

Overview of Strain Gauge and its Various Applications

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Abstract - A strain gauge is a versatile and widely used sophisticated sensing device used to measure mechanical strain or deformation in various materials. Its importance lies in their ability to provide accurate and reliable measurements, allowing for a deeper understanding of material behavior and structural integrity. It is a fundamental component in the field of engineering and plays a crucial role in measurement of a significant amount of strain on various structures. It is an essential geotechnical tool that determines strain in a range of structures such as tunnels, underground cavities, buildings, bridges, concretes, masonry dams, embedment in soil/concrete, etc. Strain gauges are utilized in a wide range of applications, including structural analysis, load testing, material testing, and stress analysis. This paper is oriented to overview everything about the Strain gauge including working principle, characteristics, and its various applications.

Index Terms- Strain Gauge, Mechanical Strain Gauge, Resistance, Wheatstone Bridge, Vibrating Wire Strain Gauge, Fiber Optic, Piezoelectric etc.

1. Introduction

A strain gauge is an instrument used to measure the strain or deformation of an object under external forces. It is widely used in the field of solid mechanics to determine the amount of stress experienced by a material. The gauge consists of a wire or a foil patterned in a zigzag or grid-like configuration, which undergoes changes in its electrical resistance when subjected to mechanical strain. Strain gauges find extensive applications in various fields, including structural engineering, aerospace, automotive, and materials testing. They are used to monitor and analyze the behavior of structures, determine material properties, assess structural integrity, and optimize designs. One of the most important applications of strain gauge technology is in structural testing. Strain gauges are widely used to measure stresses and strains in structures such as bridges, buildings, and aircraft. By monitoring these parameters, engineers can gather valuable information to design and construct safer structures.

2. History and Development of Strain Gauge

The earliest strain sensor were mechanical devices that measured strain by measuring the change in length and comparing it to the original length of the object. For example, the extensometer uses a series of levers to amplify strain to a readable value. However, in general, mechanical devices tend to provide low resolutions, and are bulky and difficult to use.

The historical journey of strain gauges is closely related to the development of theory of electrical resistance. Lord Kelvin's pioneering work in the late 19th century laid the foundation for understanding how the resistance of a conductor changes when it undergoes mechanical deformation. This concept was the basis for the development of strain gauges.

The development of strain gauges was brought about by the technical applications of the Wheatstone bridge circuit. The Wheatstone bridge was invented and popularized in 1843 by

Charles Wheatstone. Its publication mentions an effect that describes the change in resistance of an object due to mechanical stress. This invention was further worked on by William Thomson in 1856.

The resistance strain gauge was invented by Simmons and Ruge in 1938. Edward Simmons, an electrical engineer based in California, used thin resistance wires and silk threads to create a woven strain gauge. The prototype strain gauge was bonded onto a steel cylinder. It was then tested to measure force impulses from a pendulum ram impacting the cylinder.

Simultaneously, Arthur Ruge, a mechanical engineer at MIT, developed a device initially intended to measure the stress caused by simulated earthquakes to his model of an earthquake-resistant water tank. He used very thin wires stuck to a piece of paper as the strain gauge. The gauge was then bonded into a bending beam, which served as its carrier. The most common type of strain gauge consists of an insulating flexible backing which supports a metallic foil pattern. The gauge is attached to the object by a suitable adhesive, such as cyanoacrylate. As the object is deformed, the foil is deformed, causing its electric resistance to change. This resistance change, usually measured using a Wheatstone bridge, is related to the strain by the quantity known as the gauge factor. It has been nearly 80 years since resistance strain force sensors began to be produced in 1942. The strain gauge applications were quickly gaining traction as they served to indirectly detect all other quantities that induce strain. Additionally, they were simple to install by the scientists, did not cause any obstruction or property changes to the observed object and thus falsifying the measurement results. Probably the last and most important property was the ease of transmission of the electrical output signal.

Over the years, technological advancements have led to the creation of various types of strain gauges, each of which fulfills specific measurement requirements. These gauges are constructed using thin wires, foils, or semiconductor materials. When the material experiences strain, its electrical resistance changes proportionally, which can be measured and correlated with the applied force or stress.

3. Working Principle of Resistance Strain Gauge

When an external force is applied to an object, it causes the object to deform. This deformation alters the length and cross-sectional area of the strain gauge, leading to a change in its electrical resistance. This change in resistance is directly proportional to the amount of strain experienced by the object. To measure the strain, the strain gauge is typically attached to the surface of the object being tested using adhesive or solder. As the object deforms, the strain gauge undergoes the same deformation, resulting in a change in resistance.

The change in resistance can be measured by using a Wheatstone bridge circuit (as shown in figure 1), which is commonly employed in strain gauge applications. The Wheatstone bridge consists of four resistive arms, with the

strain gauge forming one of the arms. The other three arms typically consist of fixed resistors (R_1 , R_2 & R_3).

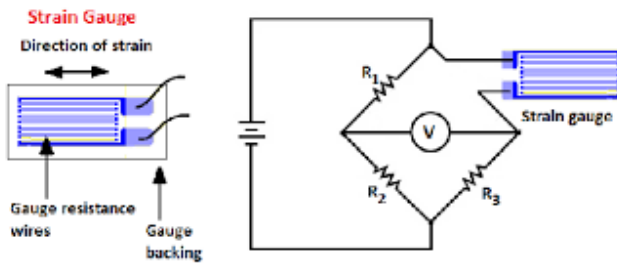


Figure 1: Diagram of Working Principle of Resistance Strain Gauge

This circuit is so designed that when no force is applied to the strain gauge, R_1 is equal to R_2 and the resistance of the strain gauge is equal to R_3 . In this condition the Wheatstone bridge is balanced and the voltmeter shows no deflection.

But when strain is applied to the strain gauge, the resistance of the strain gauge sensor changes, the Wheatstone bridge becomes unbalanced, a current flows through the voltmeter. Since the net change in the resistance is proportional to the applied strain, therefore, resultant current flow through the voltmeter is proportional to the applied strain. So, the voltmeter can be calibrated in terms of strain or force.

In the above circuit, only one strain gauge has been used. This is known as 'quarter bridge' circuit. When two strain gauges or even four strain gauges are used in the circuit, then the circuit is called 'half bridge' and 'full bridge' respectively. The full bridge circuit provides greater sensitivity and least temperature variation errors.

4. Application of Strain Gauges

4.1 Strain Gauges in Structural Health Monitoring

- **Structural integrity assessment and Failure Prevention** - Strain gauges play a crucial role in the structural integrity monitoring and assessment. They help identify potential weaknesses, prevent failures, and prevent catastrophic incidents.
- **Real-Time Monitoring of Bridges, Dams, and Buildings** - Strain gauges installed on bridges, dams, and buildings provide real-time data on structural behavior and ensure their safe operation. Continuous monitoring allows for early detection of any abnormalities, enabling timely maintenance and repair.
- **Integrating Strain Gauges with Wireless Sensor Networks** - Strain gauges can be integrated into wireless sensor networks, allowing easy access to data and simplifying monitoring systems. This integration improves data collection, analysis, and decision-making processes.

4.2 Industrial Applications of Strain Gauges

- **Automotive Industry: Enhancing Vehicle Safety and Performance** - Strain gauges are widely used in the automotive industry to measure stresses and strains in components and structures. They help improve vehicle safety, optimize performance, and ensure compliance with safety standards.
- **Aerospace Industry: Ensuring Structural Integrity of Aircraft** - Strain gauges are essential in the aerospace industry for monitoring the structural health of aircraft. They provide important information on stress distribution, fatigue, and load-bearing capacities, ensuring safe and reliable flight operations.

- **Energy Sector: Monitoring Stress in Wind Turbines and Power Plants** - In the energy sector, strain gauges are employed to monitor stress levels in critical infrastructure such as wind turbines and power plants. Accurate strain measurements help optimize maintenance schedules, avoid downtime, and ensure the long-term reliability of these assets.

4.3 Strain Gauges in Material Testing and Research

- **Measuring Material Properties and Behavior** - Strain gauges enable researchers to measure and analyze the behavior of materials under various conditions. This information is valuable for understanding material properties, exploring new applications, and improving product development.
- **Investigating the Strength and Durability of Various Structures** - Strain gauges play a crucial role in investigating the strength, durability, and failure mechanisms of structures. They help engineers design resilient structures and ensure they meet safety requirements.
- **Applications in Biomechanics and Medical Research** - Strain gauges find applications in biomechanics and medical research, contributing to the study of human movement and physiological response. They contribute to the development of medical devices, orthopedics, and rehabilitation techniques; such as posture, joint rotation, respiration and swelling both in humans and other animals.

4.4 Strain Gauges in Robotics and Automation

- **Optimizing Efficiency and Performance in Robotics** - Strain gauges are employed in robotics to monitor the forces and strains experienced by robotic components. This information enables optimization of performance, control and efficiency in robotics applications.
- **Implementing Feedback Control Systems** - Strain gauges play a central role in feedback control systems, enabling real-time adjustments and corrections. They contribute to precision, stability, and safety in various industrial and automation processes.
- **Enhancing Precision in Industrial Automation** - Strain gauges are integrated into industrial automation systems to measure and control crucial parameters. Their ability to provide precise strain measurements enables accurate process control and improves overall system performance.

5 Types of Strain Gauges

In civil engineering, strain gauges are essential instruments used to measure and monitor the strain or deformation of structural components. They play a crucial role in assessing the structural integrity and performance of various civil engineering projects. Strain gauges come in different types, each designed to suit specific applications and measurement requirements. It can be categorized into following types:

5.1 Mechanical Type Strain Gauge

Mechanical strain gauges are portable and have the additional advantage in that one gauge can be used to measure strain in a large number of specimens and therefore the strain equipment is relatively inexpensive, although it is labor intensive in terms of time required for measurement. The gauge consists of an invar bar with two conical locating

points, one fixed and the other pivoting on a knife edge, the point locating in predrilled steel discs attached to the concrete. Movement of the pivoting point is measured by a dial gauge attached to the strain gauge. Figure 2 shows diagram of a DEMEC gauge (Demountable mechanical gauge).



Figure 2: Diagram of Demountable Mechanical Gauge

5.2 Electrical Resistance Strain Gauge

Electrical resistance strain gauges are the most widely used type in civil engineering applications. They consist of a grid of fine metallic wire or foil bonded to a backing material.

When subjected to strain, the wire or foil experiences a change in resistance, which is measured using a Wheatstone bridge circuit. These strain gauges offer high sensitivity, accuracy, and stability, making them suitable for measuring small strains in structures such as bridges, dams, and buildings. Figure 3 shows a typical diagram of Foil Type Electric Resistance Strain Gauge.

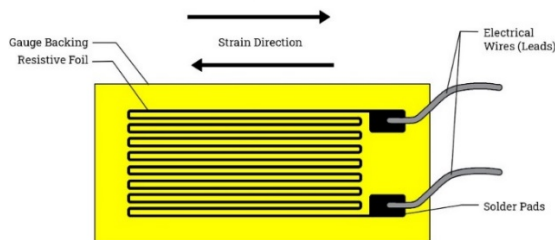


Figure 3: Diagram of Foil Type Electric Resistance Strain Gauge

5.3 Vibrating Wire Strain Gauges

The vibrating wire strain gauge is so constructed that a wire is held in tension between two end blocks. The gauge operates on the principle that a tensioned wire, when plucked, vibrates at a frequency that is proportional to the strain in the wire.

As the steel or concrete surface that encompasses the strain gauge undergoes strain, the end blocks will move relative to each other. The tension in the wire between the blocks will change accordingly, thus altering the resonant frequency of the wire. A vibrating wire readout is utilized to generate voltage pulses in the magnet/coil assembly located at the center of the strain gauge. The magnet/coil assembly plucks the wire and measures the resulting resonant frequency of vibration and the resulting readings are used to measure strain.

The advantages of vibrating wire strain gauges are that the frequency output is immune to electrical noise, able to tolerate wet wiring common to geotechnical applications, and capable of signal transmission of several kilometers without loss of signal.

Vibrating Wire Strain Gauges are designed to be welded to or embedded in various structures for monitoring strain. Vibrating wire strain gauges are found as 3 types: VWSG-A, for arc welding to steel structures; VWSG-S, for spot welding to steel structures and VWSG-E for embedment in concrete.

Arc-weldable VW strain-gauges are designed for arc welding to steel structure such as tunnel linings, piles and bridges.

Embedment VW strain-gauges (also shown in figure 4) are directly embedded in concrete structure for strain measurements of piles, foundations, dams, tunnel segments, etc.

Vibrating wire strain gauges are particularly useful in geotechnical and structural monitoring applications due to their robustness, long-term stability, and resistance to environmental factors.



Figure 4: Diagram of Vibrating Wire Strain Gauge embedded in concrete Surface

5.4 Fiber Optic Strain Gauges

Fiber optic strain gauges utilize optical fibers to measure strain. They operate based on the phenomenon of the strain-induced change in the light transmission characteristics of the fiber. The fiber optic sensor consists of a section of optical fiber embedded or bonded to the structure being monitored. As strain is applied, it alters the light intensity or wavelength propagating through the fiber, which is then detected and analyzed. Fiber optic strain gauges offer several advantages such as high accuracy, immunity to electromagnetic interference, and the ability to multiplex multiple sensors along a single fiber, operate on a very wide temperature ranges and not requiring electrical cables and also suitable for dynamic measurements with high bandwidth.

In the picture 5 of FBG type sensor, fiber is considered as a cylindrical length of transparent material, with several thin slices in it. The material interferences – the 'slices' – are placed at certain intervals. When the fiber is stretched or compressed – and is therefore subjected to positive or negative strain – these intervals change. When the fiber is stretched, it lengthens, and the spaces get bigger and vice versa.

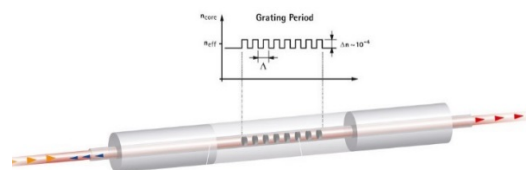


Figure 5: Diagram of Fiber Optic (Fiber Bragg Grating-FBG) Strain Sensor

5.5 Piezoelectric Strain Gauges

Piezoelectric strain gauges (as shown in figure 6) employ the piezoelectric effect to measure strain. Piezoelectricity is a phenomenon where electricity is generated if mechanical

stress is applied to a material. Piezoelectric sensors generally consist of two discs with a foil electrode between them. They consist of a piezoelectric crystal or ceramic material that generates an electric charge when subjected to mechanical deformation. This charge is proportional to the applied strain and can be measured using specialized equipment. Piezoelectric strain gauges are highly sensitive and capable of measuring dynamic strains in structures such as bridges, tunnels, and pavements. However, they are susceptible to temperature variations and exhibit a limited range of linearity.

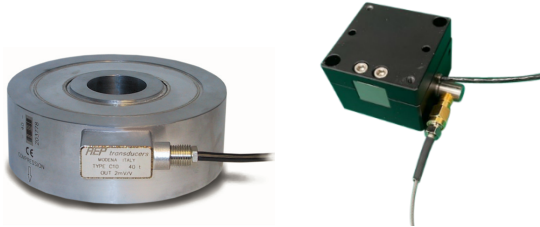


Figure 6: Diagram of Piezoelectric Strain Gauge

6. Installation and Mounting Techniques of Strain Gauge

- **Appropriate Pre-Installation Considerations** - Before installing strain gauges, factors such as material properties, surface conditions and strain gauge orientation must be considered. Proper planning and preparation ensure accurate and reliable measurements.
- **Surface Preparation Methods** - The surface preparation of the material is vital for achieving optimal performance from strain gauges. It usually involves cleaning, roughening, and applying a suitable primer or adhesive to maximize adhesion.
- **Selecting Suitable Adhesives and Protective Coatings** - The selection of adhesive and protective coating depends on the material being tested and the environmental conditions. The selected materials should ensure proper bonding, electrical insulation, and protection against moisture and dirt.
- **Mounting Techniques for Different Applications: Static vs. Dynamic Measurements** - Static measurements require strain gauges to be firmly attached to the material. Dynamic measurements involve mounting techniques that minimize the effects of vibration and strain rate variations.

7. Advantages and Limitations of Strain Gauge

Strain gauges are widely used in civil engineering applications to measure strain or deformation in structural components. While strain gauges offer several advantages, they also have certain limitations that need to be considered.

7.1 Advantages of Strain Gauge

- **High Sensitivity (High Precision and Accuracy)**: Strain gauges have excellent sensitivity, allowing for highly precise and accurate measurement of even minute deformations. This feature is crucial in civil engineering, as it helps detect structural movements or stress concentrations and to make informed decisions and predictions that may affect the integrity of a building or infrastructure. The reliability of the measurements contributes to efficient design, optimization, and maintenance processes
- **Versatility**: Strain gauges can be used on various materials such as concrete, steel, or composites, making

them versatile for different civil engineering applications. They can be attached to surfaces or embedded within structures, enabling engineers to monitor strain at specific locations of interest.

- **Cost-Effective**: Strain gauges offer a cost-effective solution for strain measurement compared to other techniques such as extensometers. They are relatively inexpensive and reusable, allowing for multiple measurements at different locations within a structure.
- **Non-Disruptive Testing and Real Time Monitoring**: Strain gauges offer non-disruptive testing and monitoring capabilities and provide real-time data, allowing engineers to monitor structural behavior continuously without disturbing the material or structure under investigation.. This feature is particularly useful during load testing, construction, or seismic events, as it enables prompt identification of any excessive strains or deformations. Real-time data acquisition ensures prompt responses to changes and deviations.

7.2 Challenges and Limitations of Strain Gauge

- **Installation Complexity**: The installation of strain gauges can be a time-consuming and complex process that requires. Specialized knowledge is necessary to ensure proper attachment, wiring, and calibration of the strain gauges, which can increase the overall project complexity.
- **Sensitivity to Environmental Factors**: Strain gauges are sensitive to environmental conditions such as temperature, humidity, and vibration. These factors can introduce additional strains or interfere with the accuracy of measurements. Proper environmental controls and shielding techniques are necessary to mitigate these influences for maintaining measurement accuracy.
- **Limited Measurement Range**: Every strain gauge has a specific measurement range, beyond which it may not provide accurate readings. This limitation restricts their application in cases where high strains are expected, such as during dynamic load testing or extreme events like earthquakes.
- **Vulnerability to Damage**: Strain gauges are delicate and can be easily damaged during construction work or due to accidental impacts. Protecting them from mechanical damage is crucial to ensure reliable and consistent measurements.
- **Strain Gauge Fatigue and Lifespan Considerations** - Strain gauges experience cyclic loading, leading to fatigue and reduced lifespan. - Monitoring fatigue and implementing appropriate maintenance practices is crucial for reliable and continuous operation.
- **Issues Related to Humidity and Environmental Influences** - Humidity and environmental factors such as moisture and contaminants can affect strain gauge performance. - Proper sealing and protection measures should be implemented to mitigate these influences.

8. Emerging Trends and Future Prospects

- **Miniaturization of Strain Gauges for Microscopic Applications** - The miniaturization of strain gauges

opens up possibilities for microscopic applications in fields like microelectronics and nanotechnology. These highly sensitive sensors contribute to advancements in miniaturized devices and systems.

- **Integrating Strain Gauges with IoT and Data Analytics** - Strain gauges integrated with the Internet of Things (IoT) enable the collection and analysis of strain data on a large scale. This integration enables proactive maintenance decisions, predictive analytics, and process optimization.
- **Advancements in Wireless Strain Gauge Technology** - Wireless strain gauge technology constantly evolving, enabling for more reliable and efficient data transmission without physical connections. This trend leads to the development of wireless monitoring systems and expands the possibilities for remote and distributed applications.

9. CONCLUSION

Conclusively, strain gauges play a vital role in measuring mechanical strain and understanding material behavior. They have evolved over time, offering a variety of types adapted to specific applications. Proper installation, calibration, and measurement techniques are essential to ensure accurate and reliable results.

Strain gauges find innumerable field-testing applications in many industries such as automotive, aerospace, energy, and research. They enable structural health monitoring, material testing, and advances in robotics and automation. Vibrating wire strain gauges are the most robust solution to monitor strain in concrete and metal structures due to their long service life and high reliability. Strain gauges are considered significant measuring instrument for ensuring productivity and safety

Emerging technologies, such as miniaturization and wireless integration, promise exciting prospects for strain gauge technology. Despite challenges and limitations, strain gauges offer significant advantages such as non-disruptive testing, high precision, and versatility, making them indispensable in various fields etc.

REFERENCES

- [1] "Concrete dam Instrumentation Manual" Scientific Publishers.
- [2] "Vibrating wire strain gauges for long-term monitoring of structures" SMAR 2015.
- [3] "Fundamental Understanding of Piezoelectric Strain Sensors". Jayant Sirohi* And Inderjit Chopra, Alfred Gessow Rotorcraft Center, Department of Aerospace Engineering, University of Maryland
- [4] IS: 13232 "Code of practice for installation maintenance and observation of electrical strain measuring device in Concrete Dams".

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