Application of Sensors in Structural Health Monitoring

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Abstract. Structural Health Monitoring (SHM) is a rapidly expanding discipline that offers a platform for continuous evaluation of civil engineering structures to assure their safety and serviceability. Based on the information collected from SHM, the structure's service life can be extended by doing the necessary maintenance/repair work, therefore averting failure. As a result, most industrialized nations are boosting their budgets for assessing the status of their important civil infrastructure. SHM quality may be increased by installing a large number of low-cost smart wireless sensors and using their computational and communication capabilities. These smart wireless sensors give critical data that may be used to detect, evaluate, and assess structural damage caused by heavy loads and environmental deteriorations. The data from these smart wireless sensors improves our understanding of the structural system's physical state. Structural health monitoring has employed a variety of sensors, including strain sensors, displacement sensors, acceleration sensors, temperature sensors, fibre optic sensors, and MEMS sensors. Force resisting sensor (FRS), piezoelectric sensor (PZS), micro-electromechanical systems (MEMS) accelerometer sensor, and Flex sensor (FLS) are used in this investigation on an RC beam. The first fracture recorded by several sensors under experimental static loading circumstances is shown, along with a comparative study. MEMS have been recommended for a range of SHM applications based on the findings.

Keywords: Structural health monitoring, RC Beam, Deflection, FRS, PZS, MEMS, FLS

1 Introduction

Our daily lives rely increasingly on civil engineering facilities such as bridges and buildings. The majority of India's current civil engineering structures have been in operation for many years. These buildings begin to degrade after they are placed into service, maybe owing to ageing and damage caused by day-to-day operations. As a

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result, assessing the status of these structures becomes more important for performing the necessary maintenance or repair [1]. Furthermore, it is vital to examine the status of civil engineering structures following natural hazards such as earthquakes, floods, and cyclones, as well as man-made disasters such as explosions. These critical/important civil engineering structures must be inspected and repaired as soon as possible to ensure their safety [2].

Tragic events involving civil infrastructure, such as bridge or building collapses, can result in a huge number of victims as well as social and economic consequences. Structural Health Monitoring (SHM) is a rapidly expanding discipline that offers a platform for continuous evaluation of civil engineering structures to assure their safety and serviceability [3]. Based on the information collected from SHM, the structure's service life can be extended by doing the necessary maintenance or repair work, therefore averting failure. As a result, most industrialized nations are boosting their budgets for assessing the status of their key civil infrastructure [4].

The SHM framework provides a chance to lower the cost of maintenance, repair, and retrofitting during the structure's lifetime. In the broadest sense, damage in civil engineering constructions alters the performance of materials, connections, boundary conditions, and so on owing to degradation. For example, material ageing has a negative impact on structural performance. Overloading frequently results in loads that differ greatly from the design loads, lowering the structure's safety and even causing it to fail. Damage to civil engineering structures can occur for a variety of reasons, including corrosion, repeated/fatigue loads, ageing, etc. Loads from vehicle movement, overloaded trucks, and wind may all harm bridge structures. However, extreme loads caused by cyclones, hurricanes, and earthquakes can also cause structural damage [5].

There are two types of damage in civil engineering structures: linear and non-linear. Linear damage causes the structure to act elastically even after the damage has occurred. Non-linear damage causes the structure to behave non-linearly after it has happened. Several SHM techniques have been presented during the last two decades. However, applying them to civil infrastructures presents a number of obstacles. To measure the performance of a structure, most contemporary SHM methodologies entail monitoring the amount of the loads acting on it. However, in many circumstances, measuring the loads acting on the structure (bridges) is difficult, and it is even more difficult to induce such loads in the structures to obtain answers [6].

This problem has limited the use of existing SHM methodologies for monitoring the health of civil engineering structures that need load measurements. Techniques based on ambient vibrations in the structure caused by loadings have gained popularity for structural health monitoring and assessment [7]. However, further study is needed to create health evaluation algorithms that exploit the ambient vibration of buildings. Another challenge in implementing the current SHM technique is that damage is a local phenomenon [8]. Sensors near the damage area provide the most responses as compared to those further away from it. To efficiently identify the site of damage in a structure, sensors must be closely dispersed throughout it [9].

Using a traditional wired sensor system, installing multiple sensors to assess a structure's health will be challenging due to the difficulties in routing the cables from the sensor sites to the central data collecting system. The cabling necessary to link the sensors instrumented for monitoring major civil engineering structures to the primary data gathering system is more complex and difficult to handle since the cables are readily broken [10]. SHM is used to analyze the health and condition of structures prior to failure by monitoring them and detecting any damage. SHM is critical for monitoring the health of any structure in order to ensure the safety of its workers and has economic repercussions. SHM is a novel idea in engineering [11].

It is designed to continuously monitor buildings in real time. It also assesses structural performance under various external stimuli in order to detect damage or degradation and guarantee the health of the structures/components. Over the last three decades, various nondestructive testing procedures have been developed to help progress SHM. Proof loading, coring, radar methods, and conductivity mapping are all examples of non-destructive testing (NDT) techniques used to improve the visual inspection approach for concrete and brickwork-based civil constructions. Many studies have attempted to identify the best ways of predicting damage in mechanical, civil, and aeronautical structures for SHM applications [12]. SHM is used to monitor operating loads and components/structures that are prone to inadvertent failure.

The SHM in real time is critical for manufacturers, end users, and maintenance teams. The SHM system provides for efficient structure utilization, prevention of catastrophic failure, and reduced downtime [13].

Structural health monitoring has employed a variety of sensors, including strain sensors, displacement sensors, acceleration sensors, temperature sensors, fibre optic sensors, and MEMS sensors. Mechanical deformation, temperature change, fibre optics-based deformation detection, and other parameters are examples of sensing techniques. Sensors are utilized in both passive and active control, enabling for online assessment, rapid evaluation during accidents, and lower inspection costs. Typically, strain sensors are employed for increased durability [14].Displacement sensors are utilised for water-based monitoring applications. Piezoelectric sensors are utilised in structural health monitoring to detect mechanical stress and analyze beam structures [15].

Objectives of the Study

The following are the aims of this research work:

1. To monitor the deflection of concrete beams with low-cost Arduino-based microcontrollers and four distinct sensors.
2. Four distinct sensors, including FRS, FLS, MEMSA, and PZS, will be used to monitor the first fractures and eventual failure of the concrete beam under static loading circumstances.

2 Methodology

The major goal of the RC design is to ensure that the structure is safe and functional. A significant amount of money is spent on a regular basis to safeguard structures and people. Monitoring structural health allows for assessment of the SHM. In

SHM, sensors are used to assess the current state of a structure. Strain gauges and other sensors are used to monitor structural deformation.

The data acquired from the SHM would aid in the structural design of structures subjected to variable mechanical, thermal, and environmental stresses. SHM is increasingly being used to detect structural failures early on. Furthermore, heritage structures rely on SHM approaches to conserve and enhance their worth. The use of sensors in SHM research is rather easy. Thus, sensor selection can have an influence on structural component accuracy. This study focuses on a beam of reinforced concrete (RC) on which a monotonic load of two-point is acting. The basic response of the RC beam under four-point bending under static loading circumstances is captured by many sensors, including the following:

i. FLEX SENSOR (FLS)
ii. PIEZOELECTRIC SENSOR (PZS)
iii.MICRO-ELECTROMECHANICAL SYSTEMS (MEMS)
iv.ACCELEROMETER
v. FORCE-RESISTING SENSOR (FSR)

The experimental results support the sensor-theoretical theories. As a result, the MEMS accelerometer sensor on the RC beam component was found to work better than other sensors.

3 Experimental Work

To evaluate the functionality and performance of various sensors, expertimental work was performed by casting an RC beam, putting the sensor, and testing. Details about test specimens To investigate the behaviour, simply supported reinforced concrete beams were used, with four points of bending in relation to the sensor. IS 10262:2009 was used to balance concrete blends, whereas IS code 456-2000 was utilised to design remaining concrete beams. The concrete's compressive strength was 30MPa.

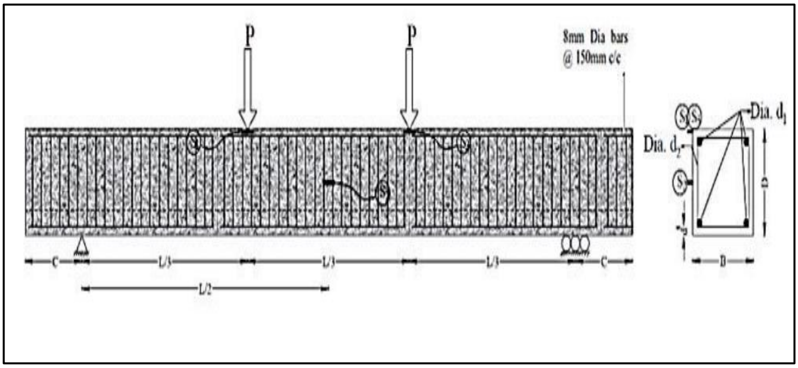
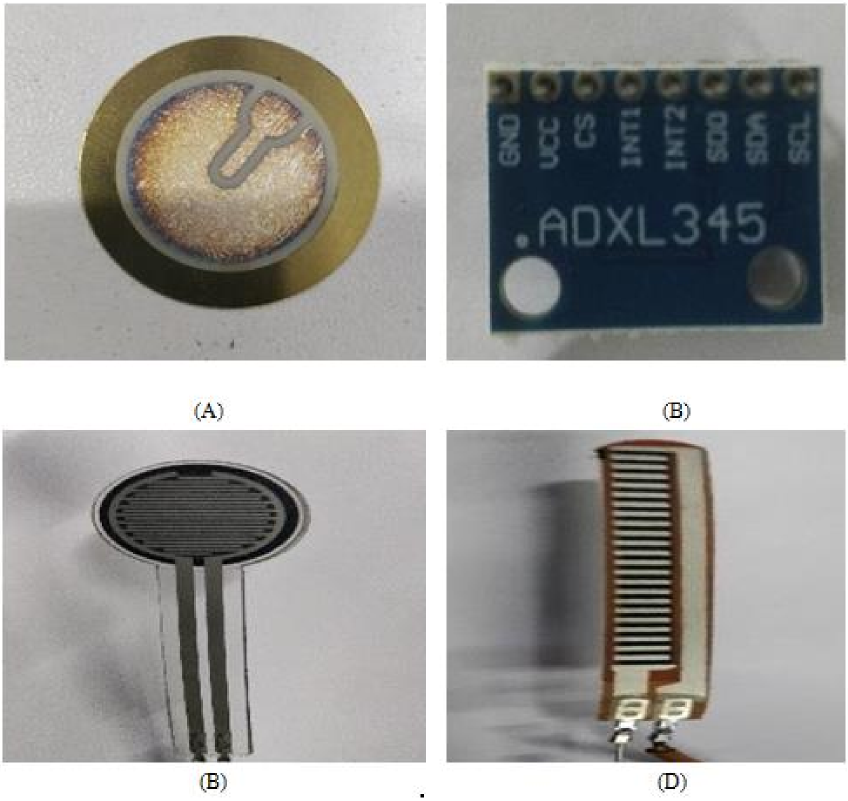


Fig.1. RC beam's geometrical details

Sensor Applications using RC Beams SHM can be accomplished using sensors, particularly on structural components, to measure stresses caused by changing mechanical loads. As a result, selecting adequate sensors will offer you with precise measurements. There is a large variety of sensors on the market, and some may be suitable for a wide range of applications. The post-yield sections of the stress-strain envelope or load-displacement are where strain measurements of RC components can be most reliable; nevertheless, these areas are rarely investigated. Spacer glue was employed to divide the conductive substrate from the FSR layer substrate, which had been inked with a carbon base.

Stressing the FSR resulted in resistance from shorted carbon-based ink traces. The resistance of the flex sensor changes when the substrate component is bent or twisted (the flex angle). Because gravity provides the energy for kinetic motion, the MEMS accelerometer's proof mass is an oscillator capable of detecting extremely small movements.



(A) (B)

(B) (D)

Fig.2. (A)Piezoelectric sensors (PZS), (B) MEMS Accelerometer sensors (MEMSA),(C) &(D) Force resisting sensor (FRS)

Software used in this experiment: The experiment's software selection is critical, thus communication between the specimen and the sensors must be reliable. Furthermore, affordable systems have been strongly sought; hence, this experiment employs open-source, free software. As a consequence, two software programmes were employed in this study.

1. XCTU : It functions as a communication protocol to set settings according to experiments to receive correct data.

2 Arduino Software : It enables to upload commands to access the Arduino board remotely.

Experimental Details:

First, degrees of deflection must be determined at three locations on the RC beam: S1, S2, and S3. We utilised a flex sensor with a length of 5.588 cm and variable resistance. When PZS is loaded, it changes form and is used to monitor voltage. Along with these three sensors, a fourth, known as the Force sensor, is employed. This sensor detects how much force is exerted on the beam at various load levels. A force sensor is a common form of transducer. It contains wires inscribed on a metal plate that is completely coated in a polyimide coating to block out external noise. When a load is applied to the sensor, the load is amplified into an electric signal, and the signal's proportional reading is calibrated.

Four sensors were connected to the Arduino board, which displayed the data using the open-source Arduino integrated development environment (IDE). The fundamental programme is designed to separate sensor data into Dimensions and Measures. The computer system allows us to monitor live data in measurements. The RC beam has dimensions of one metre in length, 150 mm in width, and 100 mm in depth. Markings were drawn across the beam at 1/3rd L (S1), 1/2L (S2), and 2/3rd L (S3), and sensors were placed in these positions. We have four identical RC beams. When a beam is exposed to a minimum tensile tension, the sensor recognises that it deforms.

A force amplifier is used to increase the intensity of deformation under different load situations. The proportional reading may be examined on a home computer with open-source software.

Fig.3. MEMSA interconnected to an Arduino Board

4 Results and Discussions

The experiment was carried out under static loading circumstances and using four separate sensors. Table 1 shows the displacements measured for all four sensors (PZS, MEMSA, FLS, and FRS) at their respective loading points at the hinge support, the centre of the effective span, and the roller support. Figure 4 depicts the load-displacement profile for three different loads @L/2. Furthermore, for a close-up visualization of the first crack and eventual failure, the plot starts at 5 mm displacement with 60kN and ends at the failure load, which matches the displacement.

Table 1. Displacement measurements for four different sensors

Time	**Load**	**Centre of effective span @L/2**			
		FRS	**FLS**	**MEMSA**	**PZS**
minutes	**kN**	**mm**			
0	0	0.000	0.000	0.000	0.000
1	10	1.410	1.830	1.710	2.310
2	20	1.530	2.120	1.930	2.940
3	30	2.310	2.930	2.840	3.260
4	40	2.900	3.840	3.200	4.180
5	50	4.260	4.860	4.370	4.920
6	60	5.380	5.320	5.990	5.870
7	70	6.360	6.140	6.710	6.770
8	80	6.910	7.270	7.380	7.600
9	90	8.140	7.970	8.810	8.870
10	100	9.310	8.700	9.910	9.980

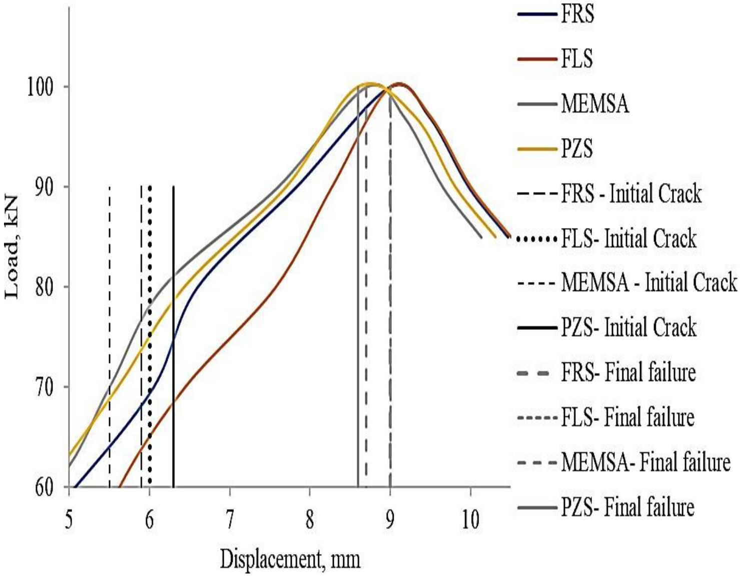


Fig.4. Load Vs Disp at half span

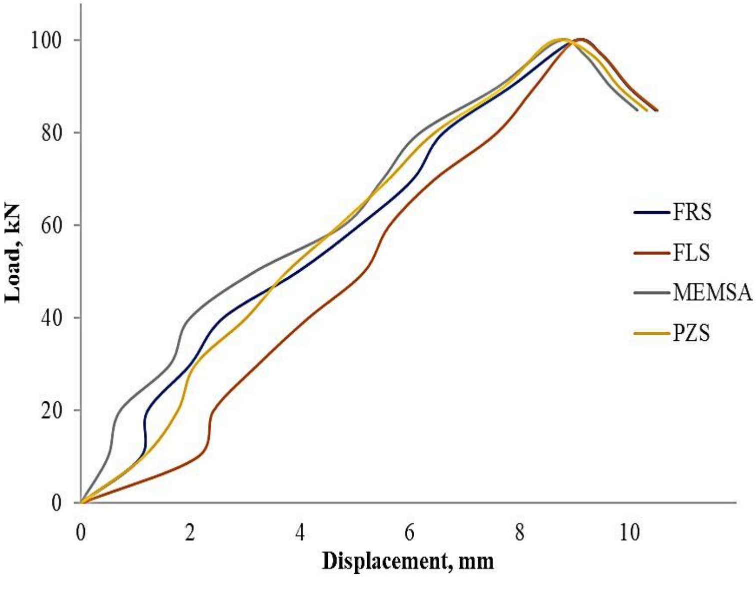


Fig.5. Load Vs Displacement at half span with cracks

Figure 5 shows that the FLS can withstand a 10 kN load without causing any displacement, whereas the FRS, MEMSA, and PZS show zero loads at the start of the experiment. Except for FLS from 0 to 2mm, no significant change in profile was seen for any of the sensors. MEMSA followed the FRS and PZS after 2 mm of dislocation and lasted till 4.1 mm. Nevertheless, FLS beats remaining sensors up to 3.3 mm.

The MEMSA recorded 58 kN, resulting in a displacement of 3.9 mm that intersected the FRS upon load of 71 kN, resulting in a displacement of 5.32 mm. MEMSA exhibited a substantial advantage over FRS until a defoemation of 6.1 mm, which is equivalent to 81 kN. Furthermore, MEMSA has less failures than other sensors. Furthermore, it is reasonable to assume that PZS and FLS are parallel, as numerous data points beyond 3.35 mm show substantial overlap. FRS has significantly greater variation than the other sensors.

The recorded loads of FLS, PZS, MEMSA, and FRS at the initial crack are 69.8 kN, 65.5 kN, 62.8 kN, 67.2 kN, which equate to displacements of 6 mm, 6.3 mm, 5.5 mm, 5.9 mm, and should be taken as a computation to detect initial damage by visual examination. Following that, a sharp slope is seen until a load of 20 kN for all sensors excluding PZS, which can detect loads up to 30 kN. A like kind of linear is detected for displacements of up to 7.3 mm, 7.4 mm, 5.8 mm, 7.6 mm for all sensors. Even a 0.5mm failure displacement shift would have a substantial impact on prototypes in construction practice.

5 Conclusions

As civil engineering breakthroughs have grown in importance, SHM has been used to improve their uniformity and efficacy. SHM gathers data from structures to detect and forecast deterioration based on present and future circumstances. FLS, MEMS, PZS, and FSR accelerometer sensors were employed in this study to investigate the structural performance of an reinforced concrete beam with 2-point loading. The following findings have been reached.

1. Force sensors (FRS), Flex sensors (FLS), Micro Electro Mechanical System Accelerometer (MEMSA), and Piezoelectric sensors (PZS) were utilised to measure progressive deflections of RC beams under force ranging from 10-100kN. It was discovered that the low-cost Arduino-based microcontroller was particularly efficient at detecting damage at an early stage.
2. A sensor's sensitivity may be anticipated from the initial fracture formed by a beam under gradual load application. As a result, L/3, L/2, and 2L/3 each have three identical sensors installed in three places.
3. The first break in MEMS was seen at 5.5mm (L/3), 5.8mm (L/2), and 5.3mm (2L/3) of deflection under static stress conditions of 62.6kN, 62.2kN, and 63.5kN, respectively. While conventional sensors anticipated first breaking outside this deflection range, MEMS can be suggested for many SHM applications.

6 References

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