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MEASUREMENT OF DEFLECTION OF BEAM USING STRAIN GAUGES

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Abstract: This paper presents a method for measuring strains and deflections using strain gauges. An Arduino Uno board is used for data acquisition due to its low cost and easy programming. The measured signals are conditioned using a Wheatstone bridge and then converted to digital form by an external Analog-Digital Converter. To validate the measurement system, experiments were conducted on beams, and the results were compared with analytical and finite element simulation findings. The results align with existing literature and demonstrate that the proposed system has satisfactory accuracy.

Keywords: Strain Gauges, Arduino, Data acquisition, Wheatstone-Bridge, Beam.

1. INTRODUCTION

Understanding the stresses and strains on a structure is crucial in engineering. This information helps predict how the materials will behave. It's also important to avoid excessive deformations that could prevent the structure from serving its intended purpose. Usually, mathematical models or finite element methods (FEM) are used to estimate the stresses. However, there are situations where modeling is not possible or the results are rough approximations that don't match the real loads. In these cases, experimentation is the way to go to avoid over-designing the structure.

There are many ways to measure mechanical strain, such as using strain-gauges. These can be optical, mechanical, or electrical, like those that use resistance, capacitance, inductance, or light. One of the most common methods is using resistive-based straingauges. These devices can directly measure strain by detecting changes in electrical resistance as they are deformed. This is often done with a Wheatstone bridge. Straingauges can also be used to measure forces and torques acting on a structure, since these are related to strain. However, strain-gauges are expensive and can't be reused, so the overall cost of this type of experiment is generally high.

In such cases, using an Arduino microcontroller along with inexpensive sensors is highly encouraged. This approach offers numerous benefits, such as easy implementation and an overall low cost for the setup. For instance, a low-cost Arduino based wire strain gauge was developed for monitoring earth flows and landslides. A prototype was built using an Arduino Uno board, a data logging real-time clock, and a temperature sensor. The field tests demonstrated the high reliability of this experimental apparatus. Another example is an ultra-light strain gauge device used to assess the mechanical properties of human skin in vivo, which employed an Arduino Mega 2560 to acquire data from the sensors. Several other similar applications have also been presented.

This paper introduces a method for measuring stress and strain using strain gauges and the Arduino microcontroller. The aim is to use this for experimental analysis in solid mechanics courses. The equipment normally used for this is expensive, and the procedures can be complex. In this paper, we propose a low-cost and easy-to-use method for strain measurement, making it suitable as an educational tool for undergraduate courses. To evaluate the proposed method, tests were conducted on two different mechanical systems, and the results were compared with analytical ones.

2. LITERATURE REVIEW

By Qing Zhang, Xing Fu and Liang Ren (Aug 2021). The author has stated that deflection is of great significance for evaluating the safety performance of long-span bridges, while it is difficult or expensive to be directly measured in actual projects despite numerous displacement sensors have been developed. This paper proposes a displacement reconstruction framework to obtain the dynamic deflection of beam structures using strain data. The framework defines the judgment criteria of curvature symbols and standard side first, and then stochastic subspace identification algorithm is used to calculate the strain mode shapes involved in the vibration, which solves the unclear calculation process and the need for considerable measurement points of the traditional mode superposition method. Furthermore, the displacement mode shapes and corresponding modal coordinates are obtained, and then the dynamic deflections are derived. Numerical simulations of cantilever and simply supported beams illustrate the effectiveness of the proposed framework, and the results show that the error is only 0.69% with only four strain measurement points. The two corresponding model experiments have also been carried out, and the results demonstrate that the deflection estimation error is only 0.14% with five measurement points, which further proves that the developed displacement reconstruction framework can accurately reconstruct the dynamic deflection of the beam structures.

By Wang Hong, Zheng Qin, Kui Luv, Xuan Fang.(April 2018) The author has stated that an indirect method for monitoring dynamic deflection of beam-like structures using strain responses measured by long-gauge fiber Bragg grating (FBG) sensors is proposed in this paper. Firstly, a theoretical derivation shows that structural deflection is in direct and linear relationship to long-gauge strain. Meanwhile, the method is suitable for structures with different boundary conditions and irrelevant to external loads. Secondly, the influence of boundary conditions, load type and sensor gauge length on the method is investigated by numerical simulation. Finally, an experiment of a simply supported beam subjected to dynamic loads was designed to verify the method. Experimental results show that both deflection time-history of arbitrary points of structures and deflection distribution along structures at a certain time can be obtained with high-precision. Therefore, the method presented can be a new alternative for the deflection evaluation and maintenance of engineering structures.

By H. M. Lee & H. S. Park (Dec 2017) The author has stated that in structural health monitoring, the safety of steel beam structures can be assessed by comparing the measured maximum stress and the allowable stress of the beam calculated by a design code. For the case of a steel beam subjected to variable lateral loadings, many difficulties exist in measuring the maximum stress in a beam with point sensors that can measure the strain only at a local point of a beam since the location and magnitude of the maximum stress induced in a beam by the loading change. Although traditional strain sensors can measure the strain only at a local point, a vibrating wire strain gage (VWSG) that measures integrated strains over its gage length can consider the variation of strains due to variable loadings. This paper presents an estimation model to determine the maximum strains or stresses in a steel beam based on average strains measured using VWSGs. The model is derived by defining the relation between the average strains measured using VWSGs and the maximum strains of beams. The model is experimentally tested by comparing the maximum strain directly obtained from electrical strain gages and the estimated maximum strain based on the average strain from VWSGs.

By Ismael Payo, Vicente Feliu (March2014): The author has stated that a sensor system has been designed for the real time measurement of 3-D deflections of flexible beams (position and orientation of the tip). The sensor system is based on resistive strain gauges placed strategically at different locations of the beam. A linear model based on the classical theory of the deflection of flexible beams has been used to calculate the position and orientation of the beam tip from the strain gauges measurements. Furthermore, it has been necessary to include a nonlinear term in the model to calculate the coordinate x of the beam tip. Experimental results demonstrate the feasibility of the sensor system.

By W Montero, R by W Montero R Farag V Díaz M Ramirez B L Boada (Sep 2010): The author has stated that resistance strain gauges have been used for the measurement of strain for more than 50 years; however, research to quantify the inherent uncertainty in a strain-measuring system has been scarce hitherto. Nevertheless, resistive strain gauges are the most widely used tool to measure strain owing to their simplicity, apparent accuracy, low cost, and ease of use. In spite of this, at times they are used improperly, and the sources of error are neglected. Every type of measurement has an uncertainty associated with it. As it is impossible to eliminate error completely, the goal must be to quantify it and to reduce it to a value that is acceptable for the purposes of the measurement being taken. The novelty of the present research is to put forward a new methodology for determining the uncertainty in a strain gauge measuring system. To achieve this, the principal sources of error that influence the measuring system are formulated in order to develop an error model. Subsequently, the law of propagation of uncertainty is applied, together with a type A and B evaluation approach to determine the combined uncertainty of the entire measuring system, taking into consideration the correlation between variables, when applicable. The new methodology is then applied to a series of strain measurements taken on aluminum flat bar subject to a bending load, and the results are discussed.

3. Relevance of the Project

Structural Integrity: Understanding the deflection of beams is essential for ensuring the structural integrity of various mechanical systems, such as bridges, buildings, and machinery. By accurately measuring deflection, engineers can assess the safety and reliability of these structures.

Design Optimization: Research in this area helps in optimizing the design of beams and other load-bearing components. By studying deflection under different loads and conditions, engineers can refine designs to maximize performance and minimize material usage, leading to more efficient and cost-effective structures

Performance Evaluation: Measurement of deflection provides valuable data for evaluating the performance of materials and structural configurations. This information can be used to validate theoretical models, identify areas of improvement, and predict the behavior of beams in real-world applications.

Failure Prevention: By monitoring deflection, engineers can detect early signs of structural problems or potential failures. This proactive approach allows for timely interventions, such as reinforcement or maintenance, to prevent catastrophic accidents and ensure the longevity of mechanical systems.

Validation of Analytical Models: Research in this area contributes to the validation and refinement of analytical models used to predict beam deflection. By comparing experimental results with theoretical calculations, engineers can improve the accuracy and reliability of these models, leading to better design and analysis tools.

Technological Advancements: Advancements in measurement techniques, such as the use of strain gauges, contribute to the development of innovative solutions for measuring and monitoring beam deflection. This ongoing research drives technological progress in the field of mechanical engineering, enabling more precise and efficient measurement systems.

4. Research Methodology and Experimentation

4.1 Theoretical Framework

Strain gauges are delicate metal wires whose resistance varies when they are stretched or compressed. As the wire is strained, its length (L) and cross-sectional area (A) change, which causes a corresponding change in the wire's resistance (R). This relationship is described by a mathematical formula.

$R = \rho L\ A$

If the wire is stretched, the length (L) will increase, the cross-sectional area (A) will decrease, and the resistance (R) will increase. It's worth noting that the wire's resistivity (ρ) may also change when stretched, but we'll not consider that here. As we'll see below, by measuring the change in resistance (ΔR), we can infer the strain and ultimately the stress. Taking the derivative of Equation 1 with respect to each variable, we get the following (derivation omitted).

$dR\ R = dL/\ L + d\rho/\ \rho - dA\ /A$

We can define gage factor, GF, as

$GF = (\Delta R\,/\,R)/\ \epsilon$

The strain in a specific direction is denoted by 'ε'. The relationship between the strain and the change in the electrical resistance of the wire can be expressed as follows:

$\varepsilon = (\Delta R\,/\,R)/GF$

A simple cantilevered beam is subjected to a force F at its end. This causes the top of the beam to experience tension, while the bottom experiences compression. The wires in the strain gauge on top of the beam will stretch, resulting in a positive strain and thus a positive change in resistance (ΔR). Conversely, the wires in the strain gauge on the bottom of the beam will be compressed, leading to a negative strain and a negative ΔR. This process can be used to determine the strain in the cantilever beam. Let's begin by determining the theoretical equation for strain in the beam, using our understanding of beams in bending. For a cantilever beam with a single force F applied at the end, the deflection at the end of the beam is given by the following expression

$$\delta = \frac{FL_2^3}{3EI}$$

(From Riley, Mechanics of Materials, 6th Ed.).

Then we can calculate the theoretical force F as

$$F = \frac{3EI\delta}{L_2^3}$$

Consider the bending stress experienced at the location of the strain gages. This is given by

$\sigma = My\ /I = FL_1y\ /I$

Where L1 is the distance from the end of the beam to the strain gauges. Now, we have

$\sigma = 3E\delta L_1 y/\ L_2^3$

The gages are mounted at the top/bottom of the beam, i.e., y = t/2. Thus,

$\sigma = 3E\delta L_1 t/\ 2\ L_2^3$

Consider the stress-strain relationship given by $\varepsilon = \sigma/\ E$

Then, we have $\epsilon = 3\delta L_1 t\ /2\ L_2^3$

The equation we developed represents the theoretical strain on the surface of the beam where the gages are located.

The present theory and practices of measuring beam deflection using strain gauges involve understanding the principles of strain measurement, careful installation and calibration of strain gauges, data acquisition, analysis, and verification of results. These techniques are widely used in engineering and scientific research to evaluate the performance of beams and other structural elements.

4.2 Traditional Deflection Measurement Techniques:

4.2.1 Dial Gauges and Vernier Scales: These manual measurement tools are still widely used, especially in smaller-scale applications or during initial setup. Dial gauges and vernier scales provide a direct reading of deflection at specific points along the beam's length.

4.2.2 Displacement Transducers: Linear variable differential transformers (LVDTs) or potentiometers are commonly used to measure beam deflection. They provide precise measurements of displacement, allowing for accurate determination of deflection under load.

4.2.3 Optical Methods: Techniques such as using laser displacement sensors or video extensometer provide non-contact measurement of beam deflection, which can be advantageous for certain applications, especially where accessibility is limited or where the beam's surface cannot be physically touched.

4.3 Strain-Based Measurement Techniques:

4.3.1 Strain Gauges: As previously discussed, strain gauges are extensively used for measuring beam deflection by indirectly assessing strain induced by bending. Advanced strain gauge technology, including thin-film gauges and rosette configurations, offers improved accuracy and sensitivity.

4.3.2 Load Cells: Load cells, combined with strain gauge technology, are employed to directly measure the applied load on the beam, allowing for the calculation of deflection based on known beam properties and load-deflection relationships.

4.3.3 Fiber Optic Sensors: Fiber optic sensors, such as Fiber Bragg Grating (FBG) sensors, offer advantages in terms of their small size, immunity to electromagnetic interference, and distributed sensing capabilities. They can be embedded within the beam or surface-mounted to measure strain and deflection accurately.

5 EXPERIMENTATION SETUP

The holding method of strain gages must be through performed to maintain a strategic distance from estimation blunders, starting with the planning of the surface for holding. The surface where the strain-gauge will be stuck must be carefully sanded utilizing fine water sandpaper with a granulation of almost 220. To begin with, the surface should to be Figure 5:

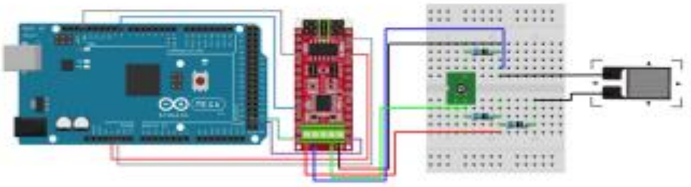


Figure 5: Connection figure of the components for the data acquisition.

sanded at 45°of the center line of the strain-gauge, then sanded at -45°of the same line, so that the point between the coming about lines of this prepare is 90°, shaping an X. After this strategy, for instructive reason experiments, the holding location must be cleaned with liquor or acetone, but in applications that require more accuracy specific products ought to be utilized. After the cleaning, it is necessary to stamp the holding location, ideally utilizing a pencil with fine graphite, so that there is no huge graphite deposition in the put, which might conclusion up influencing the measurement. The line where the miss happening is to be measured and an assistant line at 90°, comparing to the transverse affectability hub of the strain-gauge, need to be marked. After the planning handle for the strain gauge bonding, the holding prepares starts. For this, it is needed a glass base, already cleaned with liquor, tweezers, transparent tape and moment stick. To way better handle the strain gage with the tweezers, put it on the glass base so that its lattice and patch terminals are up, note that the strain gages ought to as it were be taken care of utilizing the tweezers, dodging any contact with the hands, reducing any chance of harm in them. Other than, the slickness that is display in the hand can cause the oxidation of the strain-gauge network. With the straightforward tape stick the strain gage onto the glass base. When expelling the tape the strain gage must be expelled with the tape, still stuck in it. The holding of the strain-gauge to the tape is performed to encourage the redress positioning and holding of the transducer to the surface where the deformation will be measured. The tape and the strain gauge must be carefully situated on the surface so that the already stamped lines coordinate the strain gauge indicators.

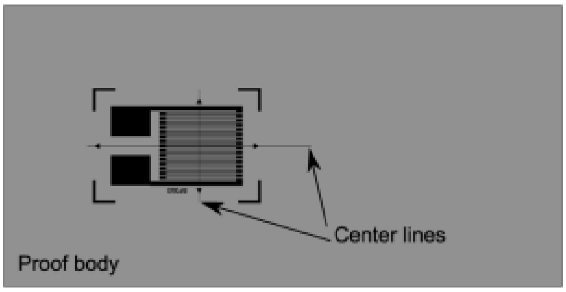


Figure 6 outlines the redress situating of the strain gage.

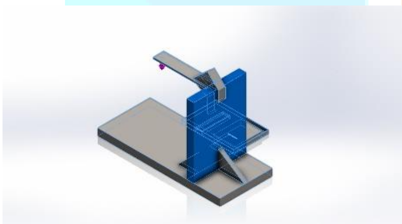
After the adjust situating, one must carefully peel off portion of the tape until the strain gage is raised to embed a little sum of moment stick beneath it, quickly reposition the tape as some time recently and press the strain gauge so that bubbles do not shape beneath it. Once more, in applications where higher accuracy is required, it might be essential to utilize particular items and more elaborate processes for holding. After the remedy time of the adhesive, carefully evacuate the tape and assess the strain gauge with an amplifying glass. If the strain gage has bubbles under its surface or if it is inaccurately situated, remove it, dispose of it, and perform the planning and gluing procedures again. For the test of the crimped-supported shaft the marking of the reference line for the strain gage was performed with the help of an attractive base, in which a pencil was settled. With the shaft connected to the bench made for assessment, a flat line was made in it with the help of a mechanical checking gage. The strain gauge on the shaft was carried out on the premise of the diagonal markings of the strain gage, in this way the measurement of the strain happens in a plane at 45°from the cross segment of the pivot, which is the plane where the primary stresses happen. In tests to degree torsion in shafts where great exactness is required, a redress marking of the lines of the shaft must be performed, positioning the shaft on a level plane, which can be done with the help of a part device. For the cantilever bar test a drive of 0.981 N was connected, by implies of situating a square with known mass being at the free conclusion of the bar, and the strain gauge was stuck at 30 mm from the settled conclusion in the center of the upper confront. In the torsion shaft experiment a torque of 3.6 N/m was connected and the strain gauge was stuck at 45°of the pivot of symmetry of the work piece. In both tests, 256 focuses were acquired. The tests were performed in two stages for each system. To begin with, the drive or the torque is connected and, after a certain time, they were taken off once. As in the second stage, the depicted prepare were performed twice, to analyze if the proposed estimation framework has repeatability. The test bench utilized for the tests can be seen in Figure 7 and in Figure 8 the strain-gauges, already stuck in the mechanical frameworks analyzed, are shown with more data

Figure 7: Test benches for experimental validation of the proposed measurement system: (7a) Cantilever beam and (7b) Crimped-supported shaft under torsion.

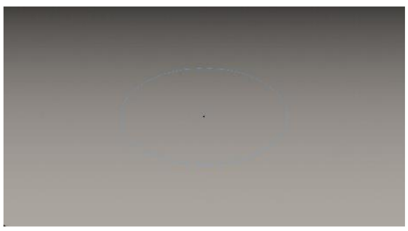
Figure 8: Strain- gauges glued to the analyzed mechanical system (8a) in experiment 1 and (8b) in experiment 2.

6 RESULTS AND DISCUSSION:

1) Material Properties

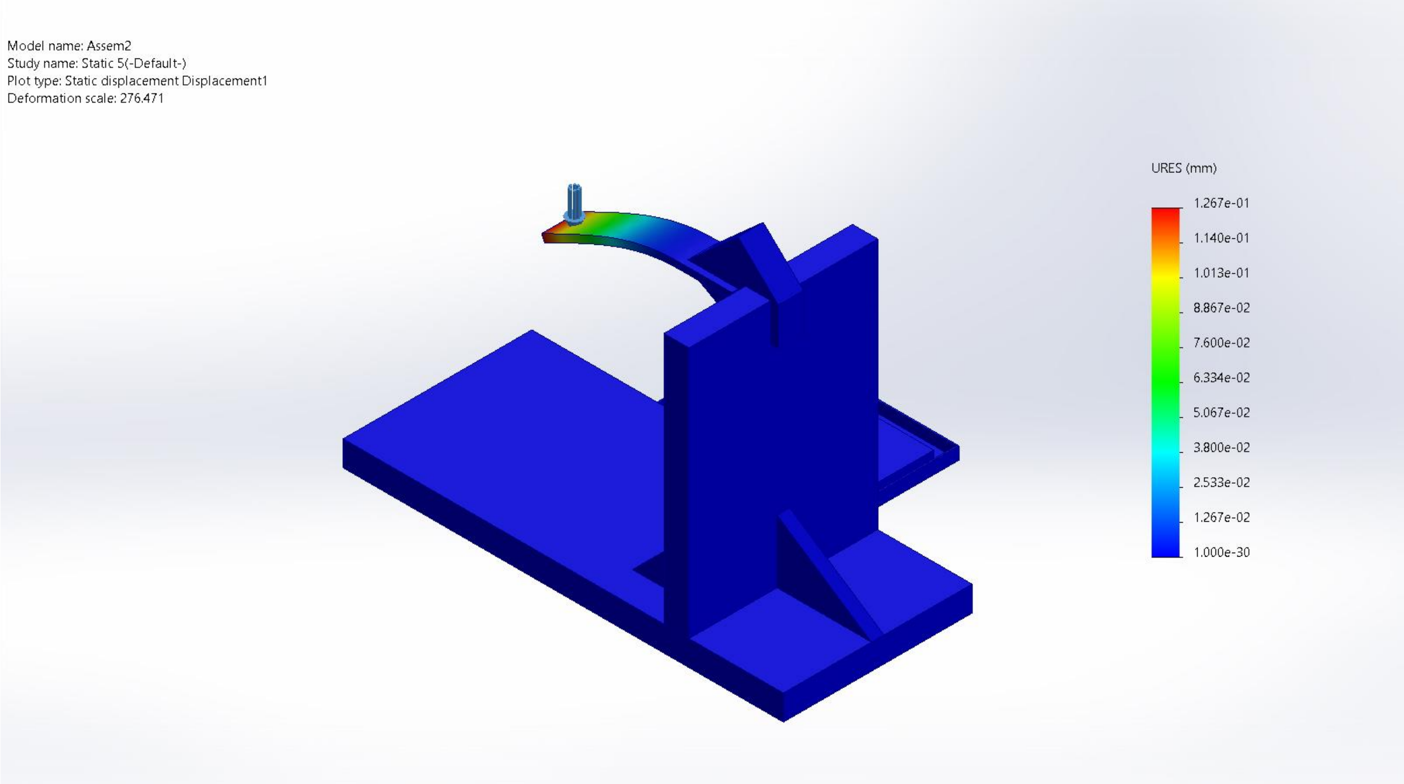
Model Reference	Properties	Components
	Name: **AISI 4130 Steel, annealed at 865C** Model type: **Linear Elastic Isotropic** Default failure criterion: **Max von Misses Stress** Yield strength: **4.6e+08 N/m^2** Tensile strength: **5.6e+08 N/m^2** Elastic modulus: **2.05e+11 N/m^2** Poisson's ratio: **0.285** Mass density: **7,850 kg/m^3** Shear modulus: **8e+10 N/m^2**	**Solid Body 1(Cut-Extrude1)(Circuit assly-1/Arduino-1), Solid Body 1(Cut-Extrude1)(Circuit assly-1/LCD Display-1), Solid Body 1(Shell1)(Circuit assly-1/base board-1), Solid Body 1(Boss-Extrude1)(base 1-1), Solid Body 1(Boss-Extrude1)(jaw-1), Solid Body 1(Boss-Extrude1)(rib 2-1), Solid Body 1(Boss-Extrude1)(rib-4), Solid Body 1(Boss-Extrude1)(rib-5), Solid Body 1(Boss-Extrude2)(specimen-1), Solid Body 1(Boss-Extrude1)(ver-1)**
Curve Data/A		

2) Loads and Fixtures

Load name	Load Image	Load Details
Force-1		**Entities:** **1 face(s)** **Type:** **Apply normal force** **Value:** **-25 N**

3) Displacement/Deflection in a bar

Name	Type	Min	Max
Displacement1	URES: Resultant Displacement	0.000e+00mm Node: 7497	1.267e-01mm Node: 8615



Assem2-Static 5-Displacement-Displacement1

7. CONCLUSION

In this work, it was proposed an elective to commercial distortion instrumented frameworks trough the Arduino microcontroller and moo taken a toll components. The main reason of utilizing moo fetched components is to permit undergraduate understudies who regularly do not have contact with miss happening instrumented, due to the tall cost of the gear and the complexity of their operation, to do viable tests that include programming, electronics and instrumented in a basic and intuitive way. The proposed framework demonstrated to be solid for the proposed reason, since it displayed great repeatability, there being no extraordinary scattering between the tests, and it too displayed great accuracy, getting values close to the numerical and explanatory ones. The equipment used is of simple operation and its components are too well documented in the literature. In future ventures we proposed to apply the methodology of estimation of distortion proposed to more complex systems, utilizing diverse arrangements of the Wheatstone bridge and beneath distinctive conditions of loads, as impact and energetic loads

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