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Detecting and Quantifying Structural Damage Using Sensor Based Algorithms

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Abstract
A crack or other type of damages causes a sharp discontinuity in the rotational displacement curve of a load-bearing structure. However, if the beam is not sufficiently loaded or the crack depth is very small, the discontinuity may be impossible to detect using conventional method. To understand cracks in concrete, important parameters such as characteristic length, fracture energy, and critical crack width are used. In this project, the crack width is estimated as either crack mouth opening displacement (CMOD/COD) or crack tip opening displacement (CTOD).This project involves early detection of cracks by sensors and quantification of the with help of algorithms. For the testing beam are used. Internal cracks are detected by ultrasonic sensors with the help of IoT. To quantify the cracks and show the position of the cracks, algorithms are used. Therefore, to monitor the damage at the early stage thereby avoiding the degradation of the structure we are proposing a regular monitoring system.
Key words: *discontinuity, crack depth, conventional method, fracture energy, critical crack width, crack mouth opening displacement (CMOD/COD), crack tip opening displacement (CTOD).*

1. INTRODUCTION

Structural health monitoring (SHM) is the process of using damage detection and characterization 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 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. The finite element method (FEM) and finite element analysis (FEA) are numerical simulation techniques employed to evaluate real-time experiments via analytical models utilizing sophisticated software; thus, complex analyses, such as those concerning stiffness and damping, can be performed with the FEM technique both easily and reliably, even for multi-story structures. In one investigation, a 15% reduction in stiffness was observed after examining the nine columns, while an overall stiffness reduction of 1.67% was noted.

METHODOLOGY

This section outlines the methodology employed during the health assessment of the selected structure. The primary steps and the operational mechanism of the developed sensor for structural health monitoring are illustrated in theaccompanying figure. Initially, the structure intended for health monitoring is identified, followed by the installation of sensors on it. Upon excitation, the data gathered by the sensors is transmitted to the acquisition system for storage. Subsequently, the collected data is analyzed to identify any variations caused by the excitation of the structure. Structural health monitoring (SHM) of beams involves the use of various techniques and methodologies to assess the condition, performance, and the integrity of 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 behavior 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:**

Analyze the collected data to understand the structural behavior. 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 behavior. 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.

2.1 Implementation Details

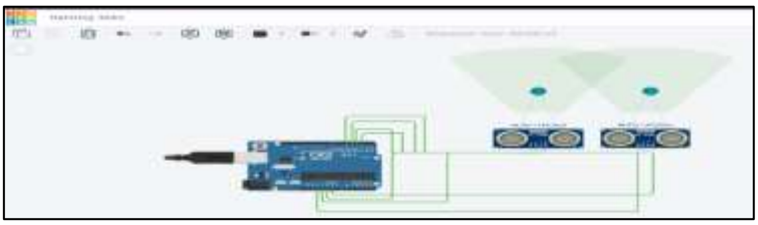

Fig 2.1 Simulation of sensors

Our suggested regular monitoring system utilized Tinker CAD software to evaluate the effectiveness of ultrasonic sensors in detecting and locating internal cracks. The software was employed to create simulations of the connection system, allowing us to ascertain the maximum distance the sensor can cover, as well as its coverage angle. The theoretical distance is 4 meters; however, for practical purposes in our project, we have set the maximum distance at 3 meters and the coverage angle at 15°.

2.2 Components of the Proposed Regular Monitoring System

Ultrasonic Sensor HC-SR04: This sensor consists of two ultrasonic transducers. One functions as a transmitter, converting electrical signals into 40kHz ultrasonic sound pulses, while the other serves as a receiver, capturing the transmitted pulses. The HC-SR04 offers a non-contact detection range from 2cm to 400cm with an accuracy of 3mm.

Fig 2.2(a) Ultrasonic sensor HC–SR04

Table2.2 (a) 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

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 is capable of communicating with a computer. The software for this board is known as Arduino IDE, which utilizes the C and C++ programming languages. Additionally, it features a serial monitor that enables the transmission of simple textual data to and from the boar

Fig 2.2(b) Arduino UNO board

Table 2.2(b) 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 15 mm

Strain gauge sensors: Strain gauge sensors operate based 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) This is affixed to the surface of the object under measurement. When the object undergoes deformation due to stress or strain, the foil similarly deforms, resulting in a variation in its electrical resistance. This variation in resistance is directly proportional to the strain that the object experiences.

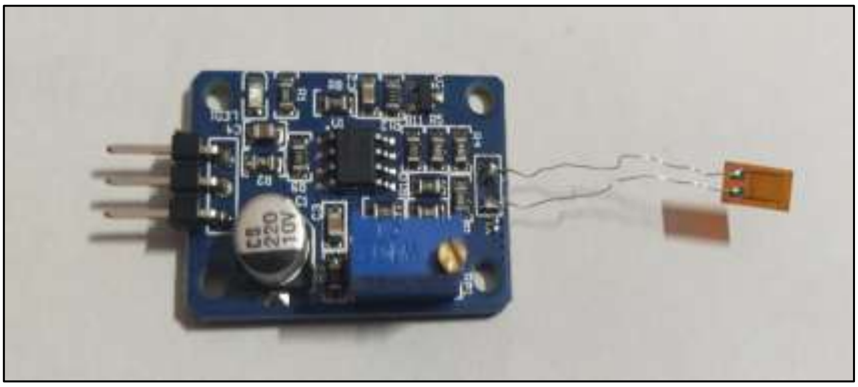

Fig2.3 Microcontroller with strain gauge sensor

Table 2.3 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 setup for measuring strain.
Dimensions	Physical measurements of the strain gauge (length, width, thickness).
Installation	Installation instructions, including recommended adhesive and curing process.

2.3 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 positioned on the beam's surface
- 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 relates to the position of greatest 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 2.3 Placement of (a) Ultrasonic sensor (b) Strain gauge sensor

- Subsequently, the sensors are linked to the Arduino UNO board, which will then connect to the laptop to upload the code using the 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 2.3(c) Experimental setup for beam testing

Fig 2.3(d) Experimental setup for cube testing

3 RESULTS AND DISCUSSION

Structural Health Monitoring (SHM) is essential for maintaining the integrity and safety of civil infrastructure. By consistently observing structures for indications of damage or degradation, SHM systems can issue early alerts, enabling prompt maintenance and repair measures to be implemented.

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 behavior 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.
- Ultrasonic sensors were positioned at various locations depicted in the figures below within each beam to evaluate the optimal placement of the sensor for achieving precise 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 despite the presence of coarse aggregates 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.

3.1 Deflection results

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

Table 3.1(a) 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

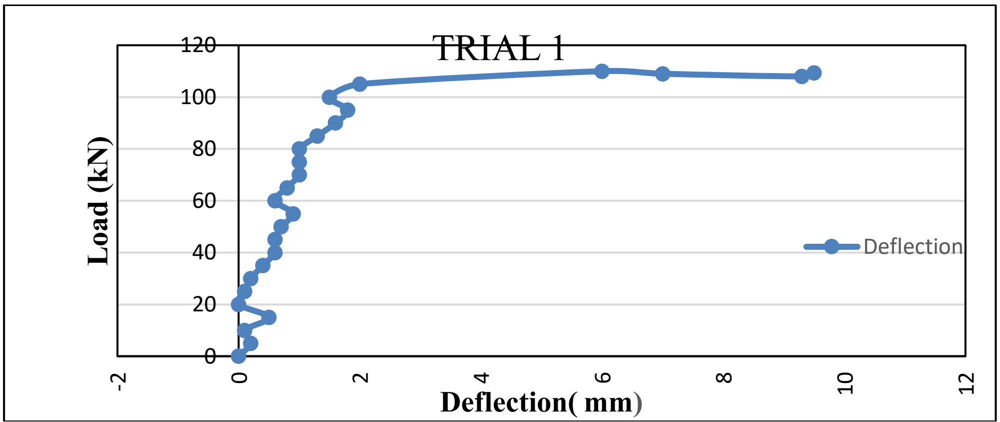

Fig 3.1(a) Load vs Deflection graph for Trial 1 readings

- 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 3.1(b) 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

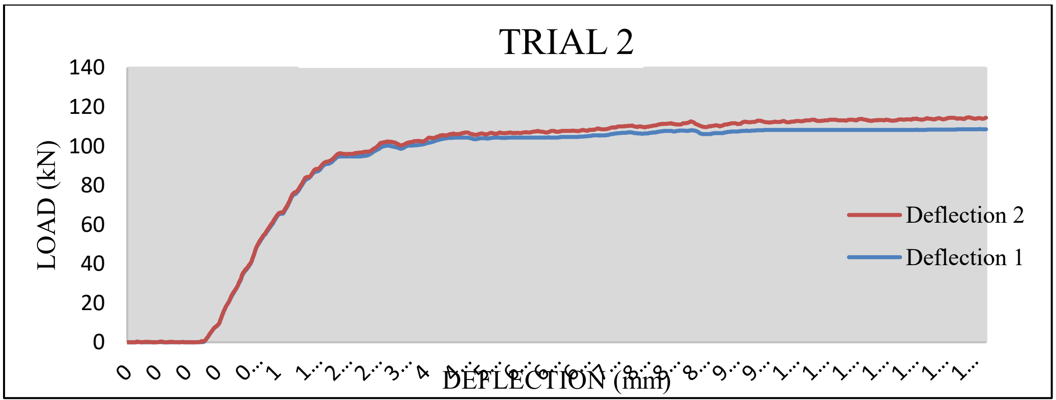

Fig 3.1(b) Load vs Deflection graph for Trial 2 readings

- 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.

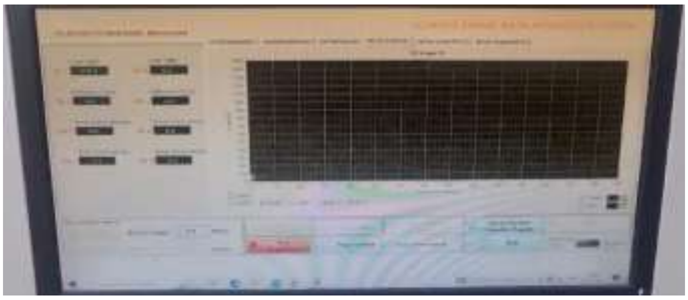

Fig 3.1(c): Deflection value obtained from loading frame

3.2 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 3.2(a) 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

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- 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 width of the crack was determined 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 3.2(b) Crack width detection readings on pre-cracked beam(c) Crack width detection readings on cube

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

(b)

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

(c)

- 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 3.2(a) 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 beam's length

Fig 3.2(b) Positioning of crack in the UI Page

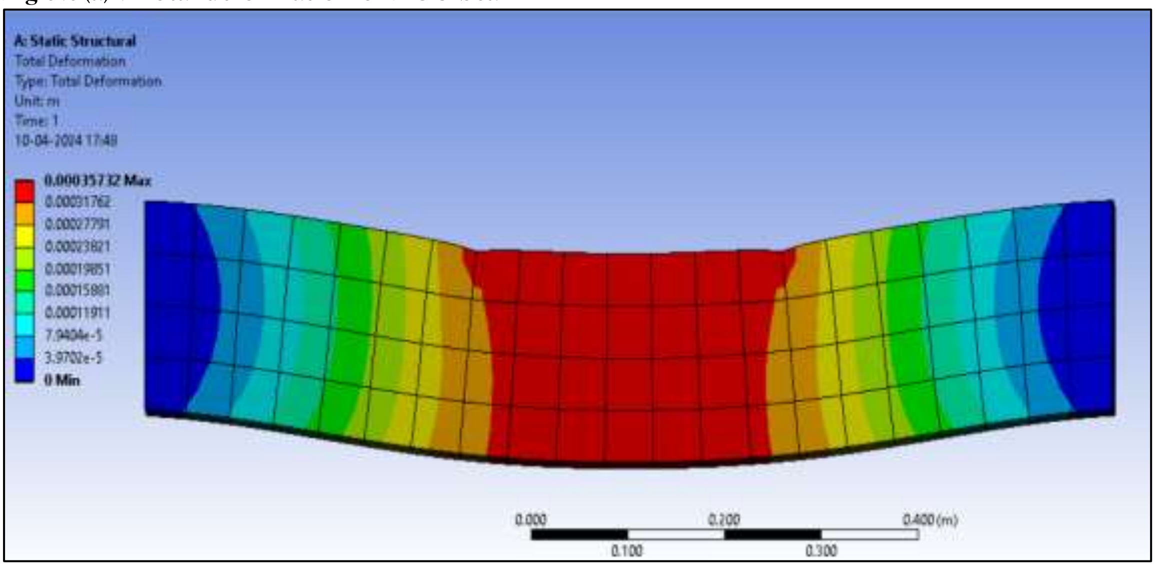
- To show the history of the cracks, deflection as well as the position of the cracks, we were successful able to develop a user interface (UI) using Languages : html, css , javascript and editor: VS code

Fig 3.2(c) History page of our UI

3.3 Validation

- The beam was verified through the use of 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 behavior of the system or structure being analyzed.

Fig 3.3(a) : Total deformation of RCC beam



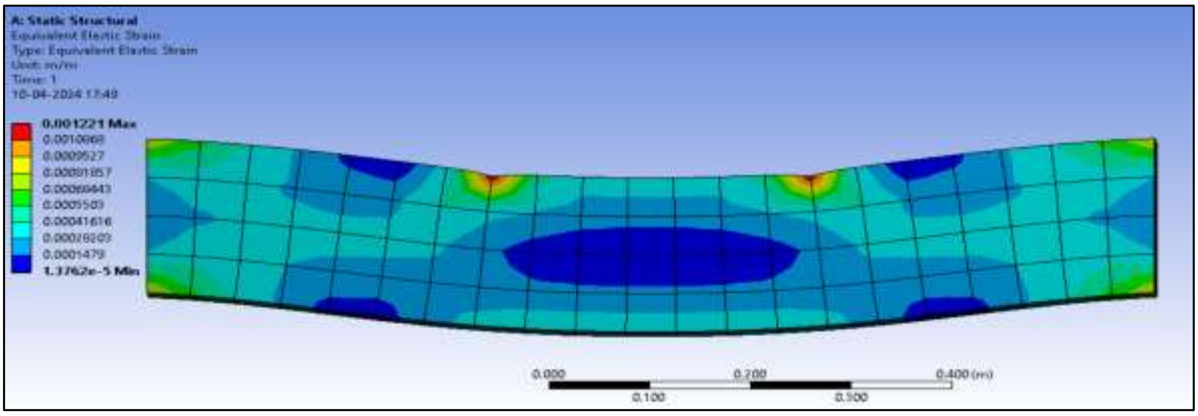


Fig 3.3(b) : Equivalent Elastic Strain after the RCC beam is Subjected to 2-point loading

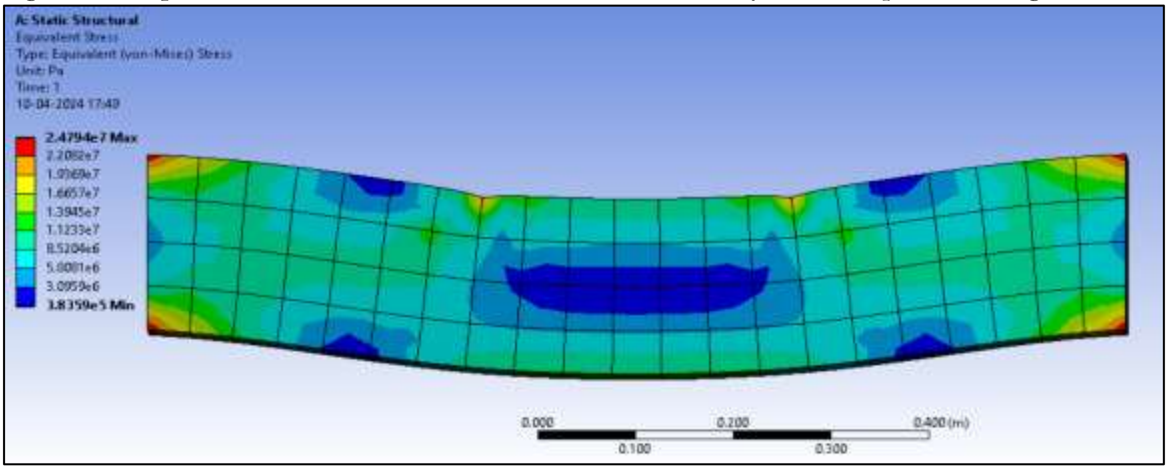


Fig 3.3(c): Equivalent Stress or Stress intensity after the RCC beam is Subjected to 2-point loading

4 CONCLUSIONS AND FUTURE WORK

4.1 Conclusions

1. Early detection and identification of internal fissures within 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 enhance structural health monitoring techniques in civil engineering.

4.2 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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