

Real-Time Strain Measurement and Monitoring of Iron Plate Structural Resistance Using a Strain Gauge Sensor and Arduino Uno Microcontroller

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Abstract

Steel plates are widely used in structural applications because of their ability to maintain structural form and their high tensile strength, which allows them to withstand significant loads in construction. This study presents the development of a monitoring system designed to measure strain in steel plate structures using strain gauge sensors. A theoretical comparison based on the elastic modulus of steel plates was employed to calculate stress, strain, and elongation under varying loads. The strain values recorded by the sensors are processed through an ESP32 microcontroller and displayed on an LCD screen for real-time observation. To enhance safety, the system is equipped with a buzzer and indicator lights that provide early warnings when the applied load exceeds a specified threshold. Experimental results show an average measurement error of only 2,98% compared to theoretical values, confirming the system's accuracy and reliability. The proposed system offers a cost-effective and practical solution for infrastructure maintenance and supports the early detection of structural strain in steel plates.

Keywords: *Structural health monitoring, strain gauge sensor, steel plate, ESP32, modulus of elasticity*

1. Introduction

The rapid advancement of technology requires engineers and technicians to design structural systems that are lighter while maintaining safety, durability, and efficiency. Therefore, comprehensive and systematic planning is essential in the construction industry to ensure structural reliability and performance. One of the fundamental aspects of such planning is material testing. Material testing plays a crucial role in evaluating the mechanical properties and behavior of construction materials under various loading conditions. When an object is subjected to a sufficiently large force, it undergoes deformation and changes in shape, which may affect its structural integrity and overall performance[1], [2].

Strain is defined as the change in the length of a material relative to its original length when subjected to an external force[3]. To ensure that a structure can withstand various operating and environmental conditions, reliable measurement instruments are required to evaluate its resistance to stress and mechanical loading. Such measurements are essential

for assessing structural performance, safety, and long-term durability[4].

Structural Health Monitoring (SHM) has been extensively investigated in previous research, with several studies focusing on different monitoring techniques and sensing technologies[5], [6], [7], [8]. For instance, a study entitled "Implementation of a Wireless Sensor Network in a Bridge Structural Health Management System" investigated the application of SHMS technology for real-time online bridge condition monitoring. The results demonstrated the potential of SHMS to support the development of more advanced, reliable, and responsive structural monitoring systems[9]. Another study, entitled "Strength Analysis of a Semi-Automatic Clothes Drying Rack Frame under Static Loading Based on an Arduino Microcontroller," investigated the structural performance of a semi-automatic drying rack frame subjected to static loading, utilizing an Arduino microcontroller as the main control system. This study utilizes a BF350-3AA strain gauge connected to an Arduino module for strain measurement in structural components. The

sensor is used to detect deformation resulting from applied loads and to evaluate the structural response under loading conditions[10]. Furthermore, a study entitled “Trends, Costs, and Challenges of Bridge Structural Health Monitoring” examined the emerging trends in the application of Structural Health Monitoring (SHM) systems for bridges, as well as the associated costs and implementation challenges. The study provided valuable insights into the barriers that must be addressed to facilitate the broader adoption of SHM technologies in bridge infrastructure monitoring.[11]

Based on the aforementioned background, this research aims to develop a strain measurement system for assessing the structural behavior of iron plates using a strain gauge sensor. The proposed method applies theoretical calculations based on the elastic modulus of the material to evaluate stress, strain, and elongation under different loading conditions. Experimental strain measurements are obtained using a strain gauge sensor attached to the iron plate. The measured data are subsequently processed by an ESP32 microcontroller and presented in real time on an LCD display.

2. Research Methods

2.1. System Design

The system workflow designed in this study is illustrated in Figure 1 and begins with the initialization process. The first step involves initializing the ESP32 microcontroller, which serves as the main controller for processing data acquired from the strain gauge sensor. This enables the system to measure the strain experienced by the monitored structure. Subsequently, the buzzer and LED are initialized to provide audible and visual warning indicators whenever the measured strain exceeds the predefined threshold. In addition, an LCD is initialized to display the measurement results directly to the user.

After the hardware initialization is completed, a database is initialized to store the data collected during the measurement process. The program then reads the output signal from the strain gauge sensor and converts the analog input into digital data. The resulting strain values are subsequently processed and calibrated to ensure measurement accuracy. The calibrated data are stored in variables and compared with theoretical values calculated using the material's modulus of elasticity.

The next stage involves evaluating the measured strain values to determine whether they remain within the normal operating range or exceed the specified threshold. If the strain value reaches or exceeds 15% of the maximum allowable strain, the buzzer and LED

are activated to provide an early warning indication. Conversely, if the measured strain remains within the normal range, the buzzer and LED remain inactive.

Finally, the processed measurement data are displayed in real time on both the Serial Monitor and the LCD and are stored in the database for further monitoring and analysis.

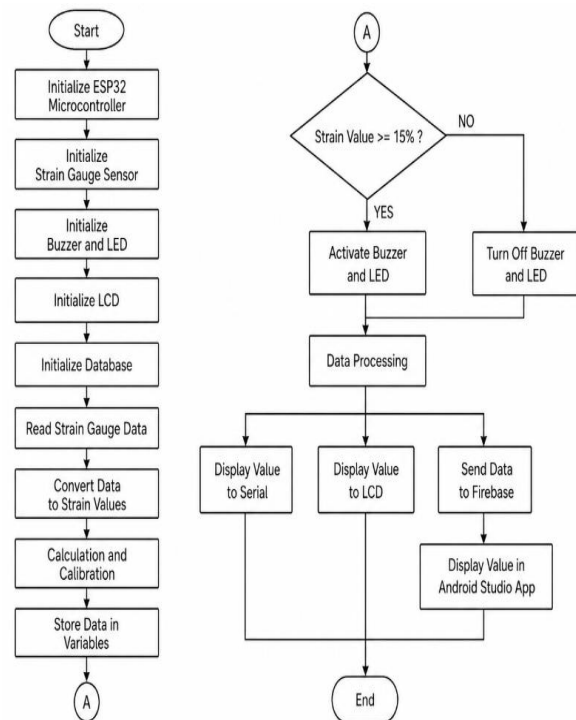


Figure 1: Flowchart System

2.2. Electrical Design

The electrical design in this study involves the development and integration of the hardware components used in the monitoring system. The system consists of a BF350-3AA strain gauge sensor as the data input device, an ESP32 microcontroller as the main processing unit, an LCD for displaying measurement results, push buttons for calibration and data display functions (including a tare button for zero calibration and a hold button for retaining measurement values), LEDs and a buzzer as overload indicators, a power switch for system activation and deactivation, and a power supply powered by an adapter.

As shown in Figure 2, the electrical design stage is a critical process to ensure that all components are correctly connected through proper wiring and assigned to the appropriate ESP32 input/output pins. This stage is essential for guaranteeing reliable system operation, accurate signal acquisition, and proper initialization of the microcontroller pins required for sensor reading and peripheral control.

In this research, the electrical design and circuit

schematic were developed using EasyEDA software, which facilitated component integration, circuit verification, and hardware implementation prior to prototype development.

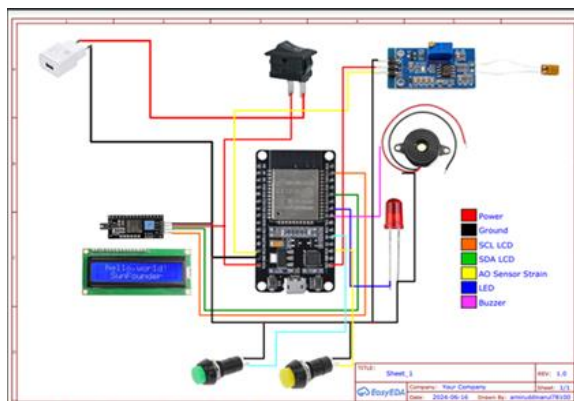


Figure 2: Electrical Design

2.3. Mechanical Design

The mechanical design stage involves the development of the structural framework and supporting components for the strain measurement system on a steel plate specimen. The main frame is constructed from aluminum profiles, with a horizontal support beam serving as the primary structure for holding the test steel plate. This design is intended to ensure uniform load distribution throughout the testing process.

The steel plate is positioned on the upper section of the frame, resembling a bridge structure on which loads are applied during testing. This arrangement enables accurate strain measurements using a strain gauge sensor mounted on the underside of the steel plate, where strain responses can be effectively detected and monitored.

The use of strong and dimensionally stable materials ensures that the supporting structure can withstand the applied loads without experiencing significant deformation. Consequently, the measurement system can provide reliable and accurate strain data, which can be utilized for the assessment and evaluation of structural health conditions.

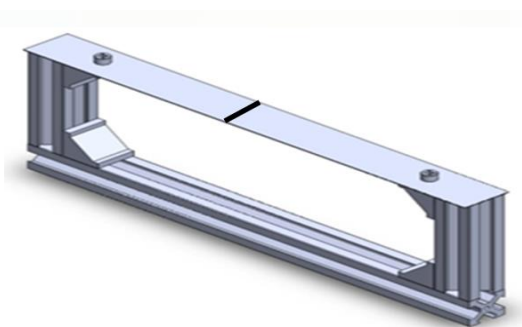


Figure 3: Mechanical Design

The mechanical design consists of two main categories: the design of the steel plate structure and the design of the enclosure that components. The steel plate structure serves as the test specimen for load application and strain measurement, while the enclosure provides protection and organization for the electronic components integrated into the system.

Figure 3 illustrates the mechanical design and overall dimensions of the developed system. The primary dimensions include a length of 500 mm, a height of 100 mm, a width of 24.7 mm, and a thickness of 1.7 mm. These dimensions represent the overall size of the test structure and provide a compact yet robust rectangular configuration suitable for load testing and strain measurement applications.

The selected dimensions were designed to ensure adequate structural strength, stability, and measurement accuracy during experimental testing. Furthermore, the compact design facilitates system integration while maintaining the structural integrity required for reliable load-induced strain analysis.



Figure 4: Box of Mechanical Design

Figure 4 illustrates the mechanical design of the enclosure used all components integrated into the monitoring system. The enclosure has dimensions of 180 mm in length, 110 mm in width, and 50 mm in height. These dimensions provide sufficient space for component installation while maintaining a compact and practical design.

Several components are mounted on the top panel of the enclosure, including the power on/off switch, hold and tare buttons, LCD display, buzzer, LED indicators, and cable routing openings. The LCD display serves as the primary interface for presenting measurement data, while the buttons enable system control and calibration functions. The buzzer and LED indicators provide audible and visual alerts during system operation.

Cable routing openings are incorporated into the enclosure design to facilitate the organized entry and exit of wires. These openings help maintain proper cable management, improve the overall appearance of

the system, and protect the wiring from mechanical damage. As a result, the enclosure enhances both the functionality and reliability of the monitoring system during operation.

3. Result and Analysis

The testing procedure was conducted to measure the strain values generated on a steel plate using a strain gauge sensor connected to an ESP32 microcontroller. The measured data were processed and subsequently displayed on an LCD screen for real-time monitoring.

During the experiment, different loads were applied to the steel plate structure to evaluate the strain response under varying loading conditions. The applied loads ranged from 0 g to 1500 g and were placed on the upper surface of the steel plate, while the strain gauge sensor was installed on the underside of the plate to detect the resulting strain.

The variation in loading conditions allowed the relationship between the applied load and the measured strain to be analyzed and evaluated. Figure 5 illustrates the position of the loads applied to the steel plate structure during the measurement process.



Figure 5: Load Application Position on the Steel

The Serial Monitor displays the data processed by the voltage and strain measurement system. The data presented in Table 1 represent the analog readings obtained when the analog pin is configured as an input. The output values range from 0, corresponding to 0 V, to 4095, corresponding to 3.3 V, based on the 12-bit Analog-to-Digital Converter (ADC) resolution of the ESP32 microcontroller.

These raw analog readings require further processing using Microsoft Excel to establish a linear relationship between the sensor output and the applied load. Through this linearization process, a calibration equation can be derived, enabling the conversion of analog readings into meaningful strain values.

The resulting linear data provide the basis for calculating strain and analyzing the structural

response of the steel plate under different loading conditions.

TABLE 1
Analog Output Data of Strain Gauge Sensor

No	Beban (Gram)	Analog Read Rata Rata	Tegangan ADC (Volt)	Tegangan Multimeter (Volt)	Error(%)
1	0	0,0	0,000	0,020	2,0
2	500	119,5	0,096	0,103	6,5
3	800	190,5	0,154	0,160	4,1
4	1000	240,8	0,194	0,197	1,5
5	1300	319,8	0,258	0,251	2,7
6	1500	366,4	0,295	0,286	3,2

The linearized data must first be converted into digital measurement values for further analysis. The ESP32 analog input supports a 12-bit resolution, resulting in output values ranging from 0 to 4095. In this range, a value of 0 corresponds to an input voltage of 0 V, while a value of 4095 corresponds to an input voltage of 3.3 V. This process of converting an analog signal into a digital value is known as Analog-to-Digital Conversion (ADC).

To convert the ESP32 output data, which are represented as digital bit values, into voltage values expressed in volts, a calibration procedure was performed. During calibration, known voltage levels were applied to the ESP32 analog input, and the corresponding digital output values were observed and recorded through the Serial Monitor. This procedure established the relationship between the ADC output and the input voltage.

Based on this relationship, the measured digital values can be converted into voltage values using Equation 1[12].

$$V_{in} = \left(\frac{\text{Analog Read Average}}{4095} \right) \times 3,3 \text{ Volt} \quad (1)$$

Based on the ADC-to-voltage conversion presented in Equation (2), the calculated voltage for an applied load of 1000 g was 0.194 V. This voltage value was subsequently used to determine the corresponding strain value of the steel plate.

$$\text{Tegangan (Volt)} = \frac{240,8}{4095} \times 3,3 = 0,194 \text{ Volt} \quad (2)$$

The results of the voltage measurement system under varying loads ranging from 0 g to 1500 g are presented in Table 2. The data were collected by recording the voltage values displayed on the Serial Monitor and measuring the corresponding voltages using a multimeter to validate the output of the BF350-3AA strain gauge module.

The results indicate that the voltage values obtained

from the Analog-to-Digital Converter (ADC) are in close agreement with those measured using the multimeter, demonstrating the reliability of the measurement system.

Furthermore, the relationship between the applied load and the measured voltage exhibits a linear trend. As illustrated in Figure 6, the voltage increases proportionally with the applied load. This observation confirms that the relationship between load and voltage is directly proportional and can be accurately represented by a linear function.

The linear behavior of the system indicates that the strain gauge sensor and signal conditioning circuit respond consistently to changes in loading conditions, making the system suitable for strain measurement and structural health monitoring applications.

TABLE 2
Voltage Measurement Results

No.	Load (Gram)	Average Analog Read	ADC Voltage (Volt)	Multimeter Voltage (Volt)	Error (%)
1	0	0.0	0.000	0.020	2.0
2	500	119.5	0.096	0.103	6.5
3	800	190.5	0.154	0.160	4.1
4	1000	240.8	0.194	0.197	1.5
5	1300	319.8	0.258	0.251	2.7
6	1500	366.4	0.295	0.286	3.2

Figure 6 shows the relationship between voltage and strain. The coefficient of determination (R^2) obtained from the linear regression analysis confirms a strong positive linear correlation between voltage and strain. As the voltage increases, the strain value also increases proportionally, indicating that the sensor provides a consistent and reliable response to structural deformation.

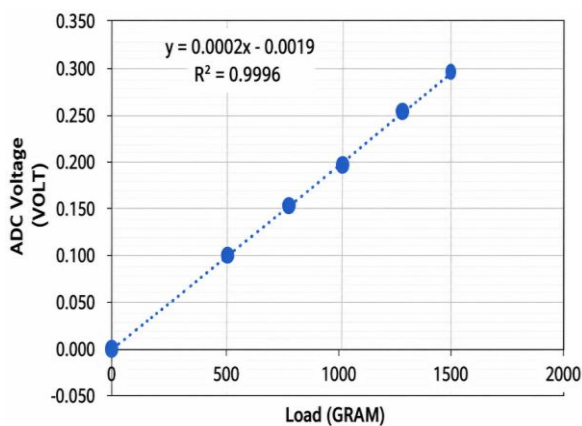


Figure 6: linear graph between voltage and strain

After the voltage measurements were obtained from

the BF350-3AA strain gauge module, the resulting voltage differences were further analyzed and converted into strain values (ϵ). This conversion was performed using Equation 5, allowing the mechanical deformation of the steel plate to be quantified in terms of strain.[4]. The voltage difference (V_r) was determined using Equation 4 under strained conditions. Because the initial condition prior to load application corresponded to a zero-reference state, the resulting V_r value represents the voltage variation induced by the applied load[4].

The Gauge Factor (GF), which represents the sensitivity of the strain gauge to mechanical deformation, was assumed to be constant with a value of 2.14, according to the manufacturer's specifications[4]. The strain calculation equation is based on the Wheatstone bridge circuit configuration. Therefore, the voltage value obtained from the ADC output must be divided by the amplification factor (G) of 1215.34, which was determined from the gain calculation presented in Equation (3). This correction is necessary to obtain the actual bridge output voltage before calculating the strain value [4]

$$G = \frac{4 + 940 \text{ k}\Omega}{RG} \quad (3)$$

$$G = \frac{4 + 940 \text{ k}\Omega}{0,776 \text{ K}} = 1215,34$$

$$V_r = \left(\frac{V_{\text{Output}}}{V_{\text{in}} \times G} \right) \quad (4)$$

$$V_r = \frac{0,194}{3,3 \times 1215,34} = 0,000048$$

$$\epsilon = \frac{4V_r}{GF(1+2V_r)} \quad (5)$$

$$\epsilon = \frac{4.(0,000048)}{2,14(1+2 \times 0,000024)} = 0,000089$$

For the applied load of 1000 g, the measured ADC voltage was 0.194 V. Using the calculation procedure described previously, the corresponding bridge output voltage (V_r) was determined to be 0.000048 V. Substituting this value into the strain equation resulted in a strain value (ϵ) of 0.000089.

The results demonstrate the conversion of the measured voltage into strain values based on the Wheatstone bridge principle and the amplification characteristics of the signal conditioning circuit. The complete strain measurement results obtained under loading conditions ranging from 0 g to 1500 g are presented in Table 3.

TABLE 3
Strain Measurement Results

No.	Load (Gram)	G	GF	DC Voltage (Volt)	Vr (Voltage Ratio)	Strain (Strain)
1	0	1215.34	2.14	0.000	0.000000	0.000000
2	500	1215.34	2.14	0.097	0.000024	0.000045
3	800	1215.34	2.14	0.154	0.000038	0.000072
4	1000	1215.34	2.14	0.190	0.000047	0.000089
5	1300	1215.34	2.14	0.247	0.000062	0.000115
6	1500	1215.34	2.14	0.285	0.000071	0.000133

The measured strain values were then compared with theoretical calculations based on the modulus of elasticity. The test specimen used in this study was a steel plate with a modulus of elasticity (E) of 100×10^9 Pa[1]. Using the obtained strain values, the corresponding stress (σ) was calculated according to Hooke's Law, as presented in Equation 6[4]. This equation defines the relationship between stress, strain, and the material's modulus of elasticity.

For the loading condition of 1000 g, the calculated strain value of $\epsilon = 0.000089$ resulted in a stress value (σ) of 8.9×10^6 Pa (N/m^2). The calculated stress represents the internal force per unit area generated within the steel plate due to the applied load.

$$\sigma = \epsilon \times E \text{ plat besi} \quad (6)$$

$$\sigma = 0,000089 \times (100 \times 10^9) = 8.900.000 \text{ PA}$$

The stress measurement results obtained through the theoretical modulus of elasticity approach under loading conditions ranging from 0 g to 1500 g are summarized in Table 4. These values were calculated based on the measured strain and the modulus of elasticity of the steel plate specimen.

TABLE 4

Stress Values Calculated Using the Modulus of Elasticity Method

No	Load (Gram)	Strain	Stress (N/m^2)
1	0	0.000000	-
2	500	0.000045	4,500,000
3	800	0.000072	7,200,000
4	1000	0.000089	8,900,000
5	1300	0.000115	11,500,000
6	1500	0.000133	13,300,000

To validate the strain measurement results obtained from the strain gauge sensor, a theoretical analysis based on beam bending theory was performed. The steel plate specimen used in this study had a thickness

of 0.0017 m and a length of 0.5 m. The distance from the load application point to the observation point (L) was 0.245 m, while the gravitational acceleration (g) was assumed to be 9.81 m/s^2 .

The validation process was conducted using applied masses ranging from 0 g to 1500 g. As an example, a mass of 1000 g (1 kg) was used to demonstrate the calculation procedure. The applied mass was converted into force (W), which was then used to determine the bending moment (M), the second moment of area (I) of the steel beam section, the distance from the neutral axis to the outer surface (y), and the resulting stress (σ).

These parameters were calculated using Equations 7–11[4] and were subsequently employed to evaluate the theoretical strain values of the steel plate. The calculated theoretical results were then compared with the strain values measured by the strain gauge sensor to assess the accuracy and reliability of the developed measurement system.

$$W = m \times g \quad (7)$$

$$W = 1 \text{ kg} \times (9,81 \text{ m/s}^2) = 9,81 \text{ N}$$

$$M = 0,5 \times W \times L \quad (8)$$

$$M = 0,5 \times 9,81 \times 0,245 = 1,2017$$

$$I \text{ beam besi} = \frac{b \cdot h^3}{12} \quad (9)$$

$$i = \frac{(0,027) \cdot (0,0017)^3}{12} = 1,105425 \times 10^{-10}$$

$$y = \frac{h}{2} \quad (10)$$

$$y = \frac{0,0017}{2} = 0,00085 \text{ m}$$

$$\sigma = \frac{M \cdot y}{i} \quad (11)$$

$$\sigma = \frac{1,2017 \times 0,00085}{1,105425 \times 10^{-10}} = 9.240.484$$

The strain measurement results obtained using the theoretical modulus of elasticity approach under loading conditions ranging from 0 g to 1500 g are summarized in Table 5. These strain values were calculated based on the stress derived from beam bending theory and the modulus of elasticity of the steel plate specimen.

TABLE 5
Theoretical Strain Values Calculated Using the Modulus of Elasticity Method

Load (kg)	W (N)	Elongation (mm)	γ (m)	Stress (N/m ²)	Strain
0,00	0,000	0,0000	0,00085	0	0,000000
0,50	4,955	0,6008	0,00085	4620242	0,000066
0,80	7,8489	0,96138	0,00085	7322388	0,000074
1,00	9,8109	1,20173	0,00085	9240484	0,000092
1,30	12,7359	1,56224	0,00085	12012650	0,000120
1,50	14,7150	1,80259	0,00085	13850727	0,000139

To assess the accuracy of the developed measurement system, the experimentally measured strain values were compared with the corresponding theoretical strain values. The difference between the measured and theoretical results was quantified using the percentage error (% error), as defined in Equation 12.

The percentage error provides an indication of the deviation between the experimental measurements and the theoretical predictions, thereby serving as a measure of the system's accuracy and reliability.

$$\% \text{ error} = \text{abs} \left[\frac{\text{Teoritis} - \text{Pengukuran}}{\text{Teoritis}} \right] \times 100 \quad (12)$$

For the applied load of 1000 g, the percentage error calculated from the comparison between the measured strain and the theoretical strain was 4.03%. This relatively low error value demonstrates that the developed strain measurement system provides results that are consistent with the theoretical predictions, indicating satisfactory accuracy and reliability.

$$\% \text{ error} = \text{abs} \left[\frac{0,000092 - 0,000089}{0,000092} \right] \times 100\% = 4,03 \%$$

The strain calculation results are comprehensively presented in Table 6, which compares the measured strain values with the corresponding theoretical values and expresses the difference as a percentage error (% error). The comparison between the experimental measurements and the theoretical calculations for loads ranging from 0 g to 1500 g indicates a relatively low average error of 2.98%.

TABLE 6
Comparison of Experimental and Theoretical Results

Load (kg)	Stress (N/m ²)		Strain		% Error Strain
	Experimental	Theoretical	Experimental	Theoretical	
0	0	0	0.000000	0.000000	0.00
0.5	4507044.95	4620242	0.000045	0.000046	2.45
0.8	7155215.96	7392388	0.000072	0.000074	3.21
1	8888123.09	9240484	0.000089	0.000092	4.03
1.3	11516491.1	12012630	0.000115	0.000120	4.13
1.5	13100937.2	13860727	0.000133	0.000139	4.94
Average % error					2.98

This result demonstrates a strong agreement between the measured and theoretical strain values, confirming the accuracy and reliability of the developed strain measurement system. The low percentage error suggests that the BF350-3AA strain gauge sensor, combined with the signal conditioning and data acquisition system, is capable of providing accurate strain measurements and can be effectively applied in structural health monitoring applications.

4. Conclusions

The study successfully demonstrated the ability of the developed system to accurately detect strain variations under applied loads ranging from 0 g to 1500 g, indicating that the measurement system functions effectively. Strain measurements obtained under different loading conditions exhibited good accuracy and precision, with an average error of 2.98% compared to the theoretical values calculated using the modulus of elasticity method.

These results confirm that the proposed instrument provides reliable strain measurements and exhibits satisfactory agreement with theoretical predictions. Although the system showed good performance, several limitations remain, including sensitivity to environmental conditions and the potential effects of material degradation on measurement accuracy. Nevertheless, the measured strain data can be effectively utilized to assess the structural condition of steel plates and support structural health evaluation.

To enhance operational safety, the system incorporates a buzzer and LED indicator designed to activate automatically when the percentage error reaches or exceeds 15% relative to the theoretical value. The activation of these indicators serves as an early warning mechanism, notifying users that the applied load has exceeded the predefined safety threshold. This feature enables timely corrective actions, such as reducing the load or reinforcing the structure, thereby minimizing the risk of structural failure.

Given its satisfactory accuracy and monitoring capabilities, the developed system demonstrates strong potential for broader implementation in Structural Health Monitoring (SHM) applications, particularly for the early detection of damage in structures subjected to heavy loading conditions.

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