STM JOURNALS

Journal of
Polymer & Composites

ISSN: 2321-2810 (Online)
ISSN: 2321-8525 (Print)
Volume 13, Special Issue 1, 2025
DOI (Journal): 10.37591/JoPC

https://journals.stmjournals.com/jopc

Research JoPC

Structural Health Monitoring of Polypropylene Fiber-Reinforced Composite Using Accelerometer Sensors

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Abstract

This study explores the application of accelerometer sensors for structural health monitoring (SHM) in evaluating the performance of polypropylene fiber-reinforced composites (PFRC). Incorporating polypropylene fibers into concrete enhances its structural integrity and durability. However, accurately assessing PFRC behavior under various conditions is crucial for its practical application in construction. This research employs advanced accelerometer sensor technology for real-time monitoring and assessment of PFRC performance. Experimental investigations captured and analyzed the dynamic response and structural behavior of PFRC specimens subjected to loading conditions of 200 kN, 400 kN, 600 kN, 800 kN, and 1000 kN. Accelerometer sensors, strategically placed on the surface of PFRC cubes, cylinders, and beam elements with 1% fiber content, provided precise data on vibration, deformation, and stress distribution, enabling a detailed evaluation of mechanical properties and durability. Frequency versus conductance graphs plotted from the accelerometer data offered valuable insights into the material's behavior, highlighting its mechanical properties and response characteristics under different stress levels. The findings contribute significantly to structural engineering and materials science, particularly in SHM and PFRC applications, supporting advancements in the design, construction, and maintenance of resilient infrastructure systems.

Keywords: Structural health monitoring, polypropylene fiber-reinforced composites, performance assessment, accelerometer sensors, structural behavior, material durability

INTRODUCTION

The structural integrity and durability of concrete are critical factors in ensuring the longevity and safety of infrastructure systems. Traditional concrete formulations have been enhanced through the addition of various materials, one of which is polypropylene fibers. These fibers, when incorporated into concrete matrices, have shown promising potential in improving its mechanical properties, particularly in terms of crack resistance and impact strength. However, the accurate assessment of the performance of polypropylene fiber-reinforced concrete (PFRC) under different loading conditions remains a challenge, necessitating advanced monitoring techniques such as structural health monitoring (SHM) for comprehensive evaluation [1].

Overview

This paper presents a comprehensive study on the utilization of accelerometer sensors for SHM in the assessment of PFRC performance. Accelerometer sensors, known for their ability to measure acceleration forces, are strategically employed to monitor the dynamic response and structural behavior of PFRC specimens under varying loading conditions. By capturing data on vibration, deformation, and stress distribution, these sensors

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Received Date: May 13, 2024
Accepted Date: July 11, 2024
Published Date: December 07, 2024

Citation: B. Vamsi Krishna, T. Sreelatha, J. Selwyn Babu. Structural Health Monitoring of Polypropylene Fiber-Reinforced Composite Using Accelerometer Sensors. Journal of Polymer & Composites. 2025; 13(Special Issue 1): S621–S634p.

provide valuable insights into the mechanical properties and durability of PFRC, thereby facilitating informed decision-making in construction and infrastructure projects.

MATERIALS

Accelerometer Sensors

Accelerometer sensors, commonly used in various engineering applications, play a crucial role in this research. These sensors detect changes in acceleration forces and convert them into electrical signals, allowing for real-time monitoring of structural behavior [2]. The placement of accelerometer sensors on PFRC surfaces enables the collection of precise data on its response to external loads, contributing to a detailed understanding of its performance characteristics shown in Figure 1.

PFRC

PFRC, on the other hand, represents an innovative approach to concrete reinforcement. Polypropylene fibers, typically ranging in length from a few millimeters to several centimeters, are dispersed throughout the concrete matrix during mixing [3]. These fibers act as a reinforcement mechanism, effectively bridging micro-cracks and improving the tensile strength and toughness of the material. PFRC has garnered significant attention in recent years due to its potential to enhance the durability and longevity of concrete structures, making it an attractive option for various construction applications shown in Figure 2.

Research Hypothesis

The primary hypothesis driving this research is that the integration of accelerometer sensors for SHM can facilitate the accurate assessment of PFRC performance under different loading conditions.

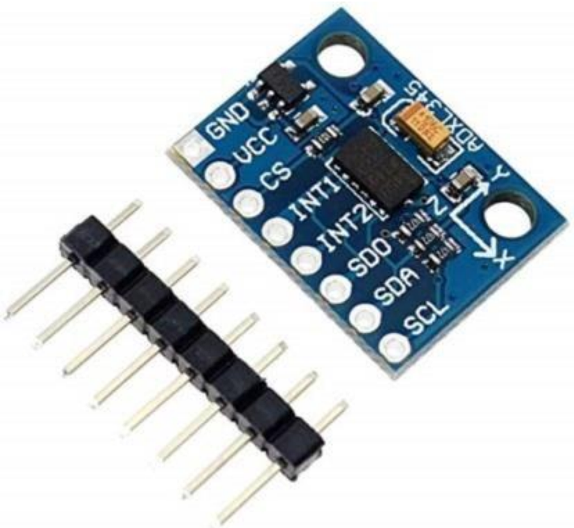

Figure1. Accelerometer sensors.

Figure2. Polypropylene fiber.

It is posited that the data obtained from these sensors will provide valuable insights into the dynamic

ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

response and structural behavior of PFRC, allowing for a comprehensive evaluation of its mechanical properties and durability.

Research Gap

While PFRC holds promise as a viable alternative to traditional concrete, there exists a notable research gap concerning the comprehensive evaluation of its performance under varying loading conditions. Existing studies often focus on specific aspects of PFRC behavior, overlooking the need for a holistic assessment that considers dynamic response, structural behavior, and mechanical properties. Additionally, limited research has been conducted on the application of SHM techniques, such as accelerometer sensors, in monitoring PFRC performance in real-time. Addressing this research gap is essential for advancing our understanding of PFRC and maximizing its potential in construction and infrastructure projects.

Scope

The scope of this research encompasses experimental investigations aimed at evaluating PFRC performance using accelerometer sensors for SHM. The study focuses on capturing and analyzing the dynamic response and structural behavior of PFRC specimens subjected to various loading conditions. The experimental setup includes PFRC specimens with different fiber concentrations subjected to incremental loading, ranging from 200 kN to 1000 kN. Data collected from accelerometer sensors positioned on PFRC surfaces will be analyzed to assess vibration, deformation, and stress distribution, providing insights into mechanical properties and durability.

Objectives

The objectives of this research are as follows:

- To investigate the feasibility of utilizing accelerometer sensors for SHM in evaluating PFRC performance.
- To analyze the dynamic response and structural behavior of PFRC specimens under different loading conditions.
- To assess the mechanical properties and durability of PFRC based on data obtained from accelerometer sensors.
- To identify potential areas for improvement in PFRC design and formulation based on experimental findings.
- To contribute to the advancement of knowledge in the fields of structural engineering, material science, and SHM through the dissemination of research outcomes.

LITERATURE REVIEW

The literature on polypropylene fiber-reinforced concrete (PFRC) and structural health monitoring (SHM) provides valuable insights into the mechanical properties, performance valuation techniques, and monitoring methodologies employed in the field of concrete technology and structural engineering.

This literature review aims to synthesize key findings from existing research studies, identify trends, and highlight gaps that warrant further investigation.

Polypropylene Fiber-Reinforced Concrete (PFRC)

PFRC represents a significant advancement in concrete technology, offering improved mechanical properties and enhanced durability compared to traditional concrete formulations [4-5]. Polypropylene fibers, characterized by their high tensile strength and flexibility, are commonly used as reinforcement elements in PFRC. These fibers serve multiple functions within the concrete matrix, including crack mitigation, impact resistance, and ductility enhancement. Numerous studies have demonstrated the beneficial effects of polypropylene fibers on various aspects of concrete performance. For example, [6] [7] investigated the influence of polypropylene fiber content on the compressive strength and flexural behavior of PFRC specimens. Their Findings indicated that the addition of polypropylene fibers led to improvements in both compressive strength and flexural performance, with optimal fiber contents resulting in enhanced mechanical properties [8].

In addition to mechanical properties, the durability of PFRC has been a subject of considerable research interest. Durability concerns such as freeze-thaw resistance, chloride ion penetration, and sulfate attack have been investigated in the context of PFRC. For instance, [9] Conducted a study on the durability properties of PFRC containing different types of fibers, including polypropylene fibers. Their results revealed that PFRC with polypropylene fibers exhibited superior resistance to chloride ion penetration compared to plain concrete, highlighting the potential of fiber reinforcement in enhancing durability [10].[11-12] Despite the significant advancements in PFRC technology, challenges remain inaccurately assessing its performance under various loading conditions. Traditional testing methods, such as static load tests, may not capture the dynamic response of PFRC structures during service life. This underscores the importance of implementing advanced monitoring techniques, such as structural health monitoring (SHM), to ensure the long-term structural integrity and safety of PFRC structures.

Structural Health Monitoring (SHM)

[13] SHM Involves the continuous monitoring of structural parameters to detect and assess changes in structural behavior, integrity, and performance. This proactive approach to structural assessment enables early detection of potential issues, thereby facilitating timely intervention and maintenance activities. SHM techniques encompass a wide range of monitoring methodologies, including sensor-based systems, non-destructive testing techniques, and data analysis algorithms. Accelerometer [14]. Sensors are commonly used in SHM applications to measure structural vibrations and dynamic responses. These sensors detect changes in acceleration forces caused by structural deformations or external loads, providing valuable data for assessing structural health and performance. In the context of concrete structures, accelerometer sensors can be strategically placed on key structural elements to monitor the irresponse to various loading conditions, including static loads, dynamic loads, and environmental factors.[15-16] Several studies have demonstrated the effectiveness of accelerometer-based SHM systems in monitoring concrete structures. For example, [17] developed a wireless accelerometer-based SHM system for monitoring the structural health of concrete bridges. Their system utilized wireless sensor nodes equipped with accelerometers to collect vibration data from bridge components, enabling real-time monitoring of structural behavior and performance.

Integration of SHM with PFRC

The integration of SHM techniques with PFRC presents a promising approach to enhancing the performance evaluation and maintenance of PFRC structures. By deploying accelerometer sensors on PFRC elements, engineers can monitor the dynamic response of structures in real time, [18] allowing for early detection of potential issues such as excessive deformation, cracking, or degradation [19]. However, the application of SHM techniques to PFRC poses certain challenges that warrant further investigation. One such challenge is the selection and placement of accelerometer sensors to ensure optimal monitoring coverage and data accuracy. Additionally, the interpretation of accelerometer data collected from PFRC structures Requires advanced signal processing and analysis techniques to extract meaningful information regarding structural health and performance [20-21].

Research Gaps and Future Directions

Despite the growing body of research on PFRC and SHM, several gaps and opportunities for further investigation exist. One notable research gap is the limited availability of studies focusing specifically on the integration of SHM techniques with PFRC. While individual studies have explored aspects of PFRC performance and SHM separately, comprehensive research on their combined application is scarce [22].

Future research endeavors should aim to address these gaps by conducting experimental investigations into the integration of SHM techniques with PFRC. This includes the development of sensor-based monitoring systems tailored to the unique properties and behaviors of PFRC structures. Additionally, research efforts should focus on advancing data analysis methodologies to effectively

Journal of Polymer & Composites
Volume 13, Special Issue 1
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

interpret accelerometer data collected from PFRC elements [23].

In conclusion, the literature review highlights the significant advancements in PFRC technology and SHM techniques, as well as the potential benefits of integrating SHM with PFRC for enhanced performance evaluation and maintenance. Moving forward, interdisciplinary research efforts are needed to bridge the gap between PFRC technology and SHM methodologies, ultimately contributing to the development of resilient and sustainable infrastructure systems [24].

METHODOLOGY

The methodology section outlines the experimental approach adopted to investigate the utilization of accelerometer sensors for structural health monitoring (SHM) in evaluating polypropylene fiber-reinforced concrete (PFRC) performance. The methodology encompasses specimen preparation, experimental setup, data collection, and analysis procedure shown in Figure 3.

PROCEDURE OF STRUCTURAL HEALTH MONITORING

Specimen Preparation

PFRC specimens are prepared in accordance with relevant standards and guidelines to ensure consistency and reproducibility. The concrete mix design incorporates polypropylene fibers at a specified dosage, typically ranging from 0.5% to 2% by volume of concrete. The mixing process ensures uniform dispersion of fibers throughout the concrete matrix to enhance mechanical properties and durability. Casting molds are prepared to fabricate PFRC specimens in various geometries, including cubes, cylinders, and beams, to simulate different structural elements. The dimensions of the specimens are determined based on experimental requirements and testing standards. Care is taken to eliminate air voids and ensure proper compaction during casting to achieve homogeneous concrete specimens [25].

Experimental Investigation

The experimental setup comprises a testing apparatus equipped with loading devices, accelerometer sensors, and data acquisition systems. PFRC specimens are subjected to incremental loading conditions ranging from 200 kN to 1000 kN to simulate varying stress levels experienced in real-world applications. Loading is applied statically or dynamically, depending on the experimental objectives and testing protocols. Accelerometer sensors are strategically placed on the surfaces of PFRC specimens to capture dynamic responses and structural vibrations [26]. The placement locations are determined based on structural considerations and sensor capabilities to ensure comprehensive monitoring coverage. Sensor calibration procedures are performed to validate accuracy and reliability prior to experimentation shown in Figure 4(a) & 4(b).

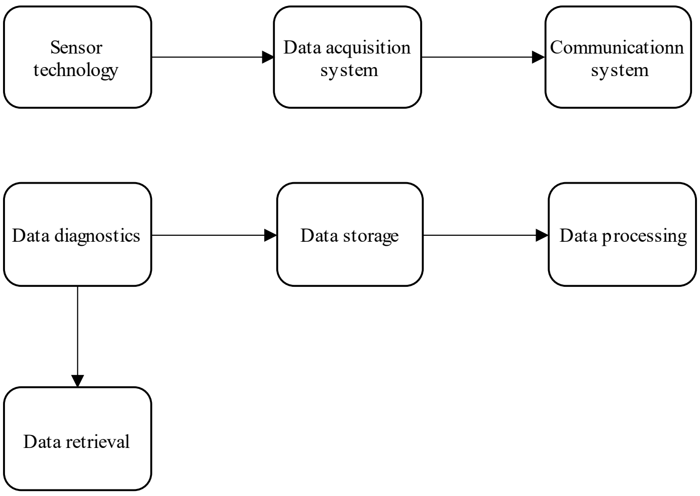

Figure3. Flow chart for SHM procedure.

Cube Setup

a. Conventional concrete cube specimen's images after1000KNloading
b. Polypropylene FRC cube specimen's images after1000KNloading

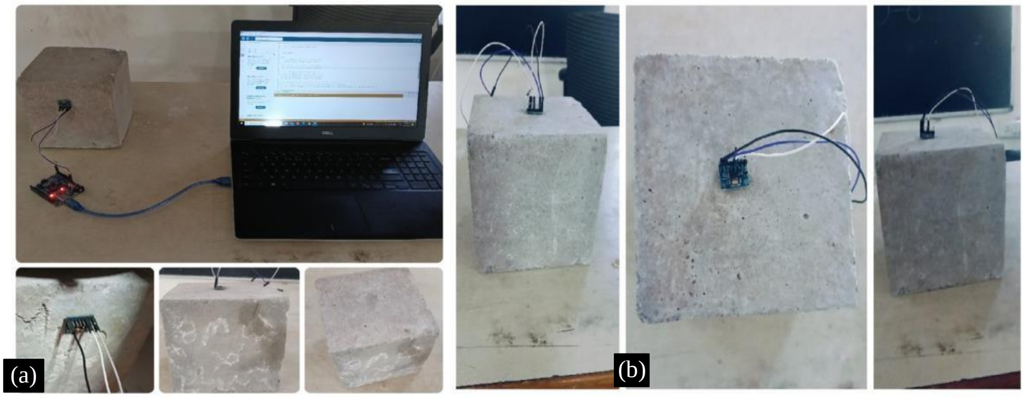

Figure. 4(a, b)

Cylinder Setup Figure 5(a) & 5(b).

a. Conventional concrete cube specimen's images after1000KNloading
b. Polypropylene FRC cube specimen's images after1000KNloading

Figure 5. (a, b)

Beam Set-up Figure 6(a) & 6(b)

a. Conventional concrete cube specimen's images after1000KNloading
b. Polypropylene FRC cube specimen's images after1000KNloading

Data Collection

Data collection involves the continuous monitoring of acceleration signals using accelerometer sensors throughout the duration of the experiments. Acceleration data are sampled at high frequencies to capture transient events and dynamic responses accurately. Simultaneously, load cells or force transducers measure applied loads to correlate structural behavior with external loading conditions Figure 7.

The three-point bending tests for the determination of the specimen flexural strength were conducted using a universal testing machine as per Code. The specimens were tested up to final failure by controlling the vertical displacement of the hydraulic jack with a rate of 2.2 mm/min. A general view of the experimental setup and the testing wiring diagram are presented in Figures 8, respectively.

Journal of Polymer & Composites
Volume 13, Special Issue 1
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

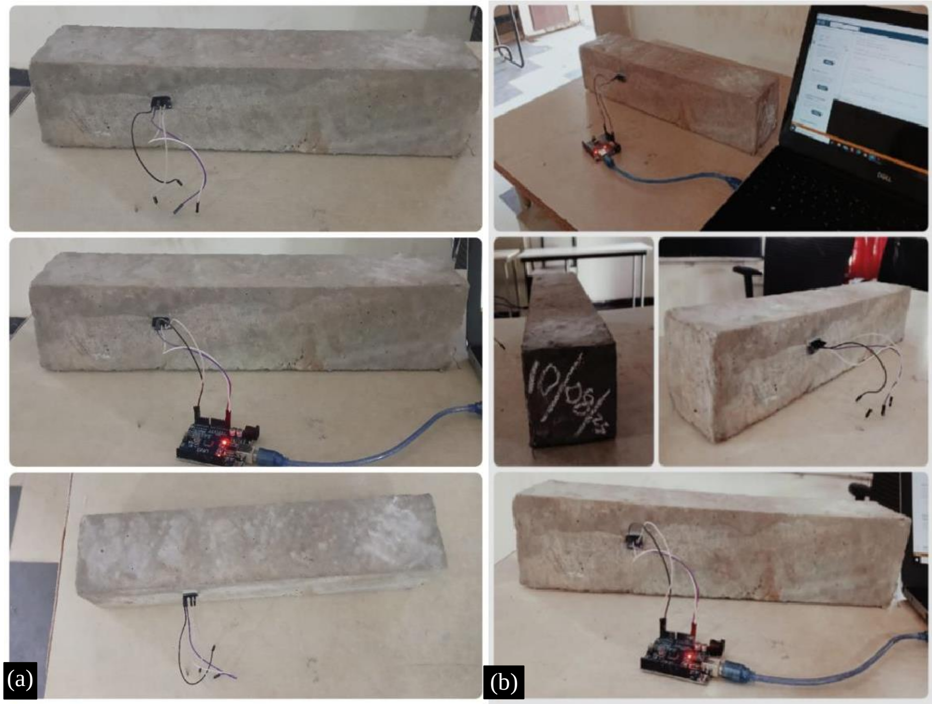

Figure. 6 (a, b)

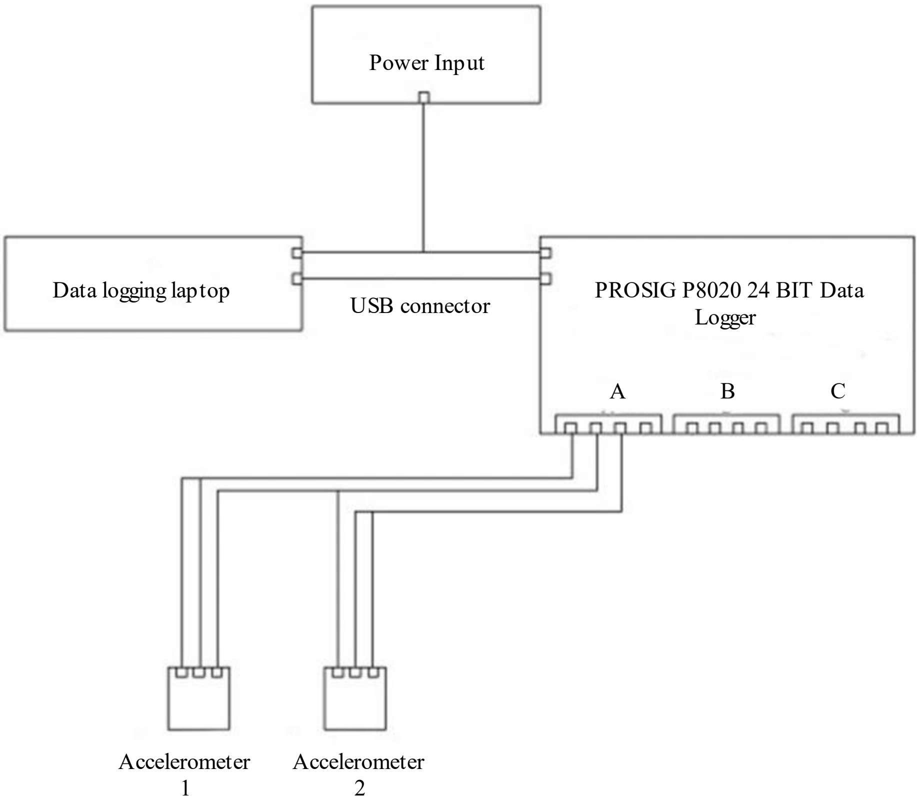

Figure 7. Testing wiring diagram.

Real time data acquisition systems record acceleration signals and applied loads synchronously, enabling the establishment of accurate load-acceleration response relationships. Data logging software facilitates the storage and analysis of collected data, ensuring completeness and integrity throughout the experimental process.

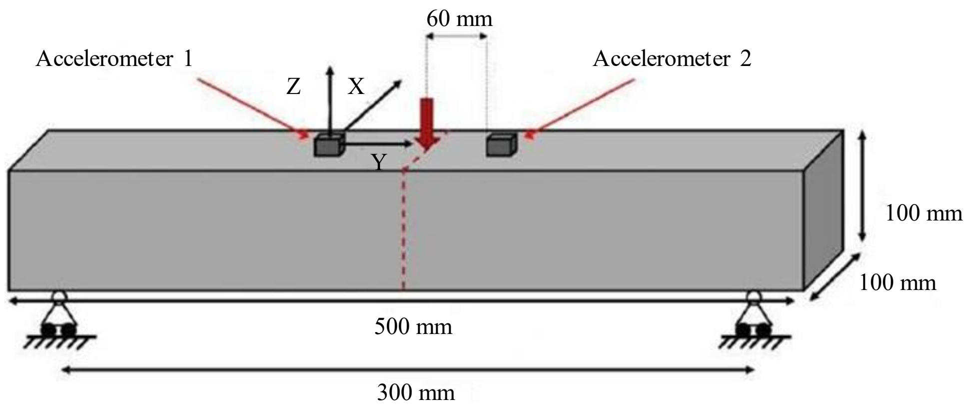

Figure 8. Experimental setup.

Data Analysis

Data analysis encompasses signal processing techniques, statistical analyses, and visualization methods to interpret accelerometer data and derive meaningful insights into PFRC performance. Time-domain and frequency- domain analyses are employed to characterize dynamic responses, identify vibration modes, and assess structural behavior under varying loading conditions.

Signal filtering algorithms remove noise and artifacts from accelerometer data to enhance signal clarity and reliability. Frequency spectrum analysis enables the identification of dominant frequencies associated with structural vibrations and resonant modes. Additionally, statistical analyses such as mean, standard deviation, and correlation coefficients quantify relationships between acceleration signals and applied loads. Graphical representations, including frequency-response curves, amplitude spectra, and stress-time histories, provide visual interpretations of accelerometer data and facilitate comparative analyses between different PFRC specimens and loading scenarios.

RESULTS AND DISCUSSIONS

Mechanical Behaviour of Plain Cement Concrete and PFRC Beams Figure3 shows two different plots obtained from the three-point bending tests of plain Cement Concrete and PFRC beams. Figure presents the force–time curves for the force measured by the loading cell at mid-span deflection, while Figure shows the displacement-force curves for assessing the effect of fibre addition on the elasticity of Cement Concrete [27]. As expected, the load-displacement curve is linear up to the maximum load for all specimens. As seen in Figure 4a, the behaviour of the plain Cement Concrete beam is typical for a brittle material with a linear force–time curve. The beam fails in tension with the crack initiating from the bottom surface and propagating towards the top, splitting it into two parts. Once the maximum load is achieved, any additional load will lead to the formation of the macrocrack and suffer a catastrophic failure Table 1 & 2 3.

Table1. Properties of materials.

Test	Cement	Fineaggregate
Consistency (%)	30	-
Initial setting time(min)	190	-
Final setting time(min)	330	-
Specific gravity	3.06	2.64
Fineness	2.8	3.06
Water absorption (%)	-	3.1
Silt content (%)	-	3.2
Bulk density(kg/m3)	Loose:1604.2 Compact:1836.3	Loose:1365.1 Compact:1557.4

Table2. Mix proportions of plain concrete (CC)and Polypropelene-fibre-reinforced (PFRC).

Mix ID	Cement (kg/m3)	Limestone (kg/m3)	Natural Sand(kg/m3)	Crushed Sand(kg/m3)	Water (kg/m3)	Superplasticiser (kg/m3)	Fibres(kg/m3)
PlainCC	480	795	668	265	187	3.95	0
PFRCC	480	795	668	265	187	3.95	5

Table3. Mechanical properties for plain CC and PFRCC.

Mix ID	Compressive Strength (MPa)	Tensile Strength (MPa)	Flexural Strength (MPa)	Max. Load Deflection(mm)
PlainCC	82.79	5.31	9.27	1.17
PFRCC	92.84	5.43	9.61	1.35

The main observation of the differences on post-peak behaviour are as follows:

i. After reaching the maximum load, energy absorption in plain Cement Concrete beams is negligible.
ii. After achieving the peak load, there is a sudden load drop on PFRC beams; however, it continues to absorb energy to the end of the test while the load gradually decreases. An increase in the force can be observed in the force–time curve for the PFRC beam after the macrocrack has formed approximately 50 s into the test. This was due to the presence of fibers over the macrocrack region. Figure 4b shows the failure of PFRC beam where it did not break into two parts after final failure due to the presence of steel fibres. It is also worth mentioning that there is a succinct step down in the force–time curve due to fibres bridging the crack being gradually pulled out as the load continued to be applied. Similar results on the modes of failure of plain Cement Concrete and PFRC is also reported in Solution. As can be seen in Table 2, the PFRC beams exhibit a higher average flexural strength and a bigger deflection at maximum load than the plain Cement Concrete beams. This may be due to the increasing width of the fracture process zone (FPZ) caused by the distribution of fracture energy in a larger volume of material. In addition, the PFRC beams have a higher elasticity than the plain Cement Concrete beams due to the inclusion of steel fibres shown in Figure 9.

Test Results of Cubes

The Figure 8 shows the relative frequency of an applied load to a conductor. The x-axis is labeled "Frequency (in Hz)”, and the y-axis is labeled "Conductance (in S)". However, the label for the y-axis should likely be" Frequency (in Hz)"to match the x-axis and correctly reflect what the graph is presenting. The data plotted in the graph suggests that higher frequencies result in a lower relative applied load. This might be because the conductor is more efficient at carrying current at higher frequencies shown in Figure 10.

The Figure 9 shows the frequency response of a material under different applied loads. It likely depicts the results of an experiment on a material rather than a conductor, although the concept is similar.

The x-axis is labeled "Frequency (in Hz)". It represents the frequency of vibrations applied to the material.

The y-axis is labeled "Conductance (in S)", but it should likely be labeled "Frequency (in Hz)"to reflect the actual data being plotted. Both axes show frequency.

There are five lines in the graph, each representing the response of the material at a different applied load. The applied loads are labeled" Applied load at 200KN" and so on, up to" Applied load at1000KN”. (KN stands for kilo newtons, unit of force).

The general trend across all the lines is that the frequency response increases as the applied load increases. This suggests that the material gets stiffer (more resistant to deformation) under higher loads.

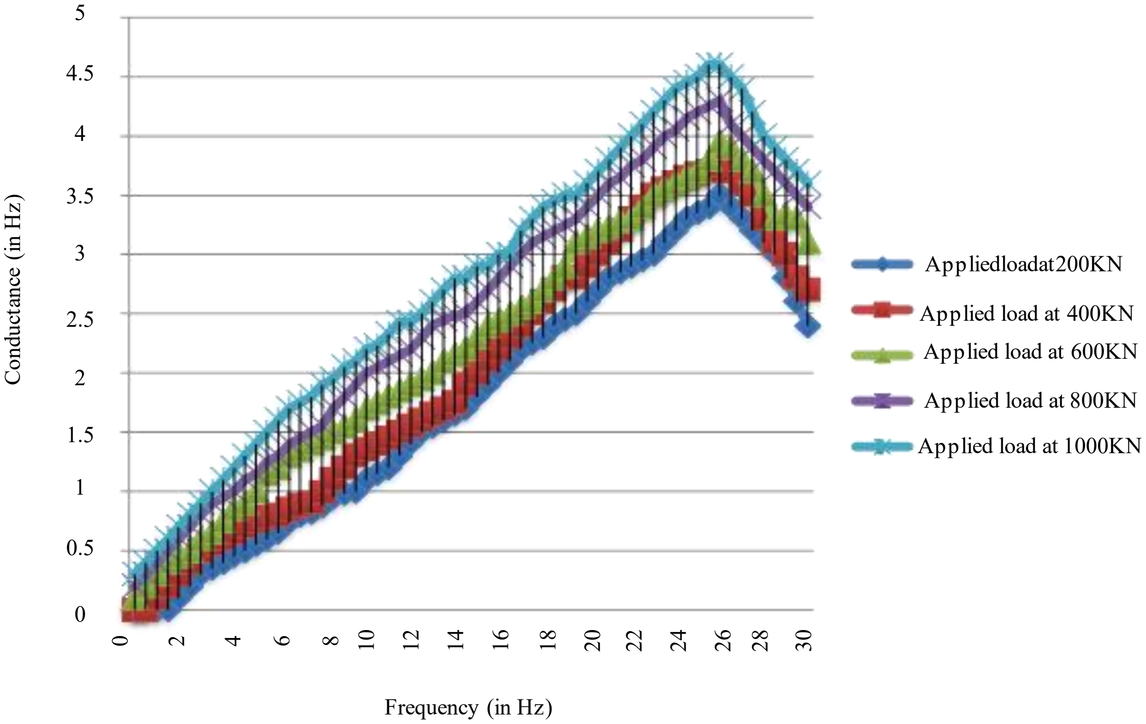

Figure 9. Conductance Vs Frequency Graph of 200,400,600,800 &1000 KN Load for CC.

Test Results of Beams

The Figure 10 shows the variation of conductance with frequency for a concrete composite (CC) material under different compressive loads [1]. While the y-axis label says "Conductance (in S)", it likely represents relative displacement of the material rather than electrical conductance. This is because the experiment likely involved measuring vibrations of the material, not its ability to conduct electricity.

The x-axis is labeled "Frequency in Hz" and represents the frequency of vibrations applied to the material.

They axis is labeled" Conductance (in S)", but it most likely represents" Relative displacement" of the material, as measured by the accelerometers.

There are five lines in the graph, each representing the response of the concrete composite material at a different applied load. The applied loads are labeled "200 KN" and so on, up to"1000KN" (KN stands for kilo newtons, a unit of force).

The general trend across all the lines is that the conductivity (or relative displacement) decreases as the frequency increases. This suggests that the material becomes stiffer (more resistant to vibration) at higher frequencies [1]. This could be because the applied load pre-stresses the material, making it less prone to deformation under vibration shown in Figure 11.

The Figure11 shows the variation of relative displacement with frequency fora concrete composite (CC) beam under different compressive loads[1]. While they-axis label says" Conductance (in S)",it likely represents relative displacement of the beam rather than electrical conductance. This is because the experiment likely involved measuring vibrations of the beam, not its ability to conduct electricity.

Journal of Polymer & Composites
Volume 13, Special Issue 1
ISSN: 2321-2810 (Online), ISSN: 2321-8525 (Print)

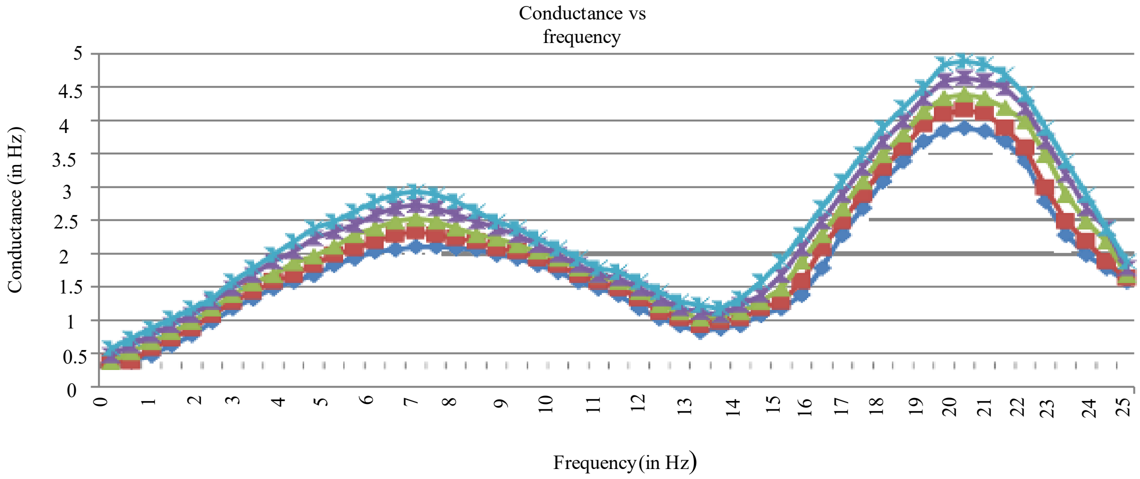

Figure 10. Conductance Vs Frequency Graph of 200, 400, 600, 800 & 1000 KN Load for CC.

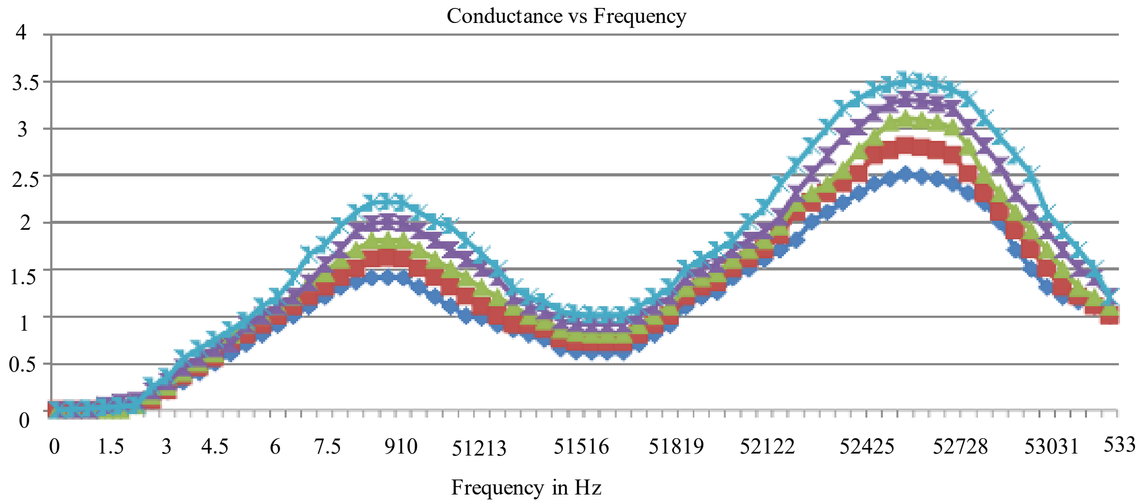

Figure11. Conductance Vs Frequency Graph of 200,400,600,800 &1000 KN Load for PFRC Cubes.

The x-axis is labeled" Frequency in Hz" and represents the frequency of vibrations applied to the beam. They axis is labeled" Conductance (in S)", but it most likely represents" Relative displacement" of the beam, as measured by the accelerometers.

There are five lines in the graph, each representing the response of the CC beam at a different applied load. The applied loads are labeled "200 KN" and so on, up to "1000 KN" (KN stands for kilo newtons, a unit of force).

The general trend across all the lines is that the relative displacement decreases as the frequency increases. This suggests that the beam becomes stiffer (more resistant to vibration) at higher frequencies [1]. This could be because the applied load pre-stresses the beam, making it less prone to deformation under vibration.

CONCLUSION

This study successfully demonstrated the potential of accelerometers for structural health monitoring (SHM) of concrete structures. By employing these sensors on plain concrete (CC)and polypropylene fiber-reinforced concrete (PFRCC) beams subjected to three-point bending tests, the research yielded valuable insights:

- *Improved mechanical performance*: PFRCC beams exhibited superior strength and enhanced post-peak behavior compared to plain concrete beams. Crack Detection and Location:

Accelerometers effectively detected crack initiation and propagation through analysis of the recorded responses, including waveform analysis for crack type identification and hodograms for crack location. This highlights the promising accuracy of this method.

- *Noise reduction with filtering:* The investigation successfully implemented filtering techniques to eliminate background noise from laboratory equipment, paving the way for broader application. Similar filtering approaches can be applied in real-world scenarios to eliminate noise from traffic or other environmental sources.
- *Simplified SHM system:* This non-destructive approach using accelerometers, wave form analysis, and hodograms offers a simpler and less technically demanding solution for SHM systems in concrete structures.

Future Research

While this study establishes the potential of the proposed method, further research is necessary to refine its applicability in real-world scenarios. One key area of exploration includes implementing this technology on bridge decks, requiring an investigation into the specific noise filtering strategies required for such environments. Additionally, research should explore the creation of a database of concrete cracking frequencies for various scenarios, allowing for more targeted filtering and broader application across different structures.

Overall, this research paves the way for a novel and simplified SHM system for concrete structures using triaxial accelerometers. Further advancements will ensure its effectiveness in real-world applications, promoting the safety and longevity of critical infrastructure.

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