their mass production. The commercial availability of piezoelectric lasted till the year 1945, it was recognized that mixed (BaTiO3) was a ferroelectric that could be cheaply produced; it was also capable of producing constant-power materials through electric polarization compared to natural materials. Material hundred times higher than piezoelectric materials. The PE was successfully used in the World-War years, piezoelectric ceramics found many applications. Most usual devices created based on the PE used by society are inkjet printers and lighters.

### 2.3 Piezoelectric Materials

Piezoelectricity in a material is determined by its atomic structure and the distribution of electric charge. Various kinds of piezoelectric materials, including crystals and organic substances. Organic and non-organic materials are given in the below figure.

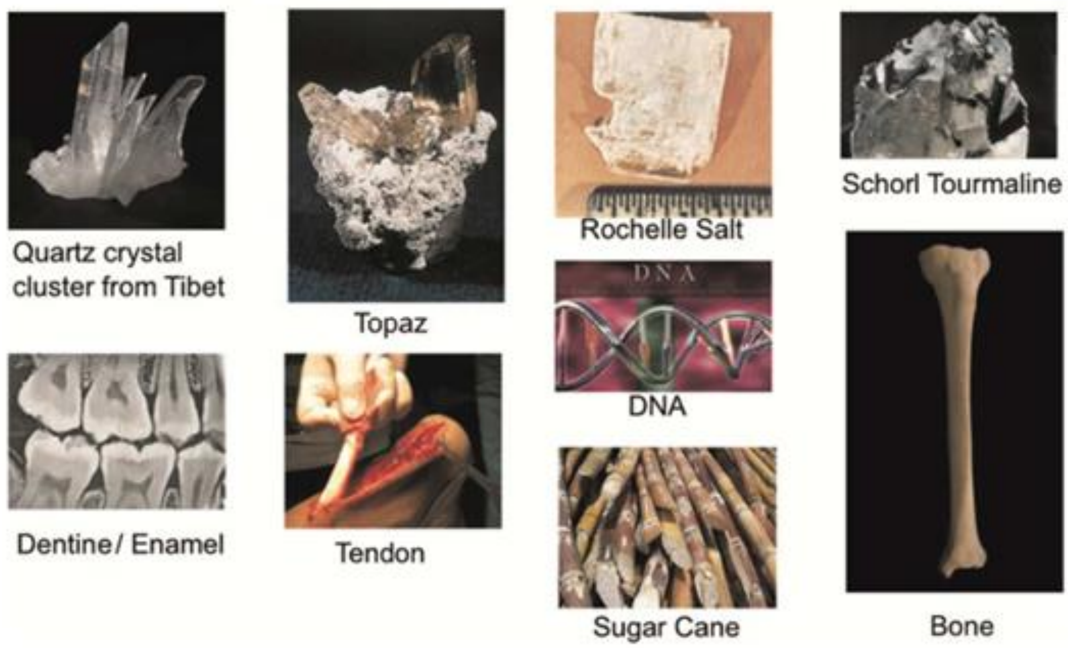



**Figure 4. Common piezoelectric materials.**

Crystalline materials are composed of atoms arranged in a 3-dimension pattern with a unit cell as their building block. Non-piezoelectric CMs have a symmetrical distribution of atoms around the center point, while CMs without a center of symmetry are classify as piezoelectric. Crystals can be divided into seven groups as represented in the figure. Out of thirty-two classes of crystals, only twenty possess piezoelectric properties. Ten are polar, requiring no mechanical stress for polarization while the other ten crystals are not polar, requiring mechanical force for polarization. (Dineva et al., 2014; Kong et al., 2014).

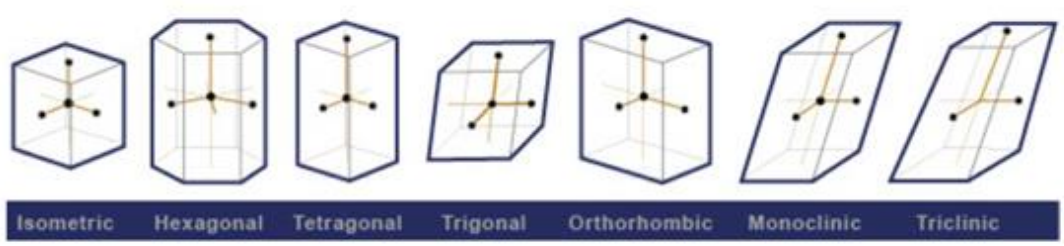



**Figure 5. group of crystals.**

PMs operate due to their non-centrosymmetric crystal structure, allowing them generating distance between negative and positive ions. This separation, known as a dipole moment, is represented as a vector extending from -ve to +ve charge in many molecules (Manbachi & Cobbold, 2011). Dipole density for a medium electric polarization is calculated by summarizing all the per volume dipole crystals of the crystal (Birkholz, 1995). Normally, the piezoelectric crystal is neutral in electric field, that is, the electric field is uniform, as represented in Figure 7, but when the PM is vibrated, its shape changes, as shown in Figure 5 (left) and (right). The atom will rotate in a specific orientation, and because of the asymmetry responsible for the distribution, dipole will no more block the other, but instead form a positive network and a positive network. An equal amount of charge passes through all elements, and the negative and positive charges accumulate on different sides of the crystal, producing a voltage that can drive the circuit.

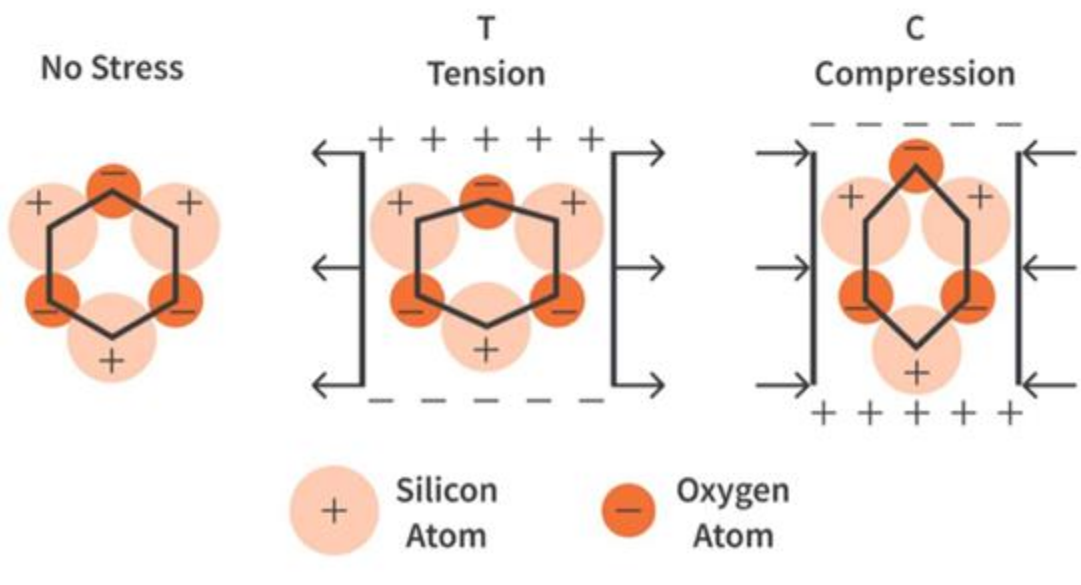



**Figure 5. Atomic structure of a Piezoelectric.**

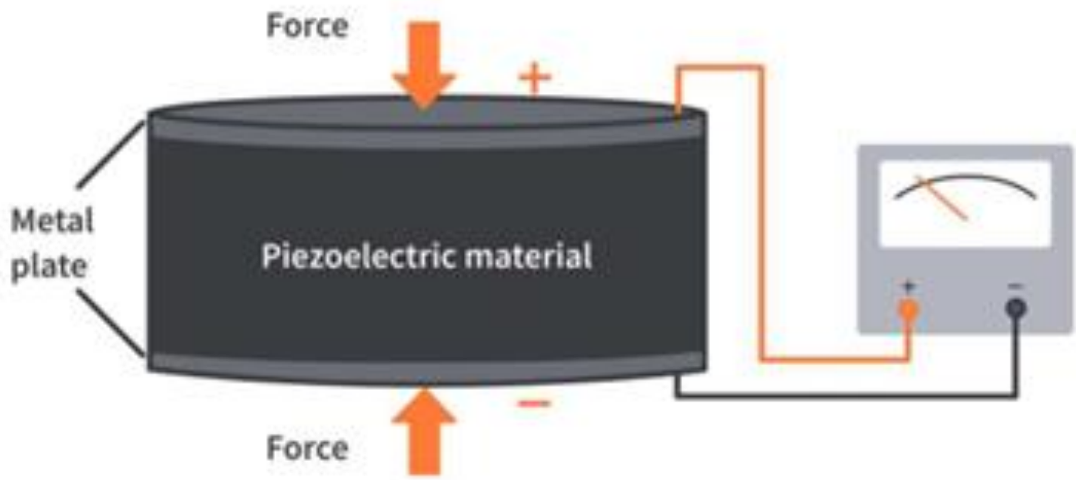



**Figure 6. Working principle of piezoelectrics.**

All types of piezoelectric materials, including polycrystalline PEMs, consist of many ferroelectric particles. These are made from crystal structures such as perovskite: (BaTiO3), (PbTiO3), (Pb [ZrxTi1-x] O3, 0 - commonly called PZT, (KNbO3), (LiNbO3), (LiTaO3) and other non-piezoceramic materials. PZT is widely used due to its stable piezoelectric properties (d31, d33 and d51), while others are used for small electronic harvesters.

Piezoelectric ceramics prepared by mixing fine powders into individual particles and then heating them to make a single powder. Flour is intertwined with organic material then turned into building material; Monitoring the conditions at particular time and temp where sintering powder and material acquire a complete crystal structure. When the object has cooled completely, it can be flattened or pulled and the electrode applied to the appropriate surface. A total of works have been comprehensively examined and their effectiveness and efficiency in generating mechanical energy in electric vehicles have been proven.

**2.4 Principles of Piezoelectric Effect**

2 types of piezoelectric effects have already been mentioned: direct and reverse effect, as in Figure 9. The indirect effect was discovered in the field of voltage-induced

electric current; on the other hand, various effects related to the mechanics of machines resulting from the use of the electric field. PM characteristics are commonly referred to as d, g, and k. The factor d is called the piezoelectric coefficient and includes d31 and d33. The factor d31 is related to the polarization produced at electrode at right angle to the third direction when mechanical stress is applied to the 1 line. Factor d33 is related to polarization in the 3 direction when voltage is applied in the same direction.

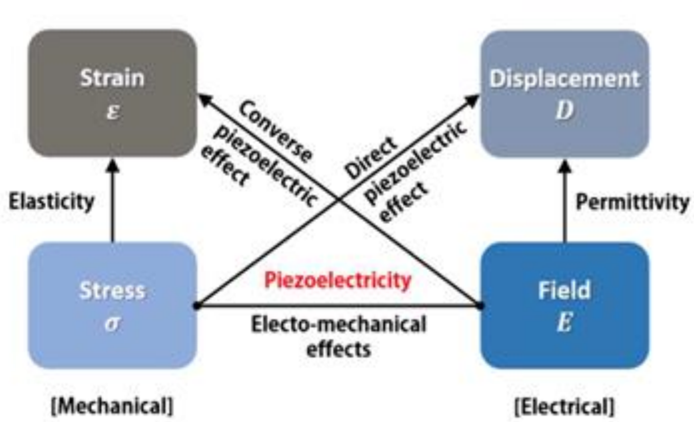



**Figure 7. Different piezoelectric effects.**

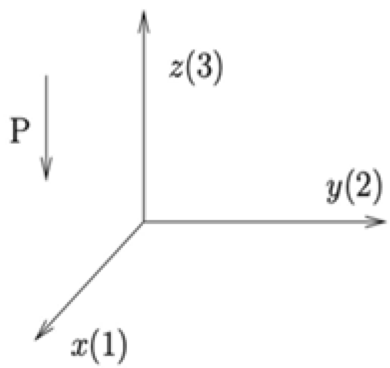
The g factor, including g31 and g33 representing the piezoelectric strain coefficient, contributes to the evaluation of the ability of piezoelectric materials to generate strain energy for each domain of the problem; g factors d can be expressed with the following parameters.

$$g = \frac{d}{Ke_o} \quad \text{(Eq 1)}$$

It is the free space permeability constant given as 8.85 x 10-12 F/m and k is the free dielectric constant. K for example k31, k33 and kp are piezoelectric coefficients; It is used as process control for piezoelectric materials. The planar coupling factor kp represents the radiative coupling, i.e. the coupling between field effects. The Kp value can be determined using resonance and anti-resonance methods; can be calculated as follows:

$$:k_p \cong \sqrt{2.51\frac{(f_a - f_r)}{f_a}} \qquad \text{(Eq 2)}$$

Where, $f_r$ and $f_a$ = resonant frequencies and anti- resonant frequencies




| # | Axis |
|---|---|
| 1 | $x$ |
| 2 | $y$ |
| 3 | $z$ |
| 4 | Shear around $x$ |
| 5 | Shear around $y$ |
| 6 | Shear around $z$ |

**Figure 8. Different axes of polarization.**

This section introduces the quantitative equations that explains the electronic specifications of PEMs. This comparison is based on the IEEE standard for piezoelectricity. This standard supposes that PMs are linear. The scaling equation describes the piezoelectric properties by assuming that the total load on the transducer is the sum of voltage and voltage controlled by the applied voltage. Axis 3 is set in the orientation of the initial polarization of the piezoceramic material, as in Fig. 10. The describing equations for a linear piezoelectric material can be written as

$$\boldsymbol{\varepsilon_i = S_{ij}^E \sigma_j + d_{m_i} E_m} \qquad \textbf{(Eq 3)}$$

$$\boldsymbol{D_m = d_{m_i} \sigma_i + \xi_{ik}^{\sigma} E_k} \qquad \textbf{(Eq 4)}$$

As seen in Figure 10, where i and j = 1, 2,..., 6 and m, k = 1, 2, 3 denote the various directions with the material coordinate system. For applications involving sensing, the aforementioned equations might instead be expressed in the following format.

$$\boldsymbol{\varepsilon_i = S_{ij}^{D}\sigma_{j\cdot} + g_{m_i}Dm} \quad \textbf{(Eq 5)}$$

$$\boldsymbol{E_i = g_{m_i}\sigma_i + \beta_{ik}^{\sigma}D_k} \quad \textbf{(Eq 6)}$$

## 2.5 Shape Optimization of Piezoelectric Energy Harvesting

Electro-mechanical Energy harvesting is a potential approach which can be utilized to produce clean, renewable energy from discarded or unused energy, even while fossil fuel supplies increase (Xiong & Wang, 2016). According to Kim et al. (2011), this method is the process of gathering, storing, and utilizing energy from nearby energy sources for possible future usage. Sun, wind, hydro, and mechanical energy are some of the possible environmental energy sources that can be used to generate electrical. Due to its ability to gather energy regardless of the weather or the season, mechanical energy is the environmental source that receives the greatest attention (Liao & Sodano, 2008; Liao & Liang, 2018; Yang, Z., Erturk, & Zu, 2017).

Because PEH makes it easy to gather ambient energy from vehicle vibration, it is becoming a hot topic for research (Song et al., 2016; Uzun & Kurt, 2013). Because it doesn't require an external power source and has a high electrical conversion coefficient, piezoelectric vibration energy harvesting technology is preferred in the field. Roads, trains, buildings, and mechanical equipment are a few examples of structures that can produce vibration energy.

As was already noted, the number of vehicles on the road increases year, which means that vibration energy is present on roads that are not in use. There would be more intelligent and clean roads as well as an impact on the environment if road engineering and PVEH technology could be used to the busiest routes. Williams and Yates, who were the first to suggest the conversion of vibrational energy into 17 electrical energies in 1996, are credited with popularizing research on the electrical conversion of vibrating micro-energy (Williams & Yates, 1996).

There are currently two piezoelectric pavement technologies that can be used to scavenge vibration: transducer embedded pavement piezoelectric power generation technology and piezoelectric material composite power generation pavement technology. In order to capture vibration energy, the first technology uses piezoelectric materials and compound pavement in road paving. When a piezoelectric module was employed in real roadways, an output voltage of 7.2 V was attained. A ductile asphalt layer and a layer of piezoelectric material were designed, and the power generation characteristics were confirmed (Guo & Lu, 2017b). piezoelectric materials and asphalt are combined to create piezoelectric asphalt composites, which can produce an output voltage of up to 7.2 V (Tan et al., 2013).

By combining piezoelectric, conductive, electrode, and pavement materials, two types of piezoelectric asphalt concrete—d31 and d33—with an output voltage of up to 2.4 V are created (Wang et al., 2016). The second approach harvests and transforms mechanical energy from roads by integrating piezoelectric transducers into the asphalt pavement. This field has been the subject of several investigations. Piezoelectric material optimization and the use of finite elements to assess the energy outputs of various transducers in a road environment are two examples of these investigations.

By mimicking the normal road load, the energy output impact of stacked piezoelectric transducers under various situations might yield an output power of up to 0.46 mW. After determining whether road 18 energy collecting was feasible, LED traffic signal guide lamps based on piezoelectric cantilever beam transducers were built (Collin, 2014). In an investigation into the viability of transducer-embedded piezoelectric power generation pavement, a maximum voltage of 14 V and an effective power of 0.44 mW were measured after a single piezoelectric element was directly buried in the pavement and the energy output effect was tested (Chao-hui, Sen, Yan-wei, Xin, & Qing, 2016).

Additionally, a different polyvinylidene fluoride-based piezoelectric energy harvesting module demonstrated 200 mW of power output (Kim, K. et al., 2018). Every simulation that used piezoelectric materials to generate energy produced energy, which is a successful outcome of this research. The piezoelectric metrical composite power generation pavement is more popular than the transducer-embedded pavement piezoelectric power generation technology, despite the fact that both are being used and researched; however, there are a number of drawbacks. According to Wang et al. (2018), the main drawbacks include the challenging polarization, intricate the preparation of material , limited energy output, and absence of a steady energy supply for practical use.

Since the transducer-embedded pavement piezoelectric power generating technology can produce a greater and more controlled output, piezoelectric transducers are now directly placed on pavement structures in modern road energy harvesting technology. The less frequency output is the key issue with piezoelectric energy harvesters. Various academics have looked into ways to improve the construction of piezoelectric energy harvesters. A rectangular cantilever harvester was reshaped in trapezoidal & triangular form to increase power density. Zhou et al. (2017) proposed a flexible longitudinal zigzag construction for the purpose of harvesting less-frequency oscillation energy. Xu, Jiang, and Su (2011) made layered stacked PEH which achieved a mechanical to electrical energy conversion efficiency of up to 26% while taking into account the flex-tensional force. the investigation of a bi-stable composite construction consisting of a flat piezo fiber laminate and a layer of bent steel (Giddings, Kim, Salo, & Bowen, 2011).

To extract high energy from places of high amplitude force, a cymbal transducer consisting of one flat piezoelectric disc and two concave-shaped metal endcaps was created ( H. W. et al., 2004). With a 0.2g mild excitation, a compressive-mode PEH made of bending beams and a flexural structure may provide more than 20 milliwatts of power. The investigation of an M-shaped framework featuring flat PZT patches and bending spring steel (Leadenham & Erturk, 2015).

## 2.6 Summary

This literature review explores piezoelectric materials, their historical background, research, and principles. It aims to understand their working mechanisms and suggest the best type for pavements. The review examines different types of piezoelectric materials, including crystals, polymers, and ceramics, and their properties and ability to convert ambient vibration into electrical energy. It compares main types and provides suggestions for the best type for pavement use

# CHAPTER 3: METHODOLOGY

## 3.1 Finite Element Analysis

In the old days, improving electro-acoustic transducers meant lots of trial and error, which took a long time and cost a lot of money. But now, instead of just guessing and testing, engineers use computer simulations to make the process faster and cheaper. These simulations help them design better transducers without needing to do as many experiments. They also give them a better understanding of how waves move through certain materials, like piezoelectric solids, and let them try out new materials for making transducers.

Finite Element Analysis (FEA) has become really important in designing lots of engineering stuff. Basically, it's a way to use numbers to solve tricky problems with boundaries, like figuring out how a structure will hold up under different conditions. When you're designing something, you need to think about two big things: how different parts fit together, like sensors and actuators, and how different fields of study, like structure and control theory, come into play. FEA is great because it can handle all sorts of complicated situations, like lots of different materials, loads, and even different physical phenomena like heat and electricity. It's especially helpful for designing smart structures because it can model everything from the basic structure to how it's controlled. Plus, there are special tools for dealing with materials like piezoelectric stuff, which are now even available in popular software like ABAQUS/Standard.

Many studies have used Finite Element Method (FEM) to analyze plates with piezoelectric materials. FEM is a math tool that helps researchers understand how these materials work in structures like cantilevers. Researchers found that by providing conductive electrodes to the model, written by Hamilton, they could make it more accurate (Junior, Erturk, & Inman, 2009). They also developed a model to understand how these devices behave in different situations (Bendary, Elshafei, & Riad, 2010b). These studies show that FEM is a good way to model these materials for energy generation.

ABAQUS is a software tool specifically tailored for structural and thermal analysis in engineering. It's adept at handling both simple and intricate scenarios, offering solutions for stress analysis, be it linear or nonlinear, across structures of varying sizes. The program comes with a variety of elements like beams, shells, and solids, which can be modeled in one, two, or three dimensions. You can also choose different levels of accuracy when modeling. Notably, ABAQUS incorporates an automatic time incrementation feature, ensuring same accuracy all over the solution process.

### 3.2 Finite Element Modelling

In this research, we're taking a closer look at how effective the piezoelectric energy harvesting (PEH) system is using a method called Finite Element modelling. A flowchart, shown in Figure 10, will help you understand exactly how we're simulating and analyzing things in this study.

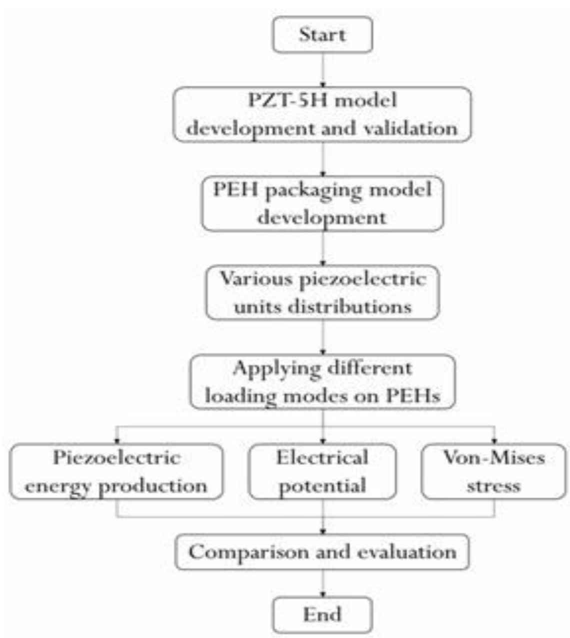



**Figure 9. Methodology Adopted.**

As per the shown flowchart various models were built in the software and were tested in different ways to get the results of the energy generation of piezoelectric devices with unalike geometric configurations.

In this study, we used ABAQUS/standard software to make different models of piezoelectric energy harvesters (PEH). These models were based on findings from Cook-Chennault's research, which suggested that the 3-3 working mode is more efficient for energy conversion in PZT materials. As depicted in Figure 11, the 3-1 mode in which stress components are applied perpendicular to the orientation of polarization the piezoelectric materials, while the 3-3 mode entails stress components parallel the direction of polarization.

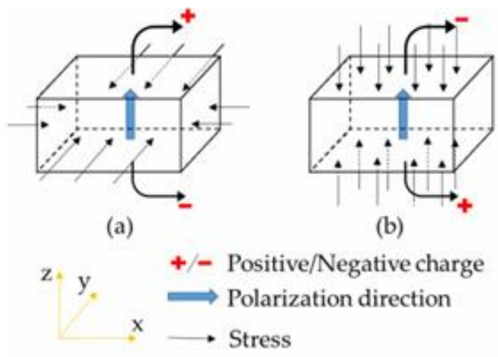



**Figure 10. Modes of operation for PZT materials: (left) 3-1; (right) 3-3**

### 3.3 Model Validation

In this part, we made sure our model was accurate by testing it with ABAQUS/Standard and comparing it to theory. The theoretical values of the model were taken from the work done by (Anwar et al,2011), where the numerical results were obtained by making a prototype in MCE in which 80 piezoelectric generators were installed between the wooden panels and they were connected in a way to get maximum output. Voltage was calculated by placing different weights on prototype. Calculations and graph are given below in Table 1.

**Table 1. Voltage vs. Load (through physical testing).**

| **Load** | 2 | 4 | 6 | 8 | 10 | 12 |
|---|---|---|---|---|---|---|
| **Voltage** | 3 | 7.4 | 9.2 | 12.7 | 14.5 | 17.1 |

A similar model with similar properties was created in Abaqus software for finite element analysis. We compared the results from the model with practical results in Fig 12. The obtained results showed remarkable consistency with the analytical solution.

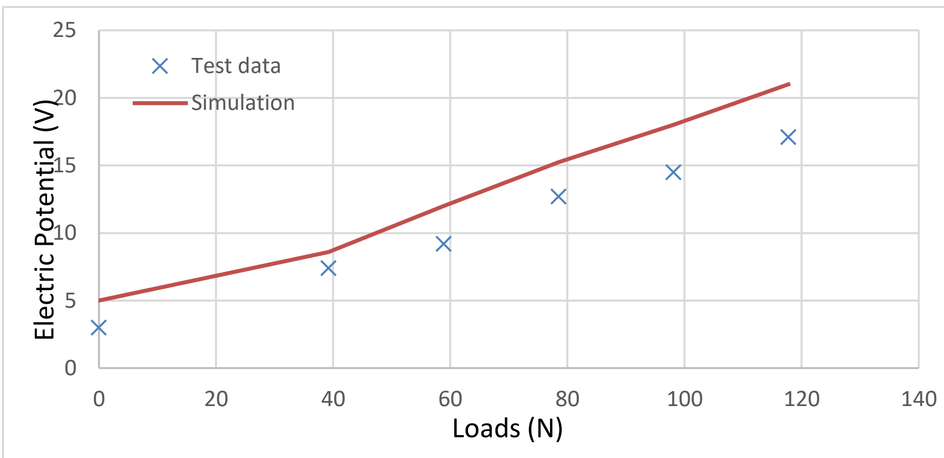
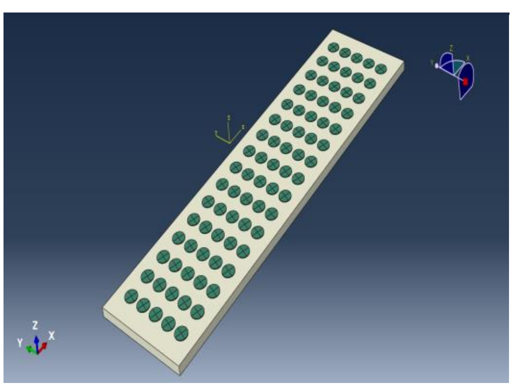



**Figure 11. Validation of piezoelectric simulation.**



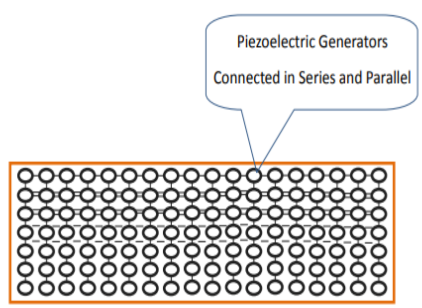



**Figure 12. ABAQUS model (left), Experimental Model (Anwar, et al.2008) (right)**

The model on the right was made in ABAQUS to validate the design. The Figure on the left is the model created for validation and the model created by (Anwar, et al. 2011) is on the right. The results of the test data and the model are mentioned above. The model is very accurate as it produces results very near to those obtained through lab experimentation.

To further confirm our findings, we referred to Cook-Chennault's research, which suggests that the 3-3 working mode is more effective for energy conversion in PZT materials. We also considered preliminary data from Yang, indicating that PZT-5H, a material comprising the lead zirconate, lead dioxide, and lead titanate, exhibits relatively larger piezoelectric coefficient values and strength in compression. Therefore, we connected three PZT-5H plates, each 0.75 cm thick, in parallel. The adjacent contact surfaces of these plates were made from the same material, as illustrated in Figure 14.

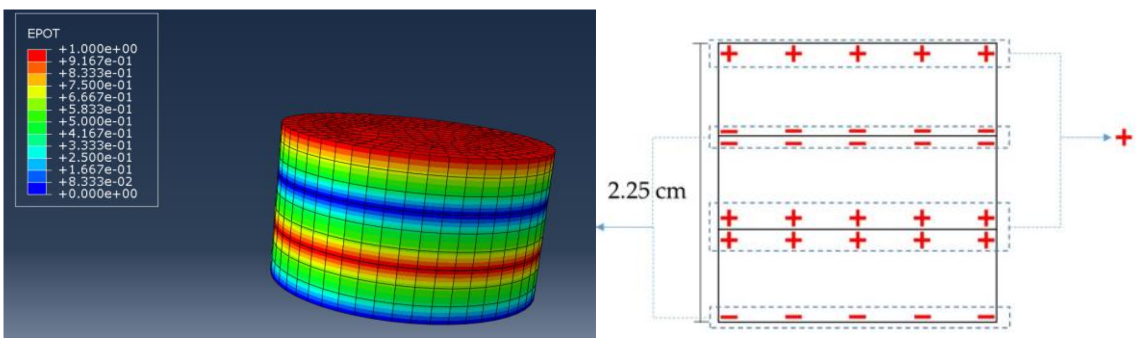



**Figure 13. Piezoelectric unit used for Validation (left) Example of Computational result.**

### 3.4 Construction of Device Finite Element Model

The Finite Element model for Piezoelectric Energy Harvester (PEH) was developed to simulate both the covers and piezoelectric materials. Figure 13 provides a detailed breakdown of the components included in the PEH model, offering an overview of its structure. We assumed tie bonding between covers and between the rubber seal and piezoelectric disks throughout the model, ensuring no slips or displacments would occur.

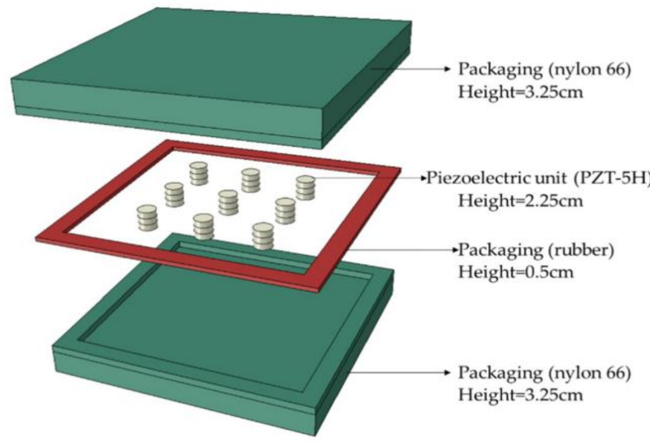



**Figure 14. Overview of PEH finite element model. (Cong Du, et al. 2021).**

According to the research conducted by Yang, three piezoelectric energy harvesters were assembled in 3x3 working mode having a depth of 0.75cm were connected in parallel, and the neighboring surfaces shared the same polarity, as illustrated in the figure 16. Which formed a total thickness of 2.25cm.

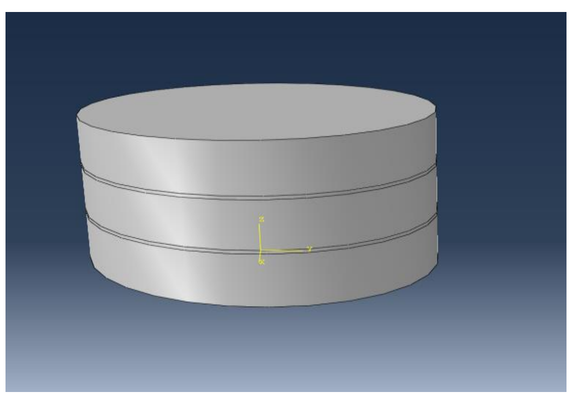


**Figure 15. Piezoelectric harvester formed by connecting three piezoelectric plates.**

To thoroughly assess the effectiveness of PEHs with various piezoelectric materials, we made six different models, shown in Figure 15. We organized the piezoelectric units in grids of 3 × 3, 3 × 4, and 4 × 4 to save space and make things easier. Previous studies showed that the cross-sectional area of these units affects how much electricity they can produce. So, we made sure the whole cross-sectional area of the disks stayed the same in our model. For the 3 × 3 grid with 2 cm wide units, the 3 × 4 grid with 1.73 cm wide units, and the 4 × 4 grid with 1.5 cm wide units, the total size was 28.27 cm2. And for the 3 × 3 grid with 2.3 cm wide units, the 3 × 4 grid with 2 cm wide units, and the 4 × 4 grid with 1.73 cm wide units, the total size was 37.7 cm2.

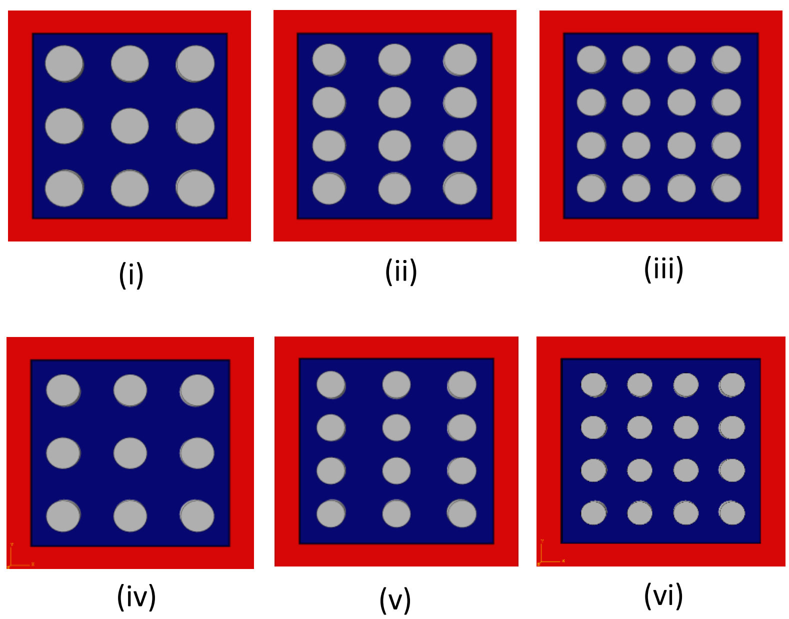



**Figure 16. PZT disks distributions in PEH by: (i) 3x3(dia = 2.3 cm), (ii) 3x4 (dia= 2cm), (iii) 4x4 (dia = 1.73 cm); (iv) 3x3 (dia = 2 cm), (v) 3x4 (dia = 1.73 cm), (vi) 4x4 (dia = 1.73 cm). Total area Piezoelectrics (above) = 37.7 cm2; Total area Piezoelectrics (below) = 28.27 cm$^2$.**

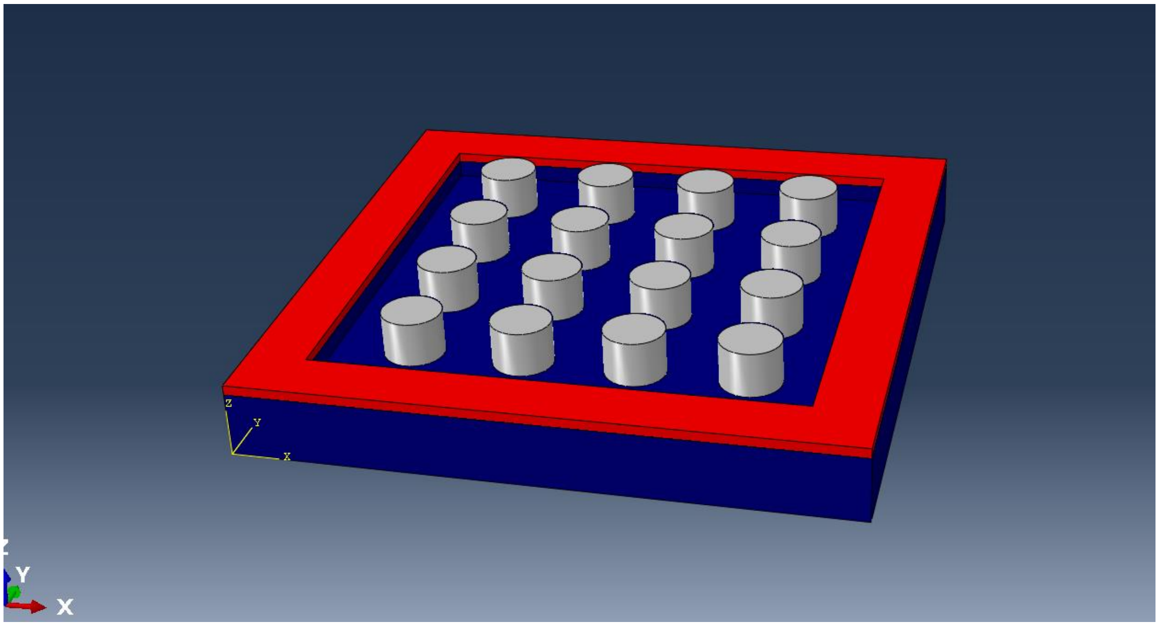



**Figure 17. Assembly in ABAQUS.**

## 3.5 Material properties

Defining material properties is an important parameter for the finite element modelling as correct parameters play an important role in producing correct results.

Elastic properties of harvester component materials were specified using standard values. The piezoelectric properties for various PZT materials were defined based on the documentation Abaqus Verification Manual version 6.6. The specific parameters utilized in the simulation are detailed in the table on the next page.

**Table 2. Material Properties.**

| Material Property | Symbol | PZT-5H | PZT-5A | PZT-4 |
|---|---|---|---|---|
| Elastic Parameters | $E_1$ | 60.61 GPa | 54.05 GPa | 65.54 GPa |
| | $E_2$ | 60.61 GPa | 54.05 GPa | 65.54 GPa |
| | $E_3$ | 48.31 GPa | 48.31 GPa | 72.43 GPa |
| | $v_{12}$ | 0.289 | 0.41 | 0.33 |
| | $v_{13}$ | 0.512 | 0.41 | 0.35 |
| | $v_{23}$ | 0.512 | 0.41 | 0.32 |
| | $G_{12}$ | 23.5 GPa | 19.14 GPa | 29.65 GPa |
| | $G_{13}$ | 23.0 GPa | 19.48 GPa | 30.47 GPa |
| | $G_{23}$ | 23.0 GPa | 19.48 GPa | 30.47 GPa |
| Piezoelectric Coupling Matrix (strain coefficients) | $d_{15,26}$ | $741x10^{-12}$ | $584x10^{-12}$ | $151x10^{-12}$ |
| | $d_{31,32}$ | $-274x10^{-12}$ | $-171x10^{-12}$ | $-521x10^{-12}$ |
| | $d_{33}$ | $593x10^{-12}$ | $374x10^{-12}$ | $127x10^{-12}$ |
| Dielectric Matrix | $\varepsilon_{11,22}$ | $1.505x10^{-8}$ | $1.72x10^{-8}$ | $6.85x10^{-8}$ |
| | $\varepsilon_{33}$ | $1.301x10^{-8}$ | $1.72x10^{-8}$ | $5.87x10^{-8}$ |
| Density ($Kg/m^3$) | $\rho$ | 7500 | 7750 | 7500 |

### 3.6 Meshing of FE Model

After conducting thorough mesh research, we determined that most suitable meshing elements for covers and piezoelectric disks were C3D8 having a size of 2 cm and C3D8E having a size of 0.25 cm, respectively.

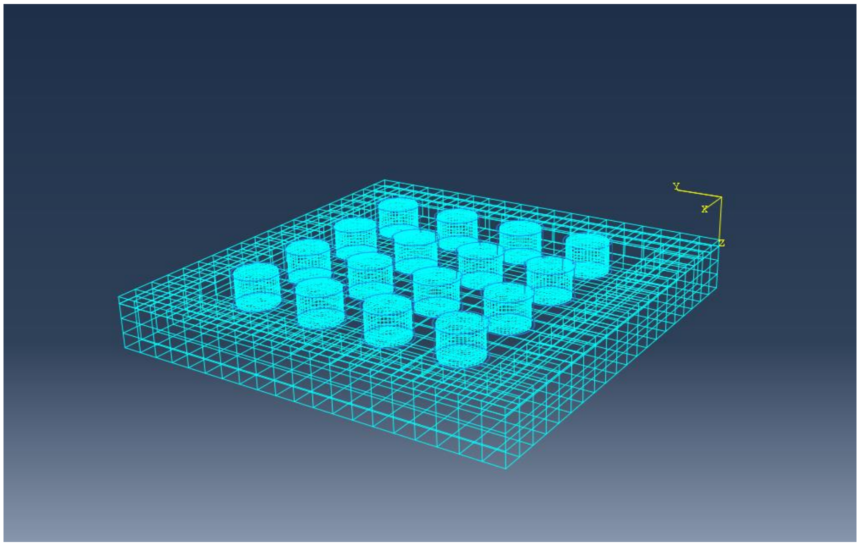


**Figure 18. Mesh of complete PEH in ABAQUS.**

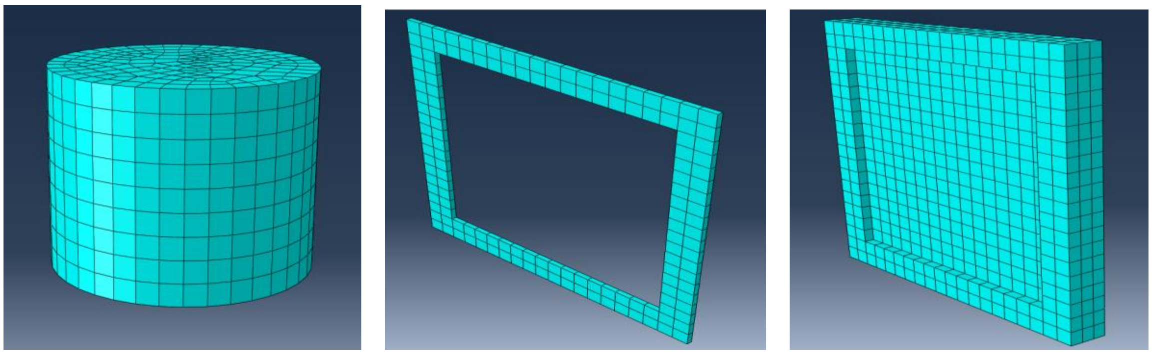


**Figure 19. Mesh of Piezoelectric harvester (left), Rubber seal (middle), MC Nylon casing (right).**

## 3.7 Loading Conditions

### *3.7.1 Amplitude*

A load of 0.7 MPa was applied at a frequency of 20 Hz for the simulation. The loading was applied sinusoidally as show by the graph.

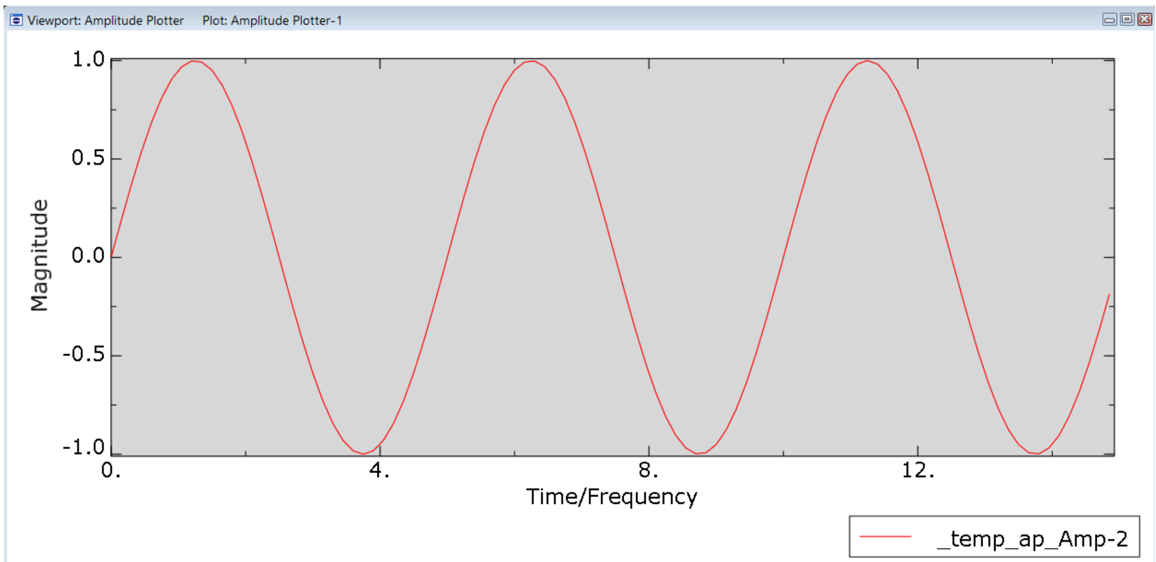



**Figure 20. Graph of amplitude of Loading for simulation.**

### *3.7.2 Load*

The constant pressure was exerted on the top surface of the device. To account for various loading conditions similar to traffic caused by vehicles in motion, Figure 8 demonstrates three modes of pressure loadings, including the complete loading, half loading, and one-fourth loading.

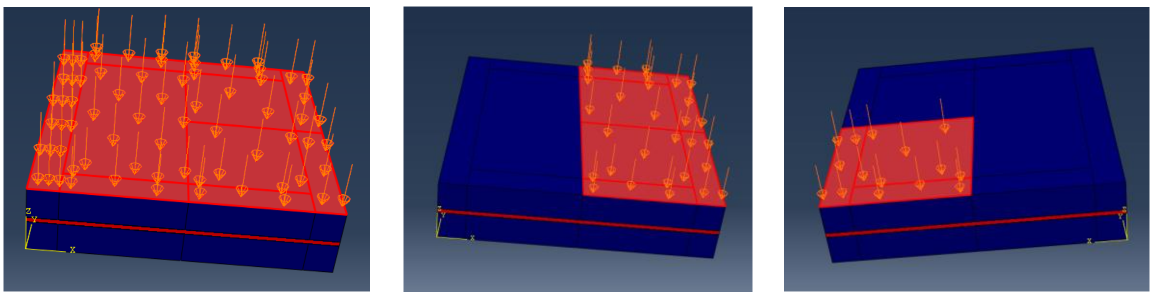


**Figure 21. Complete Loading (left), Half Loading (middle), One-Fourth Loading (right).**

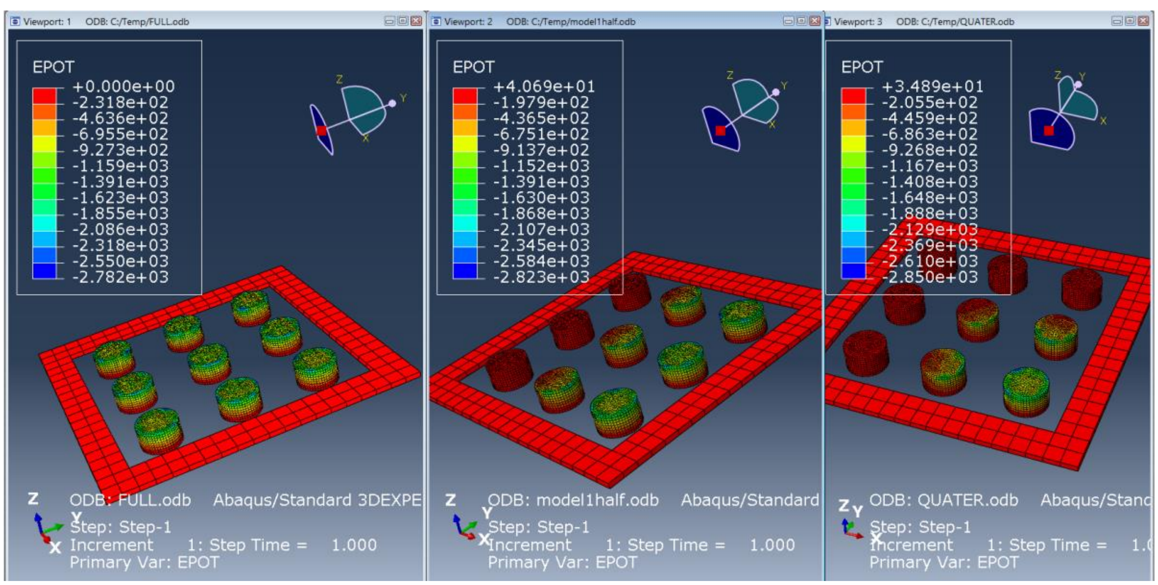



**Figure 22. Electric Potentials are obtained through three different loading conditions. Full (left), Half (middle), Quarter (right).**

### *3.7.3 Boundary Conditions*

To replicate similar loading conditions in pavements containing PEH , the sides and base of the device were constrained in both horizontal and vertical directions, respectively.

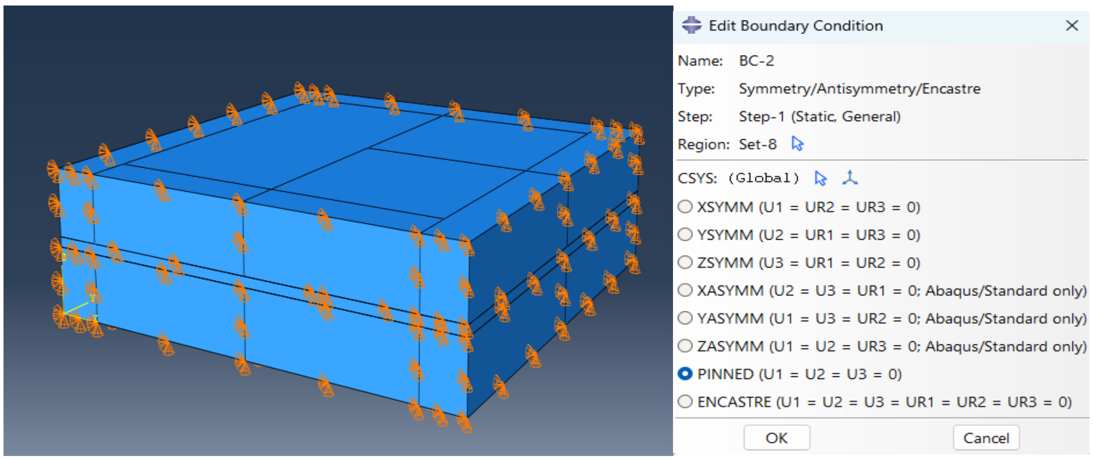



**Figure 23. Restraints on bottom and sides (pinned).**

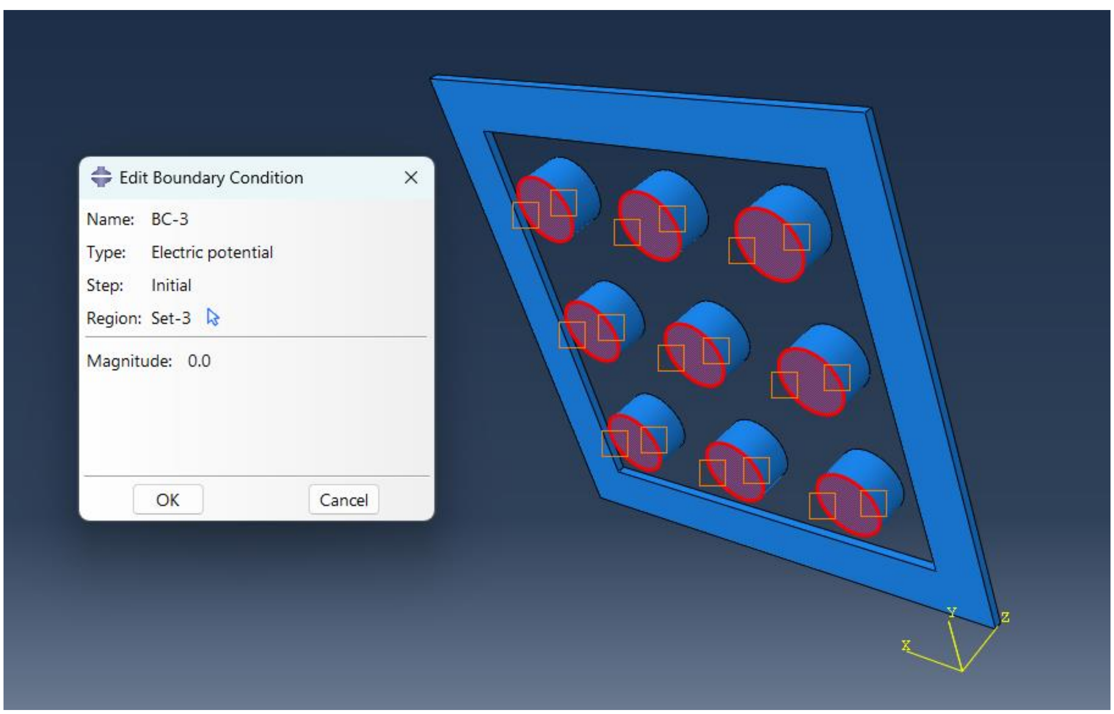



**Figure 24. Setting Boundary conditions in ABAQUS software.**

### *3.7.4 Comparison of Different Shapes*

In order to determine the optimal cross-section and ensure a better comparison, a fixed volume of 6430 mm3 was chosen for each piezoelectric disk. To assess the impact of the PZT disk's cross-section on the working of the piezoelectric devices, including electric potential and stress, four different cross-sections were examined: circular, hexagonal, pentagonal, and square, as depicted in Figure 24. A load of 0.5 MPa was applied on each of the four cross-sections.

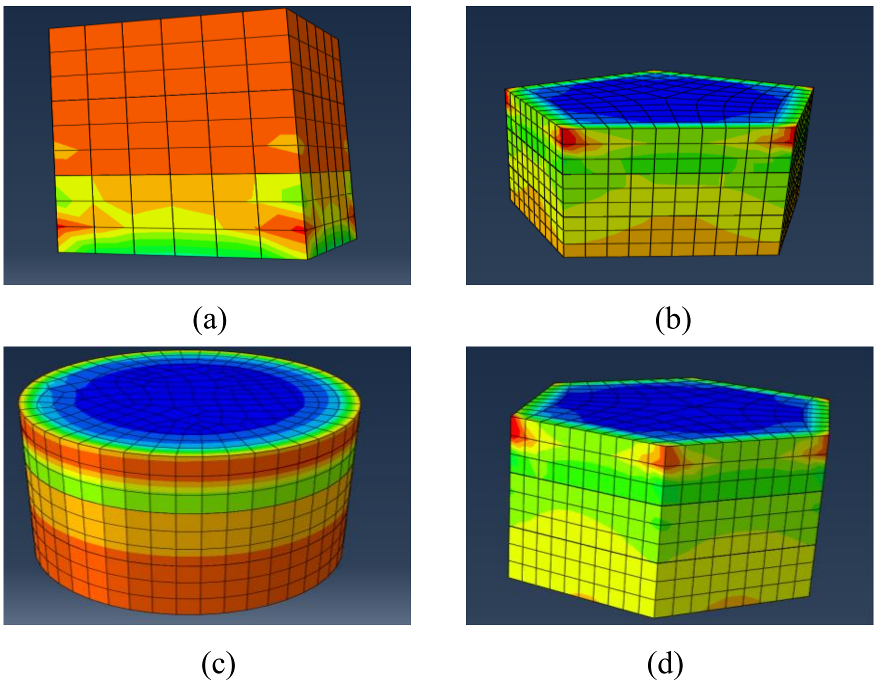
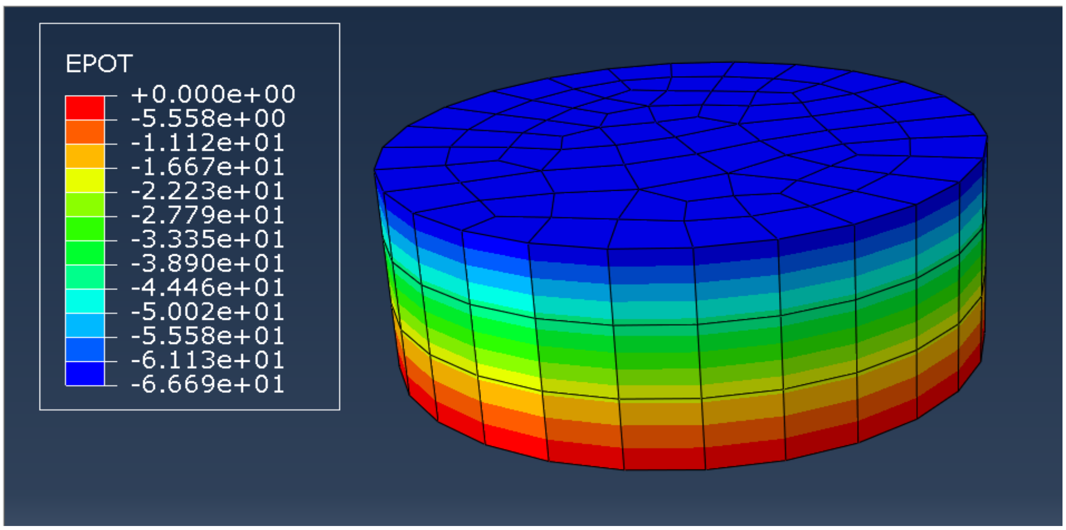


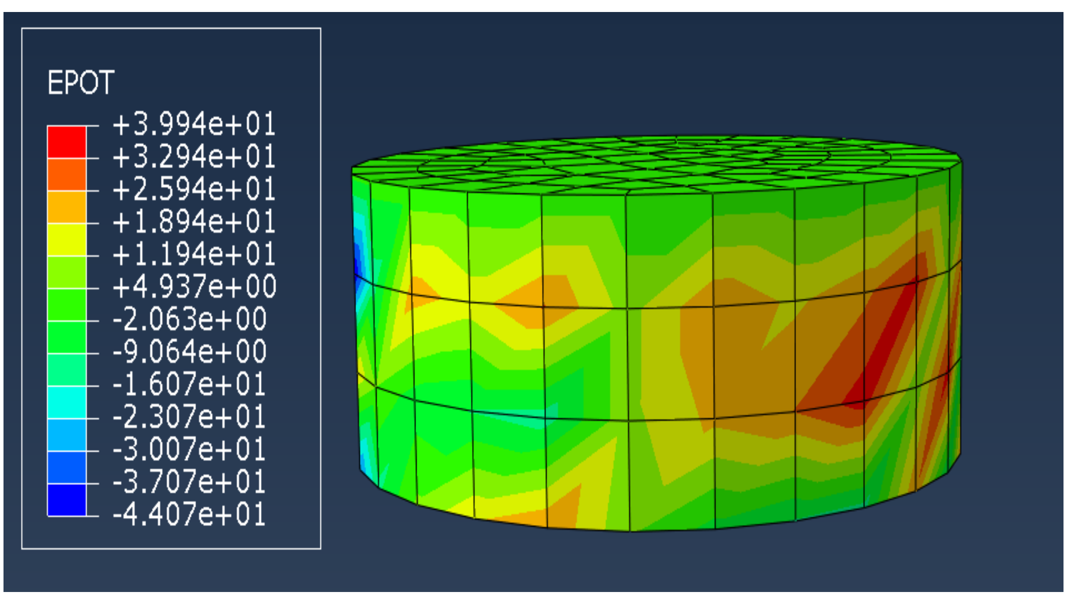

**Figure 25. Sections used for PZT disks; (a) Square, (b) Pentagon, (c) Circular, (d) Octagonal.**

### *3.7.5 Comparison of Different Materials*

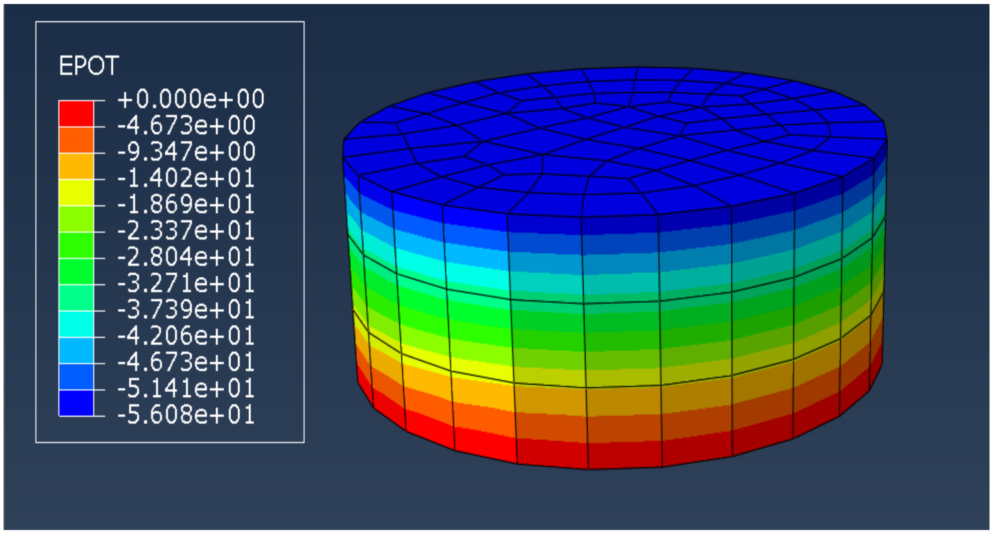
To understand the implication of the type of materials on the capability of energy harvesting of a PEH. Three different materials PZT-5A, PZT 5-H, PZT-4 were used. Other parameters and loading conditions remained consistent. The diameter of all disks was kept at 2 cm with a thickness of 0.75 cm.




(a)



(b)




(c)

**Figure 26. Electric Potential of (a) PZT-5H, (b) PZT-4, (c) PZT-5A.**

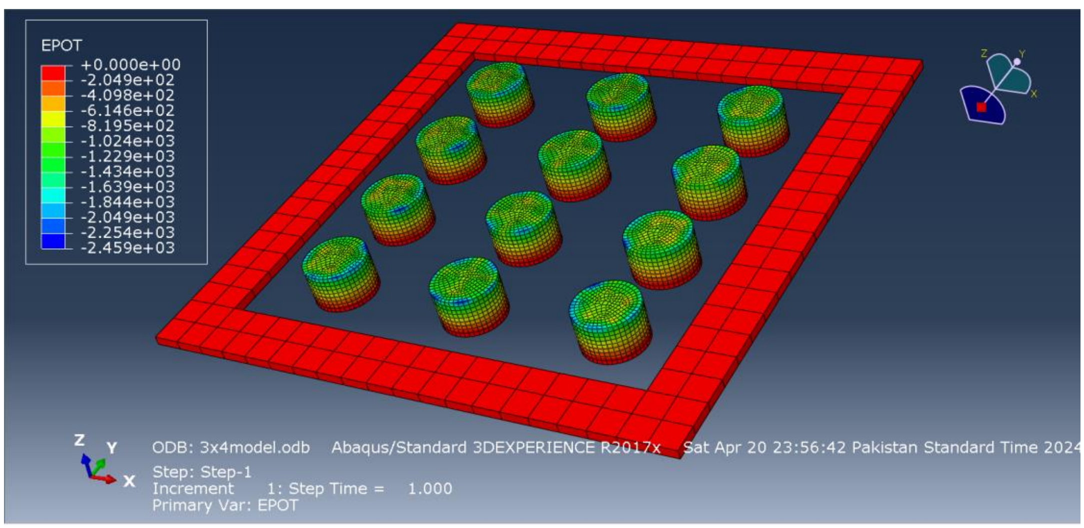
### 3.8 Summary

This chapter describe the detailed methodology that was adopted to create the different models to perform finite element analysis. The model's accuracy was verified by comparing the results obtained from the software with data collected from previous field experiments. The details of material properties are discussed because they play a vital role in FEM analysis. The details regarding preparation of assembly and meshing of FEM models are also provided.

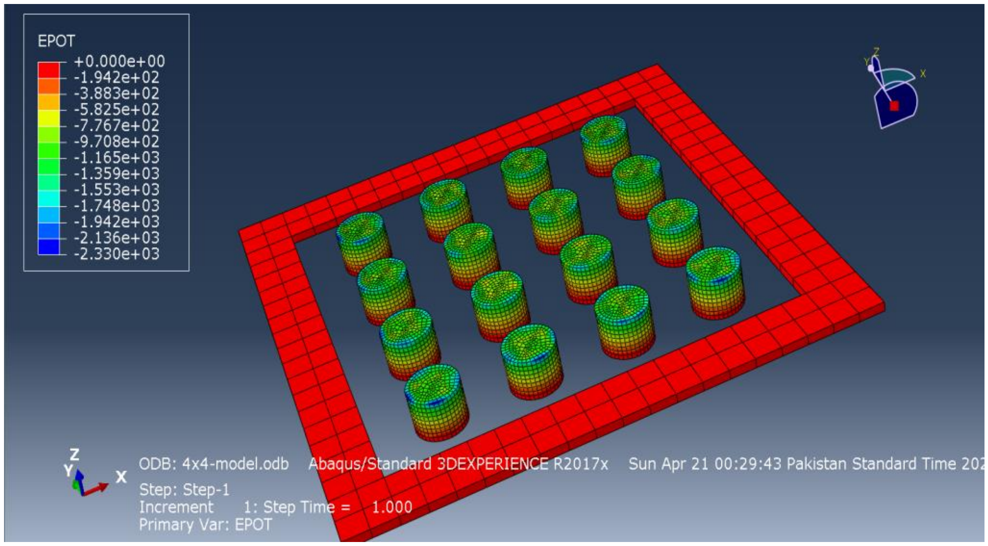
# CHAPTER 4: RESULTS

## 4.1 Comparison of Electric Potentials

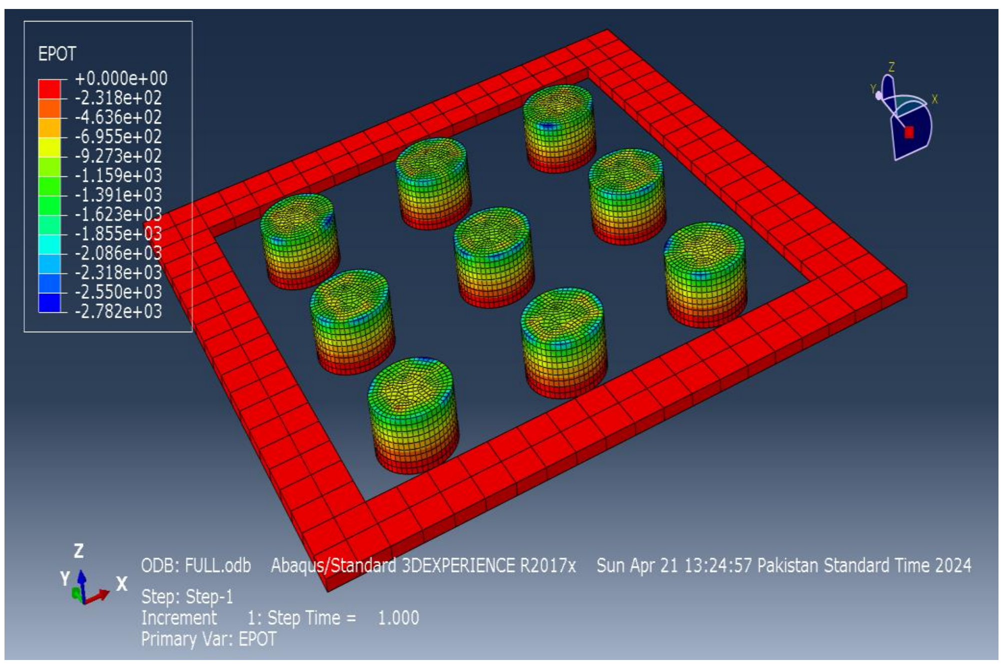
Figure 28 shows different electric Potentials as found in ABAQUS interface. The models with smaller dimensions were tested under all loading conditions.it goes to show that the electric potential is undergoing non-uniform distribution in the different PEHs. The electric potential of piezoelectrics which were near the edges was higher than those in the center. The reason for this is that the stresses concentrate at the edges of the PEHs. To conclude the current design method shows that there will be a large variation in the electric potential between different PEHs, specifically under non-uniform loading conditions.




(a)




(b)




(c)

**Figure 27. Different Electric Potentials**

The table below shows different electric potentials of different PEHs used to determine the efficiency. We see that the PEH with a distribution of 4x4 has largest electric potential. The results clearly show that the amount of electric potential is directly proportional to number of PZT disks installed in the PEH.

**Table 3. Electric Potential Difference in PEHs**

| Piezoelectric Unit | Loading Mode | Maximum Electric Potential (V) | Minimum Electric Potential (V) | Difference (V) |
|---|---|---|---|---|
| 3x3<br>Diameter = 2cm | Complete Loading | 1738 | 579 | 1159 |
| | Half Loading | 1787 | 286 | 1501 |
| | One-Fourth Loading | 1831 | 134 | 1697 |
| 3x3<br>Diameter = 2.31cm | Complete Loading | 1487 | 421 | 1066 |
| | Half Loading | 1528 | 206 | 1322 |
| | One-Fourth Loading | 1562 | 99 | 1463 |
| 3x4<br>Diameter = 1.73cm | Complete Loading | 2028 | 1217 | 811 |
| | Half Loading (x-direction) | 2118 | 185 | 1933 |
| | Half Loading (y-direction) | 2089 | 588 | 1501 |
| | One-Fourth Loading | 2110 | 76 | 2034 |
| 3x4<br>Diameter = 2cm | Complete Loading | 1499 | 986 | 513 |
| | Half Loading (x-direction) | 1653 | 140 | 1513 |
| | Half Loading (y-direction) | 1629 | 478 | 1150 |
| | One-Fourth Loading | 1667 | 74 | 1593 |
| 4x4<br>Diameter = 1.5cm | Complete Loading | 2243 | 1219 | 1024 |
| | Half Loading | 2308 | 188 | 2120 |
| | One-Fourth Loading | 2346 | 20 | 2326 |
| 4x4<br>Diameter = 1.71cm | Complete Loading | 1869 | 970 | 899 |
| | Half Loading | 1914 | 129 | 1785 |
| | One-Fourth Loading | 1944 | 21 | 1923 |

### 4.2 Comparison of Piezoelectric Energy Produced

To calculate the energy output, we can use the following equation.

$$E_i = \frac{1}{2}\frac{d_z^2 \sigma z^2 A_i h}{\varepsilon} \quad \textbf{(Eq 7)}$$

Here, $\mathbf{d_z}$ is the coefficient of piezoelectricity in the z-axis, **σz** corresponds to the stresses in the vertical direction, **ε** is the dielectric constant, **Ai** and **h** represent the cross-sectional area and thickness of i-th PZT disk, $m^2$ and m, respectively.

To quantify the energy harvested by piezoelectric energy harvesters Table 4 exhibits the total electrical energy produced under the three different loading conditions.

It can be observed that smaller size results in higher electrical energy output and vice versa. Total amount of energy productions is directly proportional to loading conditions. The total energy production along x and y axes remained same. Thus, it concludes that direction of load does not affect the energy outputs. Even with same cross-sectional area, changing the orientation and composition of the devices showed that the results varied extensively.

The difference in the energy output is shown in the tables. Even as the cross-section of a piezoelectric remained the same, the stress condition on the units varies due to various distributions and hence the energy outputs vary. As Table on the next page shows.

**Table 4. Energy outputs of different PEHS.**

| Piezoelectric Units | Loading Modes | Total Energy(J) |
|---|---|---|
| 3x3 Diameter = 2cm | Complete Loading | 2.02 |
| | Half Loading | 1.17 |
| | One-Fourth Loading | 0.7 |
| 3x3 Diameter = 2.31cm | Complete Loading | 2.14 |
| | Half Loading | 1.21 |
| | One-Fourth Loading | 0.72 |
| 3x4 | Complete Loading | 2.63 |
| | Half Loading (x-direction) | 1.43 |
| Diameter = 1.73 cm | Half Loading (y-direction) | 1.43 |
| | One-Fourth Loading | 0.74 |
| 3x4 | Complete Loading | 3.89 |
| | Half Loading (x-direction) | 1.74 |
| Diameter = 2cm | Half Loading (y-direction) | 1.74 |
| | One-Fourth Loading | 1.14 |
| 4x4 | Complete Loading | 3.47 |
| Diameter = 1.5 cm | Half Loading | 1.79 |
| | One-Fourth Loading | 1.1 |
| 4x4 | Complete Loading | 4.63 |
| Diameter = 1.71cm | Half Loading | 2.36 |
| | One-Fourth Loading | 1.12 |

## `4.3 Comparison of Von Mises Stresses

In engineering practices, it is highly desirable that the piezoelectric units mechanical respond should correspond to prevent or reduce damages. To show this tables 4 and 5 provide the Maximum and Minimum Von Mises stresses respectively. Both tables include piezoelectric with larger and smaller dimensions.

Maximum stresses exist near the edges of PEH with 3x3 units having maximum stress. Whereas the 3x4 units have slightly lesser stresses. This is the result of the way piezoelectrics were arranged in the PEH. The piezoelectric were closer to the edges in 4x4 distribution as compared to a 3x4 distribution hence the higher stresses in the 4x4 distribution. To conclude Von Mises stresses can be reduced by increasing the cross-sectional area.

**Table 5. Von Mises Stresses in PEH (28.37 $cm^2$).**

| Distribution | Diameter (cm) | Von Mises Stresses (MPa) | | |
|---|---|---|---|---|
| | | Complete Loading | Half Loading | One-Fourth Loading |
| 3x3 | 2 | 295 | 288 | 260 |
| 3x4 | 1.73 | 158 | 136 (x-direction)<br>133 (y-direction) | 134 |
| 4x4 | 1.5 | 175 | 173 | 173 |

**Table 6. Von Mises Stresses in PEH (37.7 $cm^2$).**

| Distribution | Diameter (cm) | Von Mises Stresses (MPa) | | |
|---|---|---|---|---|
| | | Complete Loading | Half Loading | One-Fourth Loading |
| 3x3 | 2.31 | 212 | 211 | 150 |
| 3x4 | 2 | 126 | 137 (x-direction)<br>124 (y-direction) | 113 |
| 4x4 | 1.73 | 125 | 173 | 119 |

### 4.4 Comparison of Different Cross-sections

Electric Potential and Von Mises stresses for different cross-sections were calculated by simulation in ABAQUS software. The results obtained from using three different cross-sections are tabulated in the Table.

**Table 7. Results obtained from different cross-sections.**

| Cross-section | Maximum Electric Potential (V) | Von Mises Stresses |
|---|---|---|
| Circular | 1.437 | $33.81 \times 10^5$ |
| Square | 1.483 | $34.05 \times 10^5$ |
| Hexagonal | 1.437 | $36.70 \times 10^5$ |
| Pentagonal | 1.44 | $36.22 \times 10^5$ |

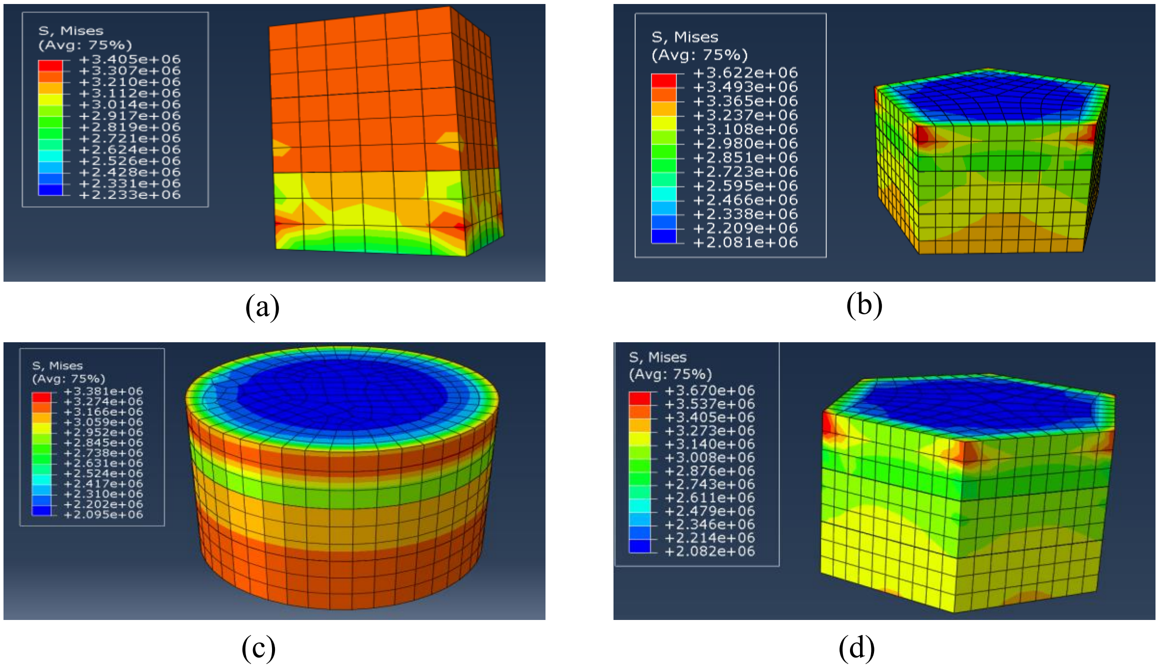



**Figure 28. Stresses in simulation (a) rectangular, (b) pentagonal, (c) circular, (d), rectangular.**

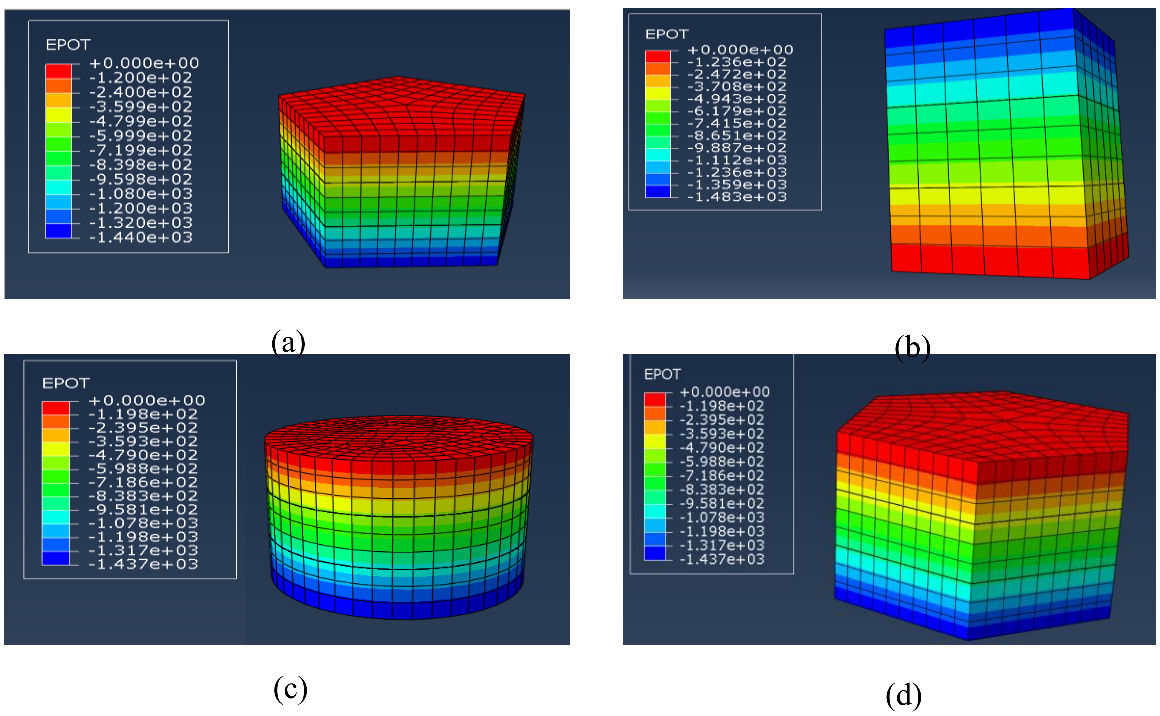



**Figure 29. Electric potentials in simulation (a) rectangular, (b) pentagonal, (c) circular, (d), rectangular.**

According to the simulation performed all the shapes almost showed equal electric potential thus we can conclude that different cross-sections play very minute role in generation of electric potential. However, the same cannot be said for the stresses produced in different shapes as the stresses on the edges were much higher than at center. Thus, the circular shape which had the least edges had the least stress hence being able to bear more load. Which means that there is less chance of failure through cracking.

### 4.5 Comparison of Different Materials

Different materials were tested in the simulation to check the effect of different piezoelectric materials as to how they affect the Electric potential of the PEH. The results were tabulated in Table.

**Table 8. Maximum Electric Potential of different piezoelectric materials**

| Material | Maximum Electric Potential (V) |
|---|---|
| PZT-5H | 66.69 |
| PZT-5A | 56.08 |
| PZT-4 | 44.07 |

.

Material producing highest potential is the most effective. As PZT-5H produces significantly greater Electric potential as compared to the other piezoelectric materials. It proves to be the most effective.

### 4.6 Evaluation of the Piezoelectric Effect

The piezoelectric effect was evaluated with the help of a radar chart, which was based on the outputs obtained under complete loading conditions. Which are as follows:

1. Electrical Energy
2. Electric Potential
3. Potential Difference
4. Von Mises Stresses

According to previous research, there is a requirement for increased electrical energy and potential for harvesting energy from piezoelectrics. Also, greater Von Mises stresses and potential difference can increase the damage incurred on the piezoelectric decreasing its overall efficiency. Also, the PEHs with greater number of piezoelectrics installed produced best results.

The PEHs with larger dimensions experienced higher stresses and potential differences as in the case of 4x4 distribution as compared to the PEH with 3x4 distribution. Among the six distributions the PEH with 3x4 distribution was the best.

### 4.7 Radar Chart

The purpose of a Radar Chart is to display multiple variables in two dimensions. It consists of multiple spokes, each representing a different variable and the length of each spoke is proportional to its magnitude.

The purpose of a radar chart is to provide a visual representation of the performance or characteristics of multiple variables relative to a central point or axis. It allows for easy comparison of different data points across multiple variables immediately. Radar charts are commonly used in various fields such as business, sports, engineering, and data analysis to analyze and communicate complex data patterns, trends, and relationships.

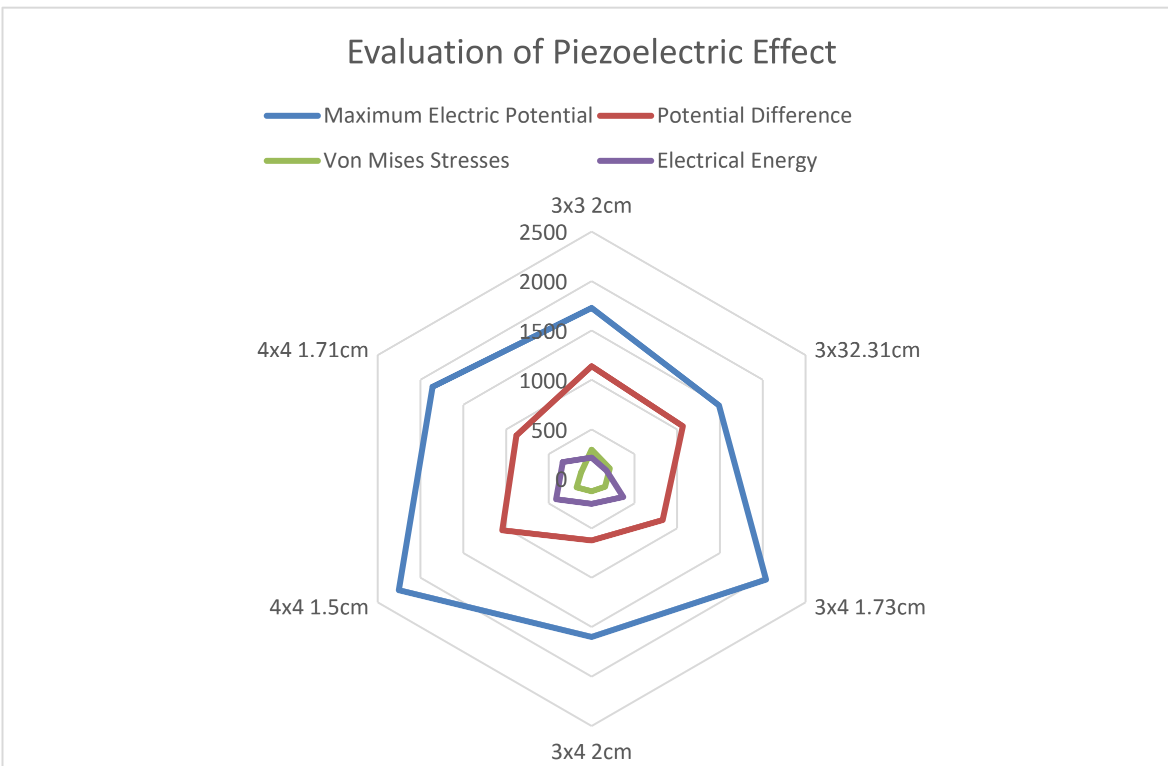



**Figure 30. Outputs of different PEHs plotted on a Radar Chart.**

## 4.8 Summary of the Results

### *4.8.1 Comparison of Electric Potential*

The PEH unit with a 4x4 distributions produced the highest electric potential. Whereas the PEH with a 3x4 distribution gained equilibrium between its ability to produce electricity and counter/undergo stresses and deformations. All facts mentioned in **Table 3.**

### *4.8.2 Comparison of Piezoelectric Energy Production*

As electric energy is produced as per the responses of piezoelectrics to the stresses applied. Hence, due to various stress distributions there is a variance in the amount of energy produced.

### *4.8.3 Comparison of Von Mises Stresses*

The Von Mises Stresses account for both normal and shear stresses in a material combining them into a single scalar value. The calculated stresses are listed in **Table 5** and **Table 6**. According to the calculations the highest Von Misses stresses occur in 3x3 distribution due to less piezoelectric units. However, the piezoelectric units with 3x4 distribution showed lessee values than with 4x4 distributions which is because 4x4 distribution piezoelectrics were closer to the edge than 3x4 distribution which resulted in 4x4 distribution having higher stresses. To conclude a piezoelectric with bigger dimensions in terms of its area of the cross-section, undergoes lower stresses.

### *4.8.4 Comparison of Different Cross-sections*

The simulation results indicated that various shapes exhibited nearly identical electric potential, suggesting that the cross-sectional differences had minimal impact on potential generation. However, the distribution of stresses varied significantly among the shapes, with higher stress concentrations observed at the edges compared to the centre. Consequently, the circular shape, possessing fewer edges, experienced lower stress levels, indicating a greater ability to withstand external loads. This implies a reduced risk of failure due to cracking in structures with circular cross-sections.

### *4.8.5 Comparison of Different Materials*

The findings highlight that the effectiveness of piezoelectric materials in generating electric potential varies, with PZT-5H emerging as notably superior compared to other materials. Its ability to produce significantly higher electric potential underscores its effectiveness and potential suitability for various applications. These results emphasize the importance of material selection in optimizing the performance of piezoelectric systems, with PZT-5H demonstrating considerable promise in this regard.

### *4.8.6 Evaluation of Piezoelectric Effect*

All of the tested parameters were considered together in order to determine the Piezoelectric Effect. It was seen that greater number of piezoelectrics produced higher electric output while reducing the potential difference and stresses.

Among the six different PEH configurations that were tested the 3x4 distribution with a cross-sectional area of 28.37 $cm^2$ achieved an overall balance between energy harvesting and stress distribution which was deduced with the help of the Radar Chart.

# CHAPTER 5: CONCLUSION AND RECOMMENDATIONS

## 5.1 Conclusion

A finite element model is constructed to design a PEH. The numerical analysis findings were confirmed by comparing them with experimental results documented in existing literature. The current design methodology presupposes a constant area of piezoelectric material. To further investigate, a parametric analysis was conducted, exploring input variables such as the shape of the piezoelectric disk (circular, square, hexagonal, and pentagonal) and the type of piezoelectric material. And a PEH model was created with various configurations of piezoelectric units (3 × 3, 3 × 4, and 4 × 4). Additionally, unlike cross-sectional areas of the piezoelectric devices were taken into account to mimic the boundary and loading conditions of PE devices in pavements. Three loading modes (complete, half, and one-fourth loading modes) were applied to the PEH models for simulation purposes.

1. The significant amount of electric potential was generated which clearly states that piezoelectrics have sufficient energy harvesting capabilities.
2. The 3×4 distribution, characterized by less cross-sectional area of the piezoelectric disks, demonstrates a more favorable equilibrium between electrical potential and stress concentration.
3. Comparing the prototype with a single PZT disk but different materials. PZT-5H exhibited the maximum induced stresses and electric potential values, at the same time the PZT-4 displayed the less values.
4. Changing the disk cross-section does not have a significant impact on the prototype's electric potential. Between the cross-sections examined, the circular shape proves to be better in generation of stress and output power.
5. When maintaining similar volume of piezoelectric disks, prototypes with higher number of piezoelectric disks tend to exhibit good performance due to the increased non-uniformity of stress distribution.
6. The highest electric potential is observed near the edges of the PEHs, while the lowest potential is found at the center of the PEH units

## 5.2 Recommendations

1. Further research could be extended by simulating the best-found model in a pavement to analyze the behavior of this pavement compared to an ordinary pavement.
2. Field implementation of proposed concept is required to check its efficiency and durability to calibrate it to suitable requirements.
3. Advanced modelling techniques can be explored by incorporating multi-physics phenomena such as temperature and pavement deterioration.

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By

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GC Hamza Jawad (Registration No:00000358956)

SGT Ali Bin Shahid (Registration No:00000358961)

GC Alamzaib (Registration No:00000358948)

Bachelor of Engineering in

Military College Of Engineering, Risalpur

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