VISVESVARAYA TECHNOLOGICAL UNIVERSITY

"JNANA SANGAMA", BELAGAVI -590 018

2023 – 2024

A Project Report
on

"DETECTING AND QUANTIFYING STRUCTURAL DAMAGE WITH SENSOR BASED ALGORITHMS "

Submitted in partial fulfillment for the award of the degree of
BACHELOR OF ENGINEERING
in

CIVIL ENGINEERING

Submitted By

SAMIDHA DHANAJI GAVADE	[1JB20CV021]
ABHILASH U	[1JB20CV001]
DHANUSH KUMAR A N	[IJB20CV009]
HARSHITH N	[1JB20CV011]

Under the guidance of

Ms. ARPITHA GOWDA S L
Assistant Professor
Department of Civil

DEPARTMENT OF CIVIL ENGINEERING

SJB INSTITUTE OF TECHNOLOGY

#67,B G S HEALTH AND EDUCATION CITY
Kengeri, Bengaluru-560 060

||Jai Sri Gurudev||

Sri Adichunchanagiri Shikshana Trust ®

SJB INSTITUTE OF TECHNOLOGY

BGS Health & Education City, Kengeri, Bengaluru-560 060.

DEPARTMENT OF CIVIL ENGINEERING

CERTIFICATE

Certified that the project work entitled ***"DETECTING AND QUANTIFYING STRUCTURAL DAMAGE WITH SENSOR BASED ALGORITHMS"*** carried out by SAMIDHA DHANAJI GAVADE, ABHILASH U, DHANUSH KUMAR A N , HARSHITH N **[1JB20CV021, 1JB20CV001,1JB20CV009,1JB20CV011]** are bonafide students of **SJB Institute of Technology** in partial fulfilment for the award of **"BACHELOR OF ENGINEERING"** in **CIVIL ENGINEERING** as prescribed by **VISVESVARAYA TECHNOLOGICAL UNIVERSITY, BELAGAVI** during the academic year **2023 – 24**. It is certified that all corrections/suggestions indicated for internal assessment have been incorporated in the report deposited in the departmental library. The project report has been approved as it satisfies the academic requirements in respect of project work phase – I prescribed for the said degree.

Ms. Arpitha Gowda S L	**Dr. Prasad CSMV**	**Dr. K V Mahendra Prashanth**
Assistant Professor	**Professor & Head**	**Principal**
Dept. of Civil Engg., SJBIT	**Dept. of Civil Engg., SJBIT**	**SJBIT**

Name of Examiners **Signature with Date**

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ACKNOWLEDGEMENT

I would like to express our profound grateful to **His Divine Soul Jagadguru Padmabhushan Sri Sri Sri Dr. Balagangadharanatha Mahaswamiji** and His Holiness **Jagadguru Sri Sri Sri Dr. Nirmalanandanatha Swamiji** for providing me an opportunity to be a part of this esteemed institution.

I would also like to express our profound thanks to **Revered Sri Sri Dr. Prakashnath Swamiji,** Managing Director, SJB Institute of Technology, for his continuous support in providing amenities to carry out this project in this admired institution.

I express our gratitude to **Dr. K V Mahendra Prashanth**, Principal**,** SJB Institute of Technology, for providing me excellent facilities and academic ambience; which helped me in satisfactory completion of project work .

I extend our sincere thanks to **Dr. Prasad CSMV**, Professor & Head, Department of Civil Engineering; for providing us invaluable support throughout the period of my project work .

I wish to express our heartfelt gratitude to my guide, **Arpitha Gowda S L,** for his valuable guidance, suggestions and cheerful encouragement during the entire period of my project work .

I express my truthful thanks to **Dr. Naveenkumar D T,** project coordinator, Department of Civil Engineering for his valuable support.

Finally, I take this opportunity to extend my earnest gratitude and respect to our parents, teaching & technical staff of the department, the library staff and all my friends, who have directly or indirectly supported me during the period of my project work .

Regards,

SAMIDHA DHANAJI GAVADE [1JB20CV021]
ABHILASH U [1JB20CV001]
DHANUSH KUMAR A N [1JB20CV009]
HARSHITH N [1JB20CV011]

||Jai Sri Gurudev||
Sri Adichunchanagiri Shikshana Trust ®

SJB INSTITUTE OF TECHNOLOGY

BGS Health & Education City, Kengeri, Bengaluru-560 060.

DEPARTMENT OF CIVIL ENGINEERING

DECLARATION

We hereby declare that the entire work embodied in this project report has been carried out under the supervision of **ARPITHA GOWDA S L , Assistant Professor** in partial fulfilment for the award of "BACHELOR OF ENGINEERING" in CIVIL ENGINEERING as prescribed by VISVESVARAYA TECHNOLOGICAL UNIVERSITY, BELAGAVI during the academic year 2023 – 24.

SAMIDHA DHANAJI GAVADE	[1JB20CV021]
ABHILASH U	[1JB20CV001]
DHANUSH KUMAR A N	[1JB20CV009]
HARSHITH N	[1JB20CV011]

Abstract

This study investigates sensors effectiveness in detecting structural cracks and monitoring deflection in reinforced beam structures. It focuses on using algorithms for precise measurement of crack dimensions and early identification of deflection. The project tests reinforced beam structures by gradually applying load using a frame.

Two sensors are employed: a strain gauge sensor and an ultrasonic sensor, both affixed to the surface of the beam. Post-positioning, the sensors gather data, which is subsequently stimulated and transmitted to the acquisition system for storage. The acquired data is scrutinized to detect any anomalies induced by structural excitation. Algorithms are employed to quantify cracks, ascertain their location, and determine the extent of deflection. This approach advocates for the implementation of a routine monitoring system to promptly identify such issues and mitigate structural degradation.

The rotational displacement curve of a structure subjected to loading demonstrates a significant discontinuity in the presence of cracks or other types of damage. Traditional methods may fail to detect this discontinuity if the beam is not adequately loaded or if the crack depth is shallow. To analyse cracks in concrete, metrics such as characteristic length and critical crack width are employed. In this project, crack width is assessed using either crack tip opening displacement (CTOD) or crack mouth opening displacement (CMOD/COD).

This research employs sensors for early detection of cracks and deflection, along with algorithms for quantifying cracks. Concrete beams serve as the fundamental structural element for testing. These beams are subjected to loading via a loading frame, with a gradual increase in load.

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CHAPTER I

INTRODUCTION

Structural health monitoring (SHM) is the process of using damage detection and characterisation techniques for critical structures like bridges, wind turbines, and tunnels. It is a non-destructive in- situ structural evaluation method that employs several types of sensors embedded or attached to the structures. SHM helps us to increase the longevity of the structure thereby reducing the over consumption of the materials involved in construction

The structural health monitoring process includes installing sensors, data acquisition, data transfer, and diagnostics through which the structure's safety, strength, integrity, and performance are monitored. If overloading or any other defects are observed, proper correction measures are suggested.

The beam like structures is usually a fundamental member that is employed in large scale architecture of civil. In the most general terms, damage can be defined as changes introduced into a system that adversely affect its current or future performance. Damage in a structure are common phenomenon and can lead to breakdown. The service life of the structure must be smooth and safe. For damage detection specifically in Structural Health Monitoring (SHM)deals with observing the changes in mode shapes and beam natural frequencies

Objectives:

- Identify damage or deterioration in structures.
- Provide real-time or periodic assessments of structural conditions.
- Enhance safety by predicting and preventing structural failures.
- Optimize maintenance and reduce life-cycle costs.
- Extend the lifespan of structures.

Structural Health Monitoring in buildings is a proactive and technology-driven approach to ensuring the safety and longevity of structures. It provides valuable insights into the condition of critical components, enabling informed decision-making and efficient maintenance practices. This proactive approach helps detect potential issues, such as damage or deterioration, in real-time or through periodic assessments. Monitoring the strain and deformation in these load-bearing elements is crucial for assessing the overall health of the building.

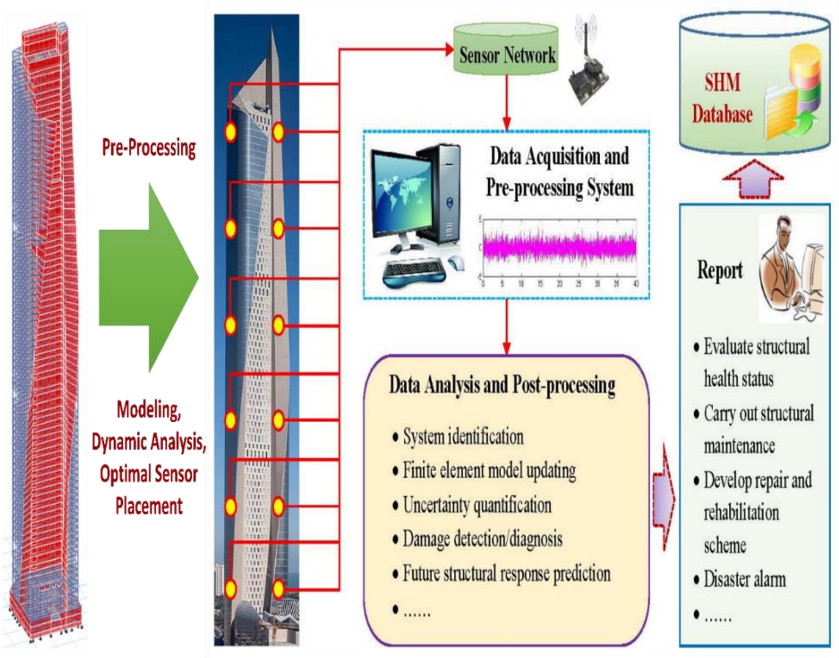


Fig1.1: SHM in Building

The finite element method (FEM) and finite element analysis (FEA) are numerical simulation techniques used to analyse real-time experiments through analytical models using advanced software; hence, complicated analysis, e.g., of stiffness and damping, can be carried out using the FEM technique very easily and reliably, even for multi-story buildings. In one study, a 15% stiffness reduction was found after analysing the nine columns, and a 1.67% stiffness reduction was found in the overall building structure. The FEM was used for steel bracing to identify damage by adopting two methods; namely, the Bayesian estimation method and the weighted least squares methods in the initial stages for the eigen-sensitivity-based FE model.

1.1 Types of Structural Health Monitoring

- **Static structural health monitoring** is aimed at the measurement of slow-varying parameters over a long period of time (e.g. inclination, rotation, static displacement, crack monitoring etc.): in other words, when the load is applied slowly, static analysis is what we need. Because the change that we want to analyse happens gradually and over time, for static monitoring data is recorded by the sensors at regular intervals, with punctual measuring.

- **Dynamic structural health monitoring** handles dynamic loading (actions having high acceleration), such as people walking, wind, waves, traffic, blasts and earthquakes; that means that when we deal with "fast" impacts, involving frequencies and vibrations, dynamic analysis is the type of monitoring we want. That involves a type of sampling that is continuous: sensors keep measuring the environment around them and when a "peak" is detected the information is then stored. The difference with static SHM, which involves punctual measuring, is that with dynamic SHM data is recorded for a few seconds before, during and after the "peak": that means that much more data is collected.

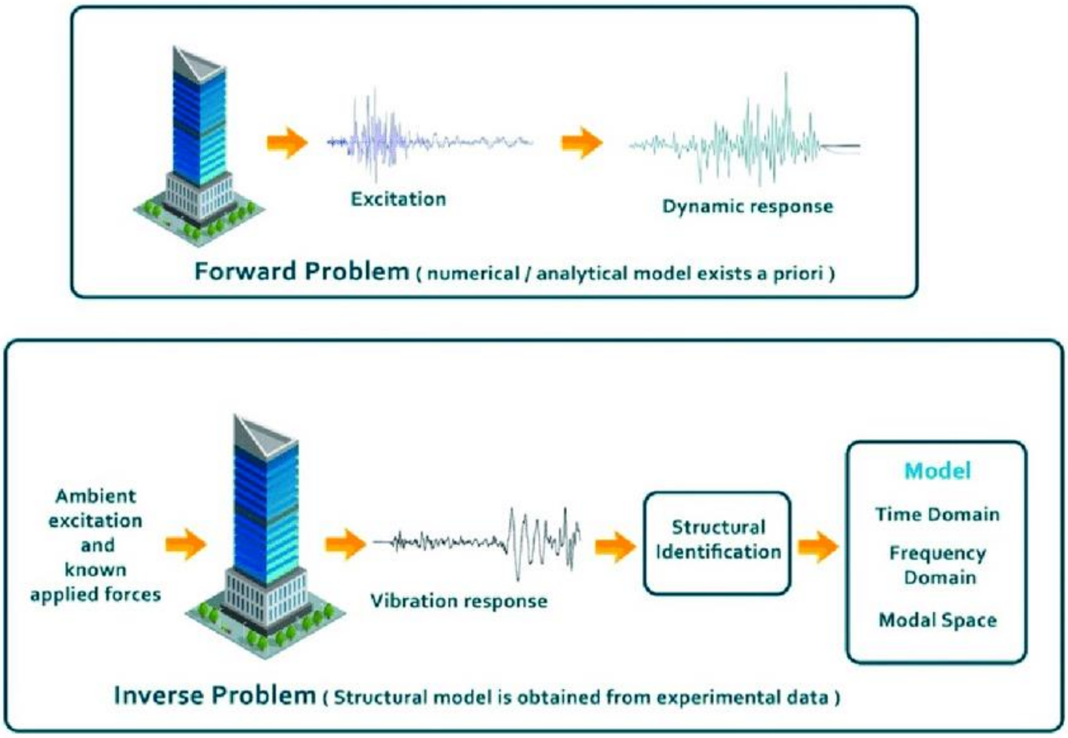


Fig1.2: Dynamic response of a multi-story building using SHM

1.2 The Purpose of Structural health Monitoring:

- Improve performance (safety and functionality) of existing structures.
- The placement of sensors during construction works enables observers to assess the structure's condition and specify its remaining life span.
- Evaluate the integrity of a structure after earthquakes.
- Structural monitoring and assessment are essential for on-time and cost-effective maintenance. So, it reduces construction work and increases maintenance

activities.

- The SHM process collects data on the realistic performance of structures. This data can help design better structures in the future.
- Shift towards a performance-based design philosophy.

1.3 Levels of SHM

SHM can be classified into five levels:

- Level 1, detection of a damage
- Level 2, localization of a damage;
- Level 3, quantification of a damage
- Level 4, typification of a damage
- Level 5, assessment of the structure's integrity. State-of-the-art SHM methods readily achieve up to Level 4.

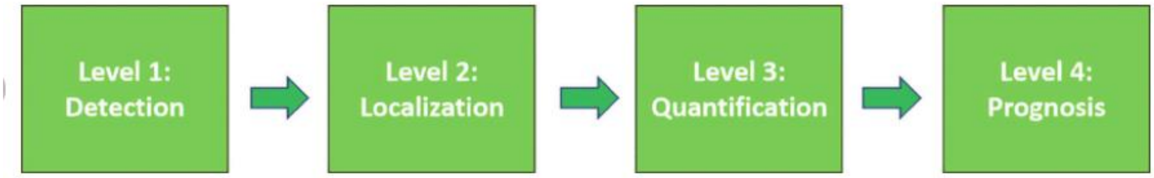


Fig 1.3: Levels of SHM

1.4 Advantages of Structural Health Monitoring (SHM):

1. Early Detection of Issues:

- Advantage: SHM allows for the early detection of structural issues, enabling timely intervention before significant damage occurs.
- Explanation: By continuously monitoring the structural health, deviations from the expected behaviour can be identified early on, helping prevent catastrophic failures.

2. Optimized Maintenance:

- Advantage: SHM facilitates targeted and cost-effective maintenance strategies.
- Explanation: Rather than relying on fixed maintenance schedules, SHM provides real-time data, allowing maintenance efforts to be directed precisely where and when needed, potentially reducing overall maintenance costs.

3. Enhanced Safety:

- Advantage: Improved safety of structures and occupants.

- Explanation: SHM helps identify potential risks and weaknesses in a structure, allowing for proactive measures to be taken to ensure the safety of the building and its occupants.

4. **Extended Lifespan of Structures:**
   - Advantage: By addressing issues early and optimizing maintenance, SHM can contribute to extending the lifespan of structures.
   - Explanation: Regular monitoring and maintenance help mitigate the effects of aging, deterioration, and external factors, contributing to the longevity of the structure.
5. **Data-Driven Decision-Making:**
   - Advantage: SHM provides a wealth of data for informed decision-making.
   - Explanation: Engineers and stakeholders can make decisions based on real-time data, enabling a more accurate assessment of structural health and the implementation of effective interventions.
6. **Reduced Downtime:**
   - Advantage: Minimization of downtime for critical infrastructure.
   - Explanation: Proactive maintenance and early issue detection can reduce the need for emergency repairs, minimizing disruptions and downtime for essential services.
7. **Customized Maintenance Plans:**
   - Advantage: SHM allows for the development of customized maintenance plans.
   - Explanation: Maintenance activities can be tailored to the specific needs of the structure, optimizing the allocation of resources and minimizing unnecessary interventions.

1.5 Disadvantages of Structural Health Monitoring (SHM):

1. **Cost:**
   - Disadvantage: Implementing SHM systems can have significant upfront costs.
   - Explanation: The installation of sensors, data acquisition systems, and related infrastructure can be expensive, especially for retrofitting existing structures.
2. **Sensor Reliability:**
   - Disadvantage: The reliability of sensors over time may be a concern.
   - Explanation: Sensors can degrade or malfunction over time, leading to potential inaccuracies in the collected data. Regular calibration and maintenance are necessary to address this issue.

3. Data Management:

- Disadvantage: Handling and analysing large volumes of data can be challenging.
- Explanation: The continuous monitoring generates substantial amounts of data that need to be processed and interpreted, requiring robust data management systems and analytical tools.

4. Integration with Existing Structures:

- Disadvantage: Retrofitting older structures for SHM can be challenging.
- Explanation: Incorporating monitoring systems into existing buildings may require modifications that are not always straightforward, especially in structures not originally designed for such monitoring.

5.Complexity of Interpretation:

- Disadvantage: Interpreting monitoring data may be complex.
- Explanation: Analysing data and distinguishing between normal variations and potential issues may require expertise, and false alarms or overlooked problems can occur.

6.Cybersecurity Concerns:

- Disadvantage: SHM systems are vulnerable to cybersecurity threats.
- Explanation: As SHM systems become more connected and data is transmitted over networks, there is a risk of cybersecurity breaches, potentially compromising the integrity of the monitoring data.

CHAPTER II

LITERATURE REVIEW

- **Ikhlas Abdel-Qader et.al. (2003):** The authors propose the use of image-processing algorithms for crack detection as a means to automate and enhance the bridge inspection process. The four edge-detection techniques are Fast Haar Transform (FHT), Fast Fourier Transform (FFT), Sobel, Canny. These techniques are implemented using MATLAB. The results show that the Fast Haar Transform outperforms other methods, making it a promising approach for automating bridge inspections and improving the overall safety and maintenance of the transportation infrastructure.
- **Hoon Sohn1 et.al.(2004):** Many SHM methods rely on analytical models, which can be uncertain. Some researchers explore unsupervised learning techniques to address this issue. Neural networks are used but have limitations, such as requiring large datasets from both undamaged and damaged structures. Environmental and operational variations of structures remain a challenge. Further work is needed in statistical model development and establishing damage decision criteria. This section covers selecting sensors, their placement, data acquisition hardware, and data normalization.
- **Charles R et.al. (2007):** SHM research has focused on identifying damage in structures on a global basis, but recent research has begun to recognize the importance of statistical pattern recognition (SPR) in addressing this problem. The challenges in implementing SHM include optimizing sensor selection and placement, identifying features sensitive to small levels of damage, distinguishing changes in features caused by damage from those caused by environmental and operational conditions, and developing robust statistical models for feature discrimination.
- **LI Huia et.al.(2011):** The paper summarizes the recent progress in SHM in mainland China and highlights the need for further research and development in sensing technology and data analysis. SHM is valuable for monitoring long-term structural performance and for assessing responses during natural disasters. The paper emphasizes the complexity of structures, loads, environments, and coupled responses, calling for more research in these areas. Model updating techniques are

used to adjust FEM based on monitoring results. Multi-scale FEM updating techniques are proposed to account for detailed structural information and damages

- **Andre enrico del grosso et.al.(2013):** The paper provides insights into maintenance strategies, cost optimization, diagnostic and prognostic algorithms, and the challenges in implementing SHM systems. It also emphasizes the need for guidelines, standards, and regulations in the field of SHM. Two approaches to SHM are discussed: permanent monitoring and periodic monitoring. Permanent monitoring systems continuously collect data and provide real-time information about a structure's health. Periodic monitoring involves temporary sensor installations and data collection at specific intervals. The choice between these approaches depends on factors like the complexity of the structure. The paper identifies several areas for future research, including the development of standards, the use of updated behavioural models, and the impact of SHM on safety coefficients in structural design.
- **Hui Xu1 et.al.(2014):** The paper discusses a method for estimating the static and dynamic deflection curves of bending beam structures using Fibre Bragg Grating (FBG) strain sensors. Traditional deformation monitoring techniques are limited to short-term measurements, and newer methods, such as GPS, laser image techniques, and FBG sensors, are explored for real-time deformation measurement. The proposed method relies on the geometric equations of a beam structure and FBG sensors to estimate the deflection curve. The proposed method, utilizing FBG sensors and geometric equations, shows promise in accurately estimating static and dynamic deflection curves for bending beam structures. Numerical simulations and experimental tests validate the effectiveness of the approach.
- **C.H Tan1 et.al.(2016):** Fibre Bragg Grating (FBG) sensors, especially those with Polydimethylsiloxane (PDMS) coatings, show promise for early corrosion detection in civil engineering. research is needed to explore protective coatings for FBG sensors, factors affecting strain transfer, and the impact of temperature on FBG measurements. This research aims to provide a non-destructive and real-time corrosion monitoring system for civil engineering structures, which could help in reducing maintenance costs and enhancing safety.
- **Ittipong Khemapech et.al.(2016):** The paper introduces an Enhanced Structural Health Monitoring System Using Stream Processing and Artificial Neural Network

- Techniques (SPANNeT) for real-time monitoring and warning of bridge structures. The structural damage detection algorithm is based on Weighted Attack Graph (WAG), considering bending strain intervals. The system is tested in laboratory and real-world settings, demonstrating accurate warning generation and at least 90% data communication reliability. Future work may include addressing additional warning criteria and enhancing damage localization and prediction.
- **Soumalya Sarkar et.al.(2016):** Propose and apply a deep learning technique for characterizing damage, specifically cracks in composite materials. Use a deep autoencoder (DAE) based on unsupervised representational learning theory. The proposed framework is tested on frames with varying load conditions. Metrics such as the number of correct cracks detected and the normalized distance between original and estimated crack lengths are used for evaluation. The framework exhibits consistency in characterizing cracks at different load levels.
- **Tao Wang et.al.(2017):** The method involves using distributed long-gage macro-strain sensors based on fibre Bragg grating (FBG) technology. The distributed macro-strain is obtained, and the classical conjugated beam theory is applied to calculate dynamic displacement. The proposed method shows promise for long-term structural health monitoring, providing an efficient and accurate way to monitor dynamic displacements in flexural structures. However, the study suggests that the sensor gage length should be limited to less than 1/20 of the beam length for precise measurements, especially in structures with complex vibrations.
- **Chirag G. Wani et.al.(2019):** The methodology includes modal analysis of healthy and cracked beams, and the study presents results for different crack locations and depths. The research contributes to the field of structural health monitoring and damage detection in beams. The proposed PSO algorithm demonstrates its effectiveness in accurately detecting and locating cracks, providing a valuable tool for ensuring the safety and integrity of structural elements. Particle Swarm Optimization (PSO) algorithm is applied for faster and accurate results, programmed in MATLAB© software. Experimental and simulation results show convergence with an error up to 10%.
- **Aamar Danish et.al.(2020):** The methodology involves placing sensors at critical locations on the structure, collecting data on dynamic properties, and analysing the effects of loading and vibrations on the structure. The wireless sensor's data is

transmitted to a base station gateway for real-time monitoring and analysis. The results of the study indicate that the wireless SHM sensor effectively detected damage in the RC beam during various loading stages. The acceleration responses were analysed, and frequency domain representation using Fast Fourier Transform (FFT) revealed changes in amplitude related to the extent of structural damage.

- **Jieming Yin et.al.(2020):** This paper proposes an FBG-based monitoring system for quasi-distributed strain measurement in beam-like structures. FBG is created by exposing a segment of an optical fiber to alter its refractive index permanently. The Bragg wavelength, representing the altered segment, is crucial for strain measurement. Changes in axial strain and temperature affect the Bragg wavelength, allowing FBG to estimate strain information. The strain mode shape is derived from the identified displacement mode shape, obtained experimentally through modal analysis. Multiple FBGs with different Bragg wavelengths can be used to form a sensing network, enabling easy and cost-effective monitoring of beam-like structures. The overall algorithm involves experimental modal analysis, fitting displacement mode shapes, acquiring strain mode shapes, obtaining dynamic strain data, and reconstructing dynamic displacement. The proposed method is validated experimentally using a cantilever beam, demonstrating its effectiveness in estimating deflection based on strain measurements.
- **Zhong Jiawei et.al. (2021):** The paper discusses the application of Structural Health Monitoring (SHM) in various engineering fields, emphasizing its importance in ensuring the safety and stability of structures. The paper highlights that SHM systems are adaptable and can be tailored to specific environmental and structural conditions. The aim is to ensure real-time monitoring to safeguard the structural integrity of these critical infrastructure elements. By using SHM, researchers can qualitatively and quantitatively analyse damage, potentially preventing structural problems before they occur. The paper also presents a new framework for predicting the remaining life of ancient structures based on deformation data from SHM systems.
- **Constantin E. Chalioris et.al. (2021):** The study presents a custom-made, portable, and low-cost structural health monitoring (SHM) system that uses PZT-based electro-mechanical admittance (EMA) methodology for damage detection and evaluation in flexural reinforced concrete beams. Statistical index values were

calculated based on the signals of the PZT transducers to represent the differences between their baseline response and their response at each loading/damage level. The findings indicate that the proposed SHM system can effectively assess structural damage caused by concrete cracking and steel yielding in flexural beams under monotonic and cyclic loading.

- **Run-Zhou You et.al.(2023):** The paper introduces an Equivalent Estimation Method (EEM) for quasi-distributed deflection estimation in bridge health monitoring. It utilizes onboard strain data from a self-designed sensing bar, establishing a versatile equivalent analysis model through an innovative Inverse Finite Element Method (IFEM). The proposed EEM is computationally efficient, independent of bridge typology, and requires no prior loading or material information. Experimental validation confirms its excellent quasi-distributed sensing capability, highlighting its potential for real-time applications in bridge health monitoring.

2.1 Objectives:

- Evaluate beam deflection through measurement to ensure adherence to structural performance standards
- Implement efficient methods for beam crack identification for improving structural integrity
- Enhance beam performance through data acquisition, precise quantification methods, and accurate positioning

CHAPTER III

METHODOLOGY

The methodology used during the health assessment of the chosen structure is discussed in this section. The main steps and working mechanism of the manufactured sensor for structural health monitoring of a structure are shown in Figure. First, the structure is selected on which the health monitoring operation is to be performed then the sensors are placed on it, upon excitement the data collected by the sensors is transferred to the acquisition system and stored. The collected data is then observed to detect the variation produced due to the excitation of the structure.

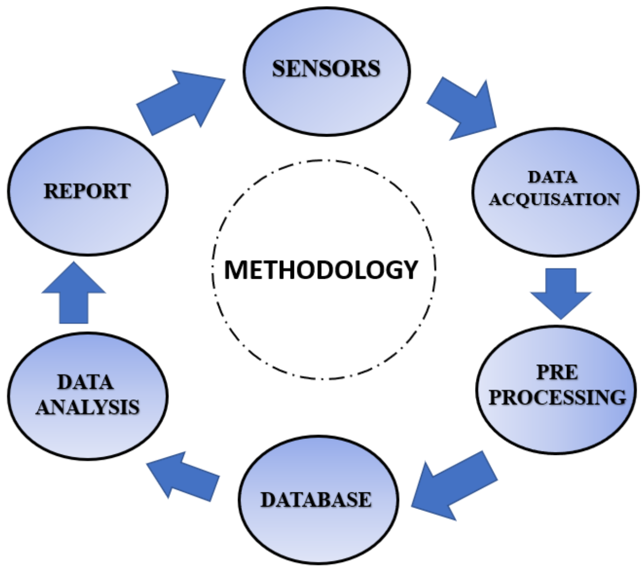


Fig 3.1 Main steps for structural health assessment

Structural health monitoring (SHM) of beams involves the use of various techniques and methodologies to assess the condition, performance, and integrity of the beams over time. The goal is to detect any potential damage or deterioration early on, enabling timely maintenance or repair interventions. Here's a general methodology for structural health monitoring of beams:

- **Sensor Installation:**

  Place sensors at critical locations on the beam. Common sensors include accelerometers, strain gauges, displacement sensors, and sometimes even non-destructive testing (NDT) methods like ultrasound or acoustic emission sensors.

  Ensure proper calibration of the sensors for accurate measurements.

- **Data Acquisition:**

  Collect data from the sensors during different loading conditions and over time. This data can include measurements of strains, accelerations, displacements, and other relevant parameters.

- **Baseline Measurement:**

  Establish a baseline for the beam's behaviour under normal or healthy conditions. This involves collecting data when the structure is in good condition and not subjected to unusual loads.

- **Analysis and Modelling:**

  Analyse the collected data to understand the structural behaviour. Finite element modelling or analytical methods may be used to simulate the expected response of the beam.

  Compare the measured data with the baseline to identify any deviations or anomalies.

- **Damage Detection:**

  Implement damage detection algorithms to identify any changes or abnormalities in the structural response. These algorithms can be based on statistical methods, pattern recognition, or machine learning.

- **Continuous Monitoring:**

  Implement a continuous monitoring system to regularly collect and analyze data over the beam's lifespan. This allows for the detection of gradual deterioration or unexpected changes.

- **Alarm and Warning Systems:**

  Establish threshold values for key parameters based on the baseline and expected behaviour. Implement alarm and warning systems to alert engineers or maintenance personnel when measured values exceed predefined thresholds.

- **Regular Inspection and Maintenance:**

  Combine SHM with regular visual inspections to ensure a comprehensive assessment of the structural health. Schedule maintenance or repairs based on the SHM findings.

- **Documentation and Reporting:**

  Maintain detailed records of monitoring data, analysis results, and any interventions made.

Generate reports documenting the structural health and any recommended actions.

- **Adaptive Strategies:**

  Develop adaptive strategies that can evolve based on the changing conditions of the structure.

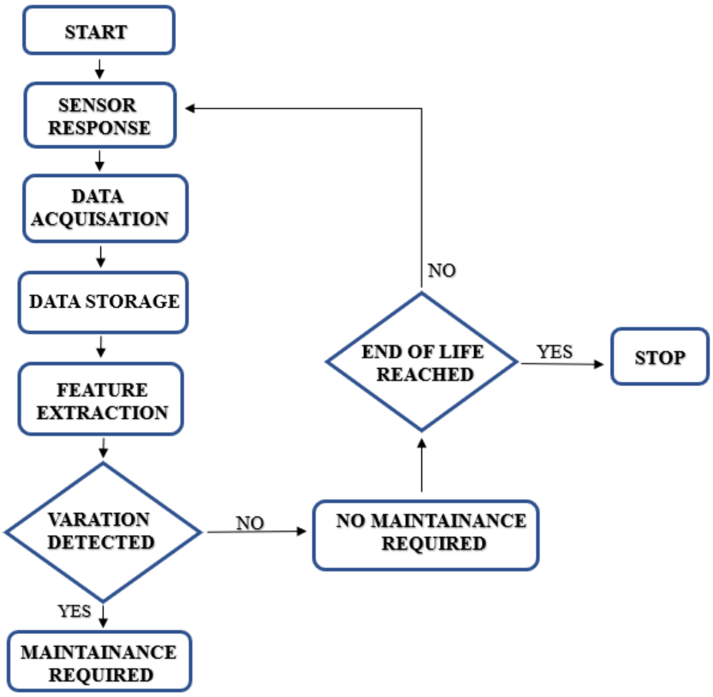


Fig 3.2 Flowchart of the sensor working for structural health monitoring

3.1 Implementation Details

Our proposed regular monitoring system used Tinker cad software in order to check the effectiveness of the ultrasonic sensors to detect and locate the internal cracks. We used the software to create simulations of the connection system and was able to determine the maximum distance which can be covered by the sensor as well as the angle of coverage. The theoretical distance covered is 4 meters but for the practical use in our project we have considered 3 meters as the maximum distance and 15° as the angle of coverage.

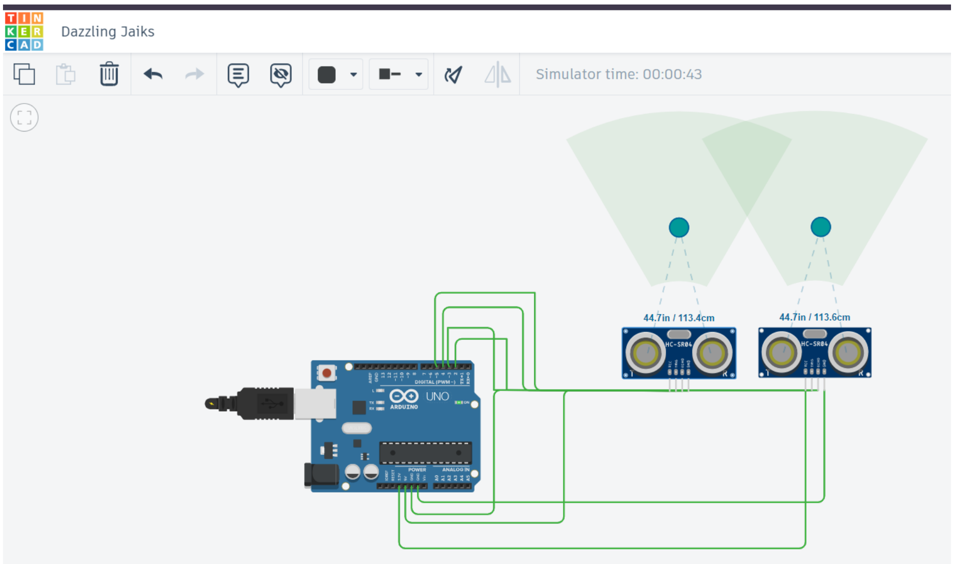


Fig 3.3 Simulation of sensors

3.1.1 Components of proposed Regular Monitoring System

1. Ultrasonic Sensor HC-SR04 :

The sensor is made up of two ultrasonic transducers, one of which acts as a transmitter, converting electrical signals into 40kHz ultrasonic sound pulses, and the other as a receiver, receiving the transmitted pulses. The HC-SR04 has a non-contact range detection range of 2cm to 400cm with a 3mm accuracy.

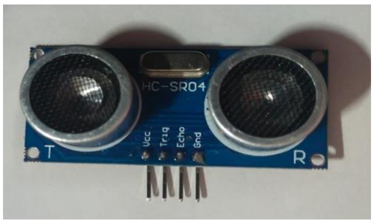


Fig 3.4 Ultrasonic sensor HC–SR04

Table3.1 Terminal Specifications of HC-SR04

Operating Voltage	DC 5V
Operating Current	15mA
Operating Frequency	40kHz
Measuring Angle	15
Trigger Input Signal	10µS TTL pulse
Dimension	45 x 20 x 15mm

2. Arduino UNO board :

The Arduino UNO microcontroller board is based on the 8-bit ATmega328P microcontroller. The Arduino Uno includes a USB interface, 6 analogue input pins, and 14 I/O digital ports for connecting to external electronic circuits. Six of the 14 I/O ports can be used for PWM output.

By connecting via USB COM drivers, this board can communicate with a computer. This board's software is called Arduino IDE, and it uses the C and C++ programming languages, as well as a serial monitor that allows simple textual data to be sent to and from the board.

Fig 3.5 Arduino UNO board

Table 3.2 Terminal Specifications of Arduino UNO board

Operating Voltage	5V
DC Current on I/O Pins	40mA
Frequency (Clock Speed)	16MHz
Flash Memory	32KB
Trigger Input Signal	10μS TTL pulse
Dimension	45 x 20 x 15mm

3. Strain gauge sensor's :

Strain gauge sensors work on the principle of measuring the deformation (strain) of an object. They are often used to measure the strain in structures such as beams, bridges, and buildings. The sensor consists of a thin metallic foil (commonly made of constantan or karma) that is attached to the surface of the object being measured. As the object deforms under stress or strain, the foil also deforms, causing a change in its electrical resistance. This change in resistance is proportional to the strain experienced by the object.

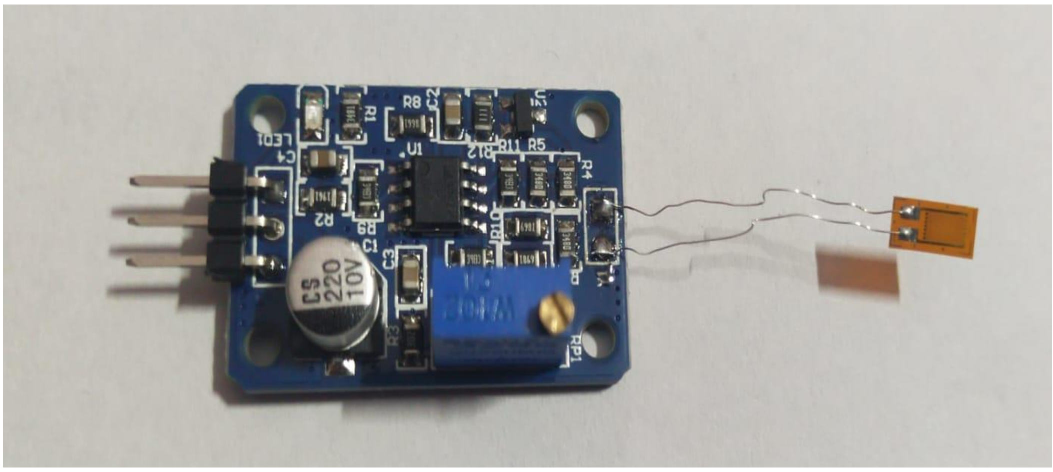


Fig3.6 Microcontroller with strain gauge sensor

Table 3.3 Terminal Specifications of Strain gauge sensor

Parameter	Description
Material	Thin metallic foil, typically constantan or karma
Resistance	Nominal resistance: 120 ohms to 350 ohms. Resistance changes with applied strain.
Gauge Factor	Dimensionless factor relating resistance change to applied strain. Typically, around 2.0 for metallic foil strain gauges.
Temperature Coefficient (TCR)	Rate of resistance change with temperature. Expressed in pm/°C.
Maximum Strain	Maximum measurable strain before permanent deformation. Typically, 0.5% to 1.0%.
Temperature Range	Operating temperature range for accurate measurements.
Bridge Configuration	Typically used in a Wheatstone bridge configuration for strain measurement.
Dimensions	Physical dimensions of the strain gauge (length, width, thickness).
Installation	Installation instructions, including recommended adhesive and curing process.

3.2 Implementation of regular monitoring system in a structural member

- The ultrasonic sensor will be placed inside the concrete beam of size (1000x150x200) mm during the casting process itself.
- The strain gauge sensor is placed on the surface of the beam
- The sensors are placed in different locations inside the beam
- The strain gauge sensor is positioned precisely at the midpoint of the beam's surface, as this location corresponds to the point of maximum deflection in a simply supported beam.
- The ultrasonic sensor was positioned at a distance of 150 mm from each end of the beam, specifically targeting the discontinuity region.

(a) (b)

Fig 3.7 Placement of (a) Ultrasonic sensor (b) Strain gauge sensor

- Then the sensors are connected to Arduino UNO board, which will be connected to the laptop in order to dump the code through Arduino IDE software.
- The strain gauge sensor is connected to the loading frame and the values are obtained
- The output will be shown as textual data through Serial Monitor in Arduino IDE software with corresponding time.
- Another concrete cube, measuring 150 x 150 x 150 mm, will be cast to measure crack widths using embedded ultrasonic sensors.
- The user interface (UI) is developed to show the position of the cracks as well as the corresponding time of crack detected.
- After obtaining the results, validation is conducted using ANSYS software.

Fig 3.8 Experimental setup for beam testing

Fig 3.9 Experimental setup for cube testing

CHAPTER IV

RESULTS AND DISCUSSION

Structural Health Monitoring (SHM) plays a crucial role in ensuring the integrity and safety of civil infrastructure. By continuously monitoring structures for signs of damage or deterioration, SHM systems can provide early warnings, allowing for timely maintenance and repair actions to be taken.

In this study, we present the results of our SHM efforts on beam. Our primary objective was to detect and quantify any changes in structural behaviour that could indicate the presence of cracks and deflection. To achieve this, we deployed a network of ultrasonic sensors and strain gauges strategically positioned across the beam.

- We casted four concrete beam of size (1000x150x200) mm which underwent gradual loading under the Loading frame , the curing period for these cubes was 14 days.
- The ultrasonic sensors were placed at different locations shown in the below figures in each of the beam in order to assess the best placement position of the sensor to attain accurate results.
- The sensors were embedded during the casting of the concrete beam. When the sensors were embedded in the concrete the initial condition is assumed to be homogeneous in nature even though coarse aggregates were present in the mix.
- The ultrasonic sensors react when the pressure is applied, while they react there is transition phase that takes place, the transition state is brittle to ductile. While we tested the concrete beam, the transition phase took place from 76 kN to 120 kN. When the maximum load is applied, we attained constant readings. When the pressure or the load applied is removed the sensors regains its original wavelength.
- That shows the moment at which the applied stress starts to cause the beam to exhibit the first indication of deformation in beam.

4.1 Deflection results

- The following presents the experimental findings for deflection, represented in tabular format and graphically depicted.

Table 4.1 Deflection trial 1 readings

Time (sec)	Load (KN)	Deflection 1 (mm)	Deflection 2 (mm)	Strain 1	Strain2
0	0	0	0	0	0
23	5	1.9	0.2	0.7	0
23.6	10	2.2	0.1	1.7	0
24.6	15	0.7	0.5	2	0
25.6	20	1.3	0	3.2	0
26.1	25	0.9	0.1	4.6	0
27.1	30	1.9	0.2	10	0
27.9	35	2.4	0.4	0	0
28.5	40	1.2	0.6	0	0
29.2	45	3.4	0.6	11.2	0
30.2	50	1.4	0.7	19.3	0
30.8	55	0.7	0.9	19.3	0
31.8	60	0.5	0.6	0	11.2
32.9	65	0	0.8	0	10.5
34	70	1	1	0	0
35	75	2.6	1	0	0
35.9	80	2	1	0	0
37.6	85	1.6	1.3	0	0
39	90	1.6	1.6	0	0
41	95	2.6	1.8	0	0
42.8	100	3.2	1.5	0	0
44.8	105	2.4	2	0	0
64.7	110	5.9	6	0	0
66.1	109	4	7	0	0
95.2	108	2.3	9.3	0	0
98.3	109.4	4.8	9.5	0	0

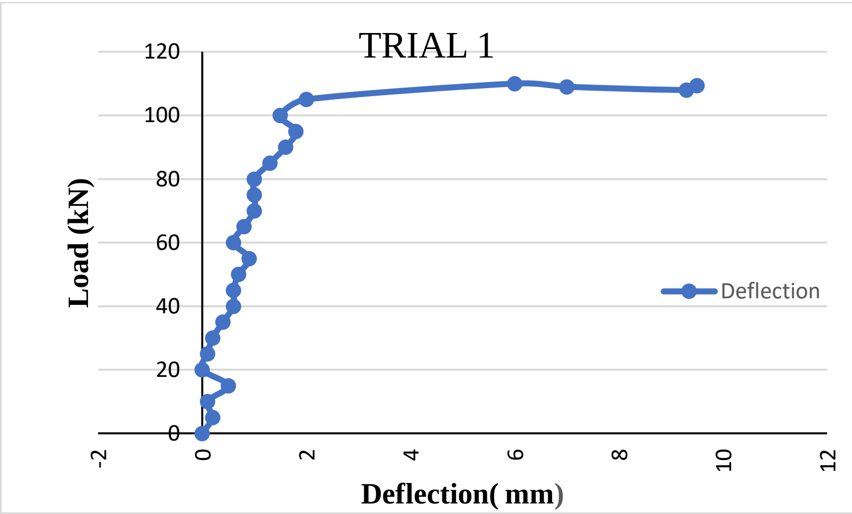


Fig 4.1 Load vs Deflection graph for Trial 1 readings

- The above graph is Load vs Deflection Graph ,the concrete beam's microcrack initiation is depicted in graph that increases in load value from 76 kN to 110 kN. This shows the moment at which the applied stress starts to cause the beam to exhibit the first indication of microcrack development and also the initiation of deflection.

Table 4.2 Deflection trial 2 readings

Time (sec)	Load (kN)	Deflection 1 (mm)	Deflection 2 (mm)	Strain 1	Strain2
0	0	0	0	0	0
14.5	5	0.1	0	0	1.2
15.8	10	0	0	0	5.5
16.4	15	0	0	0	6.2
17.2	20	0	0.3	0	4.7
18.1	25	0.4	0.4	0	4.6
18.9	30	0.3	0.6	0	1.9
19.7	35	0.5	0.3	0	0.6
20.8	40	0.3	0.6	0	1
21.4	45	0	1.1	0	2.9
22.1	50	0.5	1	0	5.1
23.2	55	0.4	1.1	0	7.5
24.3	60	0.8	1.4	0	10.1
25.3	65	0.5	1	0	13
26.9	70	0.6	1.8	0	14.7
27.7	75	0.8	2.2	0	16.2
29.1	80	0.9	1.3	0	17
30.6	85	0.4	1.7	0	17.9
32.5	90	1.2	2.5	0	18.6
39	95	2	2.7	0	19.4
42.3	100	2	3.1	0	19.1
44.6	99	1.8	3.8	0	18.7
45.9	100	1.5	3.9	0	19.1
48.7	101	1.4	2.3	0	19.2
49.9	102	2.2	3.9	0	18.7
50.8	103	1.8	4.2	0	19.2
52.3	104	1.4	4.3	0	19.2
74.7	105	3	7.1	0	22.2
78.7	106	3.2	7.3	0	22.4
81.6	107	3.3	7.6	0	22.3
91.6	108	4.5	8.6	0	22.3
139.2	108.6	5.9	13.7	0	23

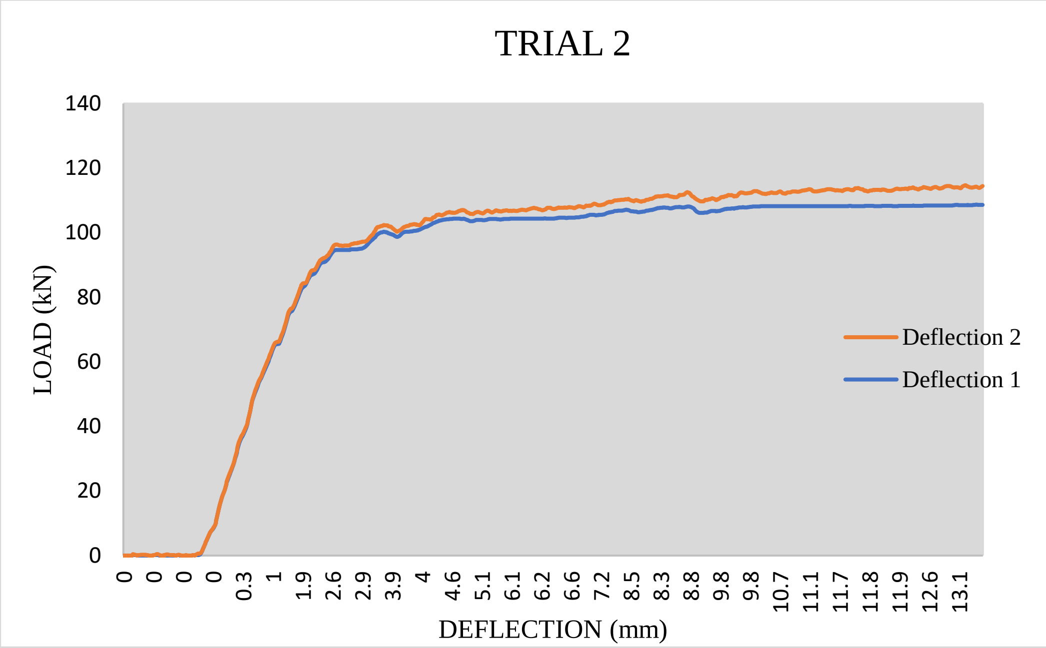


Fig 4.2 Load vs Deflection graph for Trial 2 readings

- The above graph is Load vs Deflection Graph ,the concrete beam's microcrack initiation is depicted in graph that increases in load value from 100 kN to 110 kN. This shows the moment at which the applied stress starts to cause the beam to exhibit the first indication of microcrack development and also the initiation of deflection.

Fig 4.3: Deflection value obtained from loading frame

4.2 Crack detection results

- In this section, we present the results of the crack detection analysis, focused on identifying the locations where cracks have formed using ultrasonic sensor

Table 4.3 Crack detection readings

Time (sec)	Load (kN)	Result
0	0	Not detected
14.5	5	Not detected
15.8	10	Not detected
16.4	15	Not detected
17.2	20	Not detected
18.1	25	Not detected
18.9	30	Detected
19.7	35	Detected
20.8	40	Detected
21.4	45	Detected
22.1	50	Detected
23.2	55	Detected
24.3	60	Detected
25.3	65	Detected
26.9	70	Detected
27.7	75	Detected
29.1	80	Detected
30.6	85	Detected
32.5	90	Detected
39	95	Detected
42.3	100	Detected
44.6	99	Detected
45.9	100	Detected
48.7	101	Detected
49.9	102	Detected
50.8	103	Detected
52.3	104	Detected
74.7	105	Detected
78.7	106	Detected
81.6	107	Detected
91.6	108	Detected
139.2	108.6	Detected

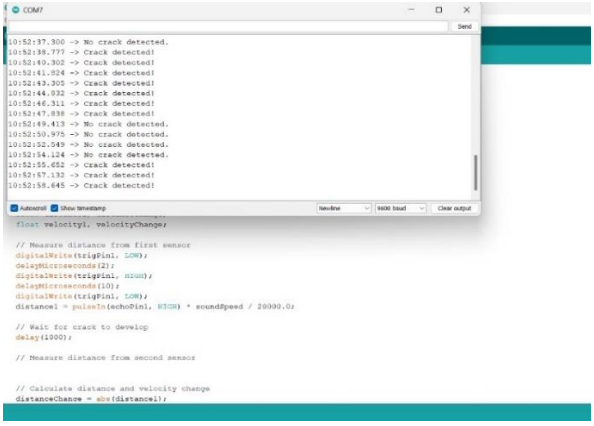


Fig 4.4 Outputs obtained for crack detection

- Utilizing the aforementioned results, a program was developed to successfully detect the presence of cracks, as demonstrated in the image above.
- Initially, the crack width of the beam was determined using an ultrasonic sensor on a pre-cracked beam to validate the functionality of the algorithms. The crack width was calculated by using the formula which is present in IS 456 (2000) Page 95 Annex F The crack width is given by:

$$W_{cr} = \frac{3a_{cr}\varepsilon_m}{1 + \frac{2(a_{cr} - C_{min})}{h - x}}$$

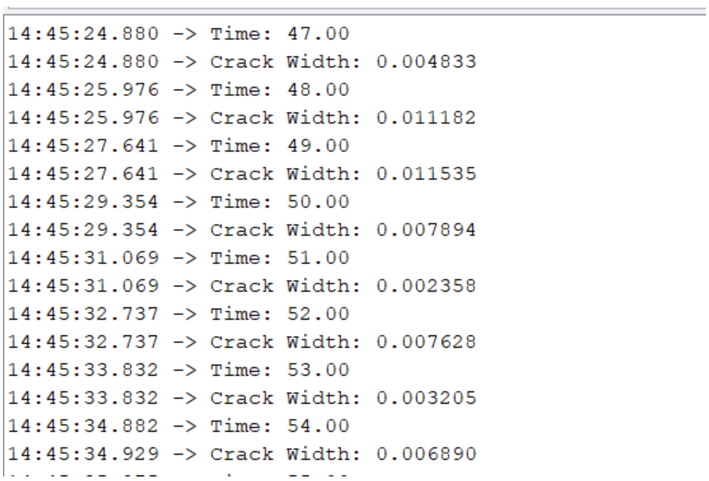
Table 4.4 Crack width detection readings on pre-cracked beam

Time (sec)	Crack width (mm)
0	0.0022
1	0.0064
2	0.0088
3	0.0073
4	0.0045
5	0.0087
6	0.0059
7	0.0093
8	0.0038
9	0.0024
10	0.0055
11	0.008
12	0.0107
13	0.0057
14	0.102

Table 4.5 Crack width detection readings on cube

Time (sec)	Crack width (mm)
28	0.00986
29	0.003196
30	0.005107
31	0.011
32	0.00432
33	0.002846
34	0.0083
35	0.00267
36	0.00499
37	0.0096
38	0.00663
39	0.009660
40	0.003885
41	0.0085
42	0.009
43	0.011
44	0.0055
45	0.010
46	0.006

- The above measurements represent the determination of crack width in a cubic specimen measuring 150 x 150 x 150 mm, tested under a Compression Testing Machine (CTM) to ascertain the extent of crack formation.



```
14:45:24.880 -> Time: 47.00
14:45:24.880 -> Crack Width: 0.004833
14:45:25.976 -> Time: 48.00
14:45:25.976 -> Crack Width: 0.011182
14:45:27.641 -> Time: 49.00
14:45:27.641 -> Crack Width: 0.011535
14:45:29.354 -> Time: 50.00
14:45:29.354 -> Crack Width: 0.007894
14:45:31.069 -> Time: 51.00
14:45:31.069 -> Crack Width: 0.002358
14:45:32.737 -> Time: 52.00
14:45:32.737 -> Crack Width: 0.007628
14:45:33.832 -> Time: 53.00
14:45:33.832 -> Crack Width: 0.003205
14:45:34.882 -> Time: 54.00
14:45:34.929 -> Crack Width: 0.006890
```

Fig 4.5 Outputs obtained for crack width detection in a cube

- The positioning of the crack is typically described in terms of its distance from a reference point, that is the sensor location. This helps to locate the crack along the length of the beam

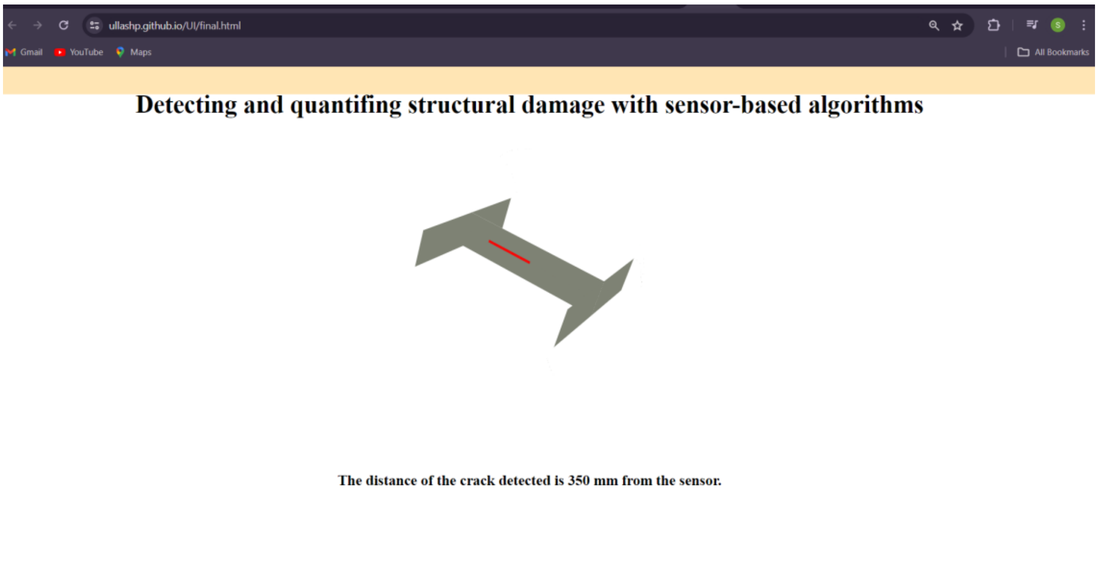


Fig 4.6 Positioning of crack in the UI Page

- To show the history of the cracks, deflection as well as the position of the cracks, we were successful able to develop a user interface (UI) using Languages : html, css , javascript and editor: VS code

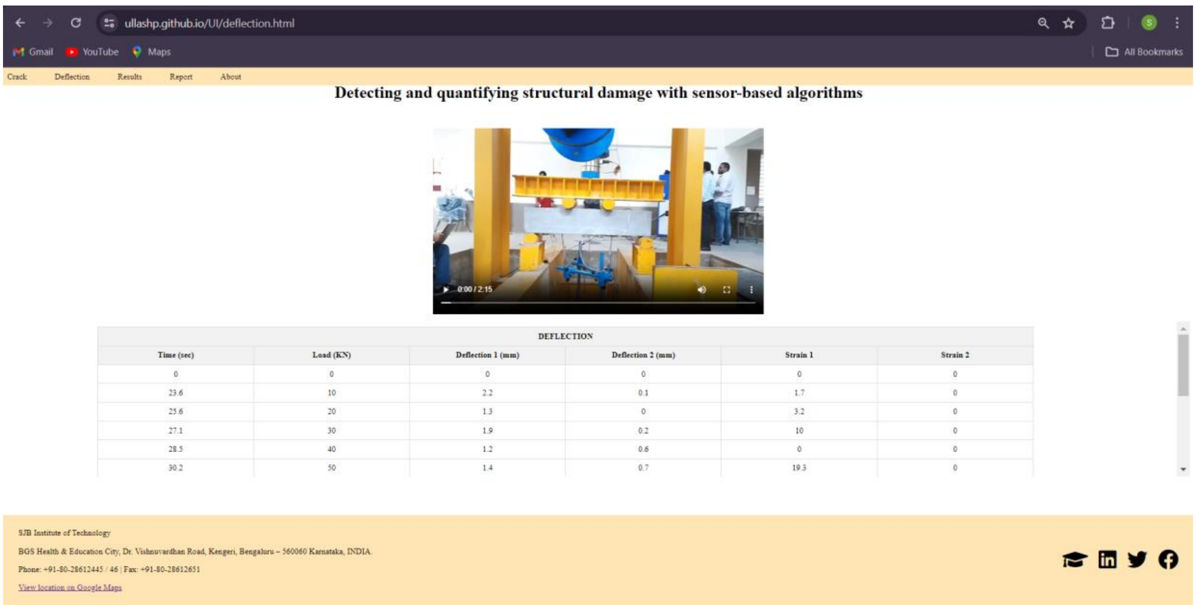


Fig 4.7 History page of our UI

4.3 Validation

- The beam was validated using finite element method (FEM) software, specifically ANSYS, to ensure the accuracy of the simulation results.
- Validation through ANSYS software involves comparing the results obtained from the software simulation with experimental or analytical results to ensure that the simulation accurately represents the real-world behaviour of the system or structure being analysed.

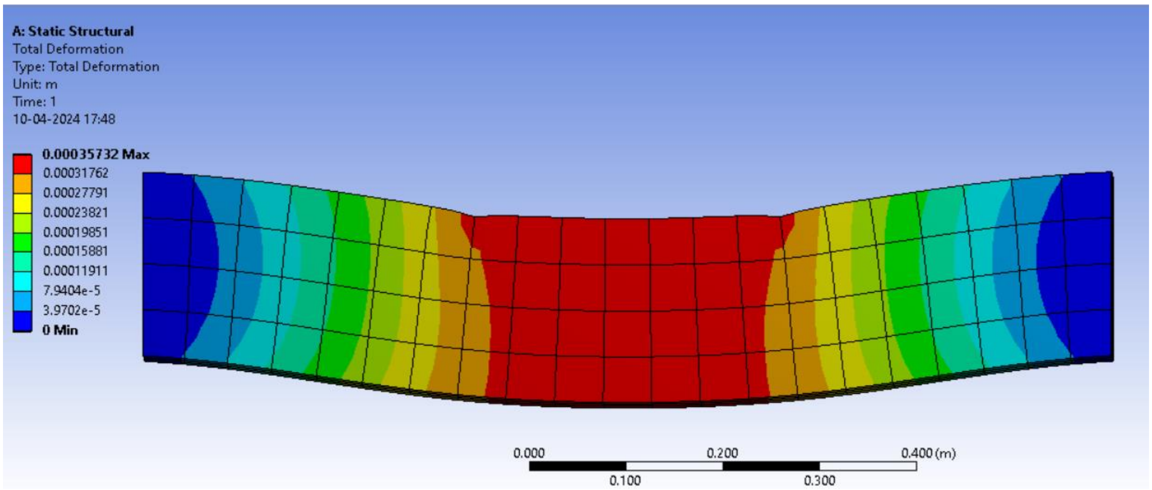


Fig 4.8 : Total deformation of RCC beam

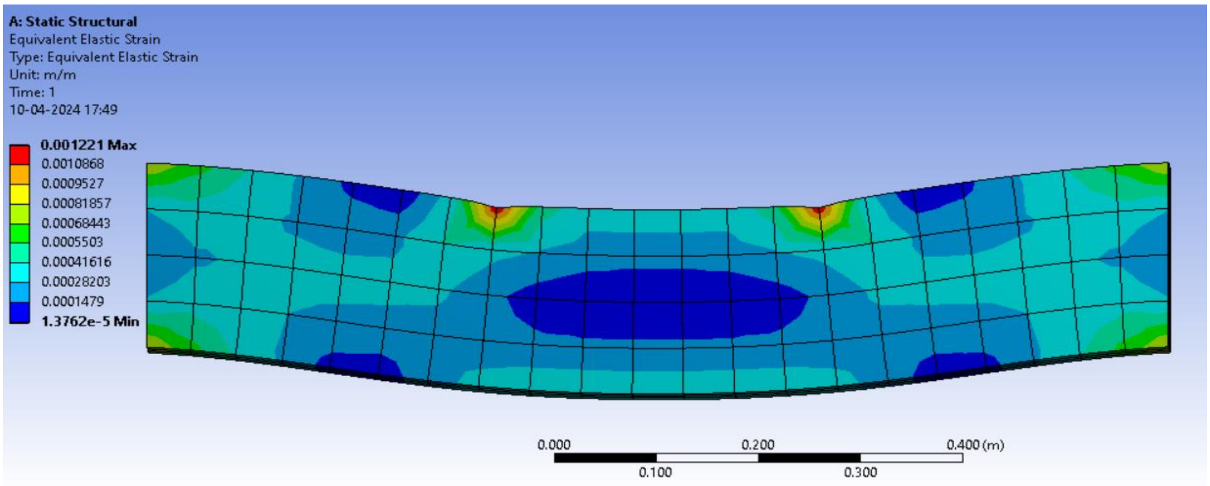


Fig 4.9 : Equivalent Elastic Strain after the RCC beam is Subjected to 2-point loading

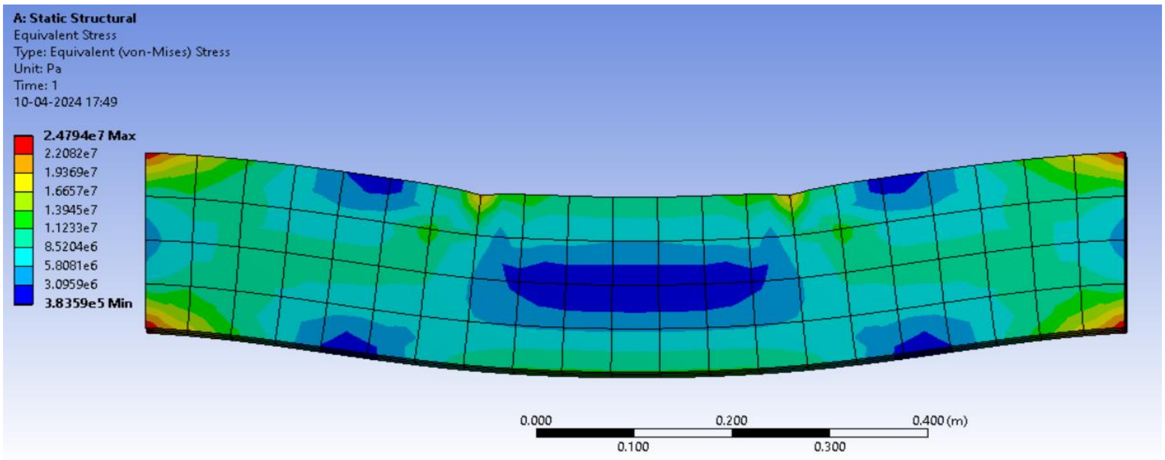


Fig 4.10: Equivalent Stress or Stress intensity after the RCC beam is Subjected to 2-point loading

CHAPTER V

CONCLUSION AND FUTURE WORK

5.1 Conclusion

1. Early detection and localization of internal cracks in the concrete beam were made possible by the introduction of a gradual load.
2. The beam's internal crack development was tracked in real-time by integrated ultrasonic sensors.
3. There was no sign that the ultrasonic sensors' extended lifespan would be harmed by being embedded within the beam.
4. Since ultrasonic sensors can measure cracks precisely, they may eventually supplant conventional methods.
5. With a low initial investment and ongoing maintenance expenses, the real-time monitoring system is reasonably priced.
6. Ultrasonic sensors are anticipated to offer accurate crack readings and could eventually take the place traditional ones.
7. It has been demonstrated that the use of strain gauge sensors is a dependable and effective method for identifying deflection in structural parts.
8. Strain gauges exhibit excellent sensitivity and the capacity to detect even the smallest deflections, allowing them to record and track deflections in real-time with reliability.
9. The wide range of structural materials that strain gauges work with improves their application.
10. By evaluating structural integrity, identifying problems, and making precise maintenance and repair decisions, the data collected by strain gauge sensors can be used to improve structural health monitoring practices in civil engineering.

5.2 Future Works

- Quantification of internal cracks that develop in structural members.
- Creating the user interface for the alarm system that is convenient to use.

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