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PRINCIPLES OF EXPERIMENTAL MEASUREMENT OF STRESSES AND STRAINS IN STEEL STRUCTURES

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Abstract: *This paper presents an analysis of the principles and practical aspects of experimental measurement of stresses and strains in steel structures using strain gauges. The fundamental design and operating principles of strain gauges are explained and discussed with a focus on their application to steel structures. Basic concepts of strain gauge measurements are examined in relation to the possible stress-strain state of the tested steel structures. Additionally, Wheatstone bridge configurations for connecting strain gauges are presented to achieve compensation for temperature, vibrations, and other parasitic effects during experimental testing. Finally, practical examples of testing steel structures, with special emphasis on railway vehicles, using strain gauges are provided. The results and discussions aim to support engineers and practitioners in accurately and reliably applying strain gauge technology in real-world experimental stress and strain measurements of steel structures.*
Key words: *Strain gauges, Mechanical stress, Stress measurement, Steel structures.*

1. INTRODUCTION

The measurement of mechanical stresses is one of the key aspects in analyzing the behavior of steel structures under external loads. Accurate determination of stress and strain distribution in engineering structures enables design optimization and validation, testing and certification, increasing the system reliability and the prevention of potential failures, particularly in specific fields of engineering such as the aerospace industry, automotive industry, railway industry, civil engineering, etc. [1]. One of the most commonly used methods for experimental stress measurement is the application of strain gauges – sensors that detect mechanical deformation through changes in electrical resistance. The operating principle of a strain gauge is based on the proportional relationship between the relative change in length and the change in resistance, which serves as the basis for quantifying of mechanical strain – stress in a material [2, 3]. This paper provides a detailed examination of the fundamental structural and functional principles of strain gauges, as well as their application in measuring different stress-strain states in steel structural systems. Special attention is given to the Wheatstone bridge configuration, which enables temperature compensation and enhances measurement accuracy [4, 5]. Practical examples of strain gauge applications in testing real steel structures are presented, demonstrating their broad applicability and importance in engineering diagnostics and numerical model verification. Results obtained from experimental measurements of mechanical stress are frequently used to validate Finite Element Method (FEM) analyses, thus achieving synergy between numerical simulation and experimental analysis. Measurement techniques and systems play a vital role in the design and certification of railway vehicles and their components, ensuring compliance with safety standards and optimal performance throughout their operational lifecycle [6–8]. Measurement systems based on strain gauges are crucial in the development and testing of railway vehicles, where reliable stress measurement is essential for ensuring the safety, comfort, and durability of components. By directly measuring the static strength and dynamic response of elements such as wheels, axles, supporting structures, and suspension systems, these systems facilitate the verification of calculations and the optimization of structural designs in accordance with various international standards [9, 10].

The aim of this paper is to provide engineers and practitioners with a solid theoretical foundation and practical guidelines for the correct and efficient application of strain gauge technology in real-world conditions. Through the presented results and analyses, the paper aims to improve the accuracy and reliability of mechanical stress measurements, which is essential for the testing and evaluation of steel structures. .

2. PRINCIPLES OF STRAIN GAUGE MEASUREMENT

A strain gauge is a conductor (sensor) with a defined electrical resistance that is affixed to the surface of the tested object or structure. The gauge is typically attached using adhesive bonding, following appropriate surface preparation and treatment of the measuring location. Any deformation of the tested object due to applied loads causes a corresponding deformation of the strain gauge, resulting in a change in its electrical resistance.

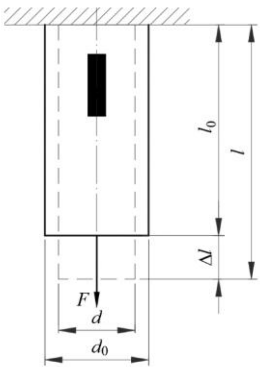

Fig. 1. Uniaxial tension

Under the action of a force on the structure shown in Fig. 1, the relative strain is:

(1) $\varepsilon = \frac{\Delta l}{l_0} = \frac{l - l_0}{l_0}$

The ratio of transverse to longitudinal strain (Poisson's ratio) is:

(2) $\mu = -\frac{\varepsilon_{tr}}{\varepsilon}$

It is known that the Poisson's ratio for steel is approximately 0.3. The transverse strain is:

(3) $\varepsilon_{tr} = \frac{\Delta d}{d_0} = \frac{d - d_0}{d_0}$

If the measured strain of the structure is denoted by ε, the resistance of the strain gauge attached to the structure by R, and the change in resistance due to the applied load (force F) by ΔR, the following relationship exists between these quantities:

(4) $\frac{\Delta R}{R} = k.\varepsilon$

In the previous expression, k is so-called gauge factor or strain gauge factor. It is a fundamental characteristic of the strain gauge that depends on the material of the wire from which the strain gauge is made. Under normal testing conditions, this factor typically has a value of approximately 1.8 to 2.2.

In practice, direct measurement of the resistance change in a strain gauge is not used. Instead, Wheatstone bridges are employed for this purpose. A Wheatstone bridge consists of four resistors connected to form a rectangle, a power supply U_E, and a measuring instrument that detects the output voltage of the bridge U_A (Figs. 2–4).

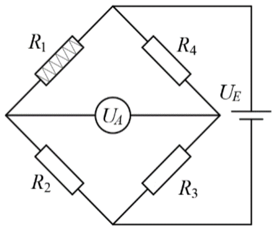

Fig. 2. Quarter-bridge

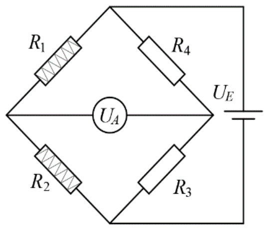

Fig. 3. Half-bridge

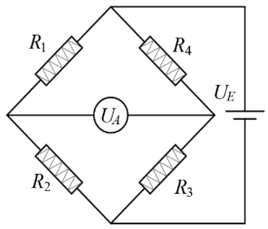

Fig. 4. Full-bridge

The principle of using balanced Wheatstone bridges is based on the fact that the output voltage of the bridge U_A=0, when the products of the resistances in the opposite branches of the bridge are equal, i.e.:

(5) $R_1.R_3 = R_2.R_4$

For unbalanced Wheatstone bridges composed of four identical strain gauges with nominal resistance R, the output voltage U_A can be calculated based on the values of R_1, R_2, R_3, R_4, and the supply voltage U_E:

(6) $$U_A = U_E \cdot \frac{\frac{\Delta R_1}{R} + \frac{\Delta R_3}{R} - \frac{\Delta R_2}{R} - \frac{\Delta R_4}{R}}{4}$$

In measurements using unbalanced Wheatstone bridges, the output voltage U_A is influenced by the resistance changes of all resistors (strain gauges) in the bridge. An increase in the resistance of R_1 and R_3 leads to an increase in U_A, while an increase in the resistance of R_2 and R_4 causes a decrease in UA. Therefore, the output voltage U_A increases if strain gauges R_1 and R_3 are placed in the direction of tension, and strain gauges R_2 and R_4 in the direction of compression. When measuring strain using an unbalanced measuring bridge, the measurement error is typically on the order of up to 3%. This error arises due to various factors such as voltage nonlinearity, cable resistance, moisture, etc.

By combining active strain gauges, passive strain gauges, and resistors, it is possible to implement three types of Wheatstone bridge configurations – quarter-bridge, half-bridge and full-bridge (Figs. 2–4). In the measurement of mechanical stress in steel structures, the half-bridge configuration (Fig. 3) is commonly used, as it allows compensation or neutralization of the effects of temperature, vibrations, and other parasitic influences that may affect the measurement results. One strain gauge (R_1) is attached to the structure at the appropriate measuring location, while the other strain gauge (R_2) serves for compensation and is placed on a small block made of the same material as the structure, positioned close to the measuring point.

3. MEASUREMENT DEPENDING ON STRESS STATE

3.1. Uniaxial stress state

In the case of a uniaxial stress state, the strain gauge is always bonded in the direction of the maximum stress σ_{max}, i.e., in the direction of the applied tensile or compressive load. Based on the measured strain ε_{max}, the stress is determined by multiplying it with the material's modulus of elasticity E, according to Hooke's law:

(7) $\sigma_{max} = E.\varepsilon_{max}$

3.2. Plane stress state – directions of principal stresses known

If a plane stress state is considered, and the directions of the principal stresses σ_1 and σ_2 are known (they occur in two mutually perpendicular directions), the strain gauges are applied along those directions. Based on the measured strains ε_1 and ε_2, the principal stresses are determined using the generalized Hooke's law, according to the following expressions:

(8) $$\sigma_1 = \frac{E}{(1-\mu^2)}(\varepsilon_1 + \mu\varepsilon_2)$$
$$\sigma_2 = \frac{E}{(1-\mu^2)}(\varepsilon_2 + \mu\varepsilon_1)$$

The equivalent stress is calculated using the following expression:

(9) $\sigma_i = \sqrt{\sigma_1^2 - \sigma_1.\sigma_2 + \sigma_2^2}$

3.3. Plane stress state – directions of principal stresses unknown

If the directions of the principal stresses are unknown, which is the most common case in testing mechanical structures, strain measurements are performed in three different directions using independent strain gauges, or strain gauges in the form of a "fishbone" configuration, known as strain rosettes. Based on the measured strains in three different directions (Fig. 5), it is possible to determine the principal stresses and the equivalent stress using methodologies known from strength of materials and the theory of elasticity.

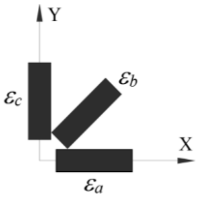

Fig. 5. Strain measurement in three different directions

The relationship between the strains in the directions along which the strain gauges are applied and the strains in the X and Y axes directions is as follows:

$$\varepsilon_a = \varepsilon_x.cos^2\varphi_a + \varepsilon_y.sin^2\varphi_a + \gamma_{xy}.sin\varphi_a.cos\varphi_a$$

(10) $$\varepsilon_b = \varepsilon_x.cos^2\varphi_b + \varepsilon_y.sin^2\varphi_b + \gamma_{xy}.sin\varphi_b.cos\varphi_b$$

$$\varepsilon_c = \varepsilon_x.cos^2\varphi_c + \varepsilon_y.sin^2\varphi_c + \gamma_{xy}.sin\varphi_c.cos\varphi_c$$

The angles φ_a, φ_b, and φ_c can be arbitrary and are measured in the positive mathematical direction with respect to the X axis (Fig. 5). Based on the measured strains ε_a, ε_b, and ε_c, the unknown strain components ε_x and ε_y, as well as the shear strain γ_{xy}, are determined from equations (10). The values of the principal strains are determined from the following expression:

(11) $\varepsilon_{1,2} = \frac{1}{2}(\varepsilon_x + \varepsilon_y) \pm \frac{1}{2}\sqrt{(\varepsilon_x - \varepsilon_y)^2 + \gamma_{xz}^2}$

The direction of the first principal strain (stress) is determined by the following angle, which is measured from the X axis in the positive mathematical direction:

(12) $\theta = \frac{1}{2} arctg \frac{\gamma_{xy}}{\varepsilon_x - \varepsilon_y}$

The inclination angle of the second principal strain is equal to $\theta+(\pi/2)$ and is also measured from the X axis in the positive mathematical direction. The values of the principal stresses can be calculated from equations (8) based on the determined principal strains. The value of the shear stress is determined by the product of the shear modulus G and the shear strain γ_{xy}:

(13) $\tau_{max} = G.\gamma_{xy} = \frac{E}{2.(1+\mu)}$

4. PRACTICAL EXAMPLES

Some practical examples of experimental measurements of stresses and strains in steel structures using strain gauges, conducted at the Laboratory of Railway Vehicles of Faculty of Mechanical and Civil Engineering, University of Kragujevac, Kraljevo, and Testing Center of the Kraljevo Wagon Factory are shown in next figures. The static strength testing of the supporting structures of the tank wagon, open wagon, flat wagon and closed freight wagon is shown in Figs. 6–9.

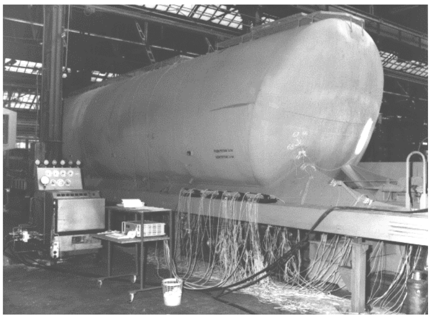

Fig. 6. Testing of static strength of tank wagon

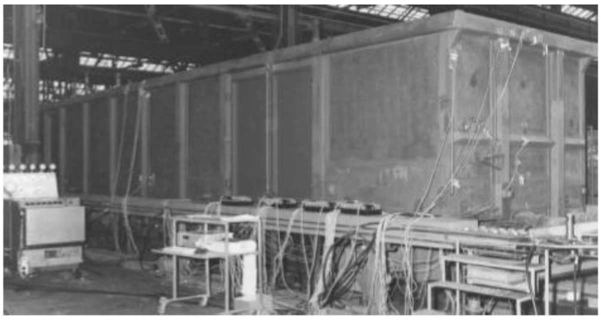

Fig. 7. Testing of static strength of open wagon

Fig. 8. Testing of static strength of flat wagon

Fig. 9. Testing of static strength of closed freight wagon

The static strength testing of the pole-mounted transformer substation is shown in Fig. 10. The static strength testing of the stationary vertical tank is shown in Fig. 11 while the static strength testing of the stationary horizontal tank is shown in Fig. 12.

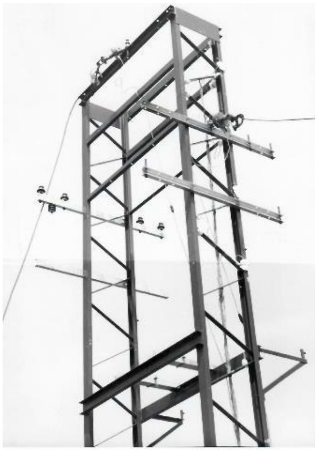

Fig. 10. Testing of static strength of pole-mounted transformer substation

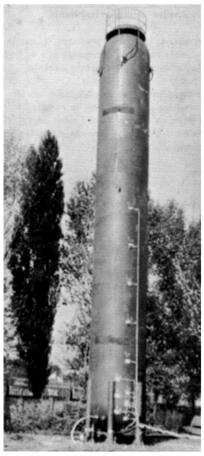

Fig. 11. Testing of static strength of stationary vertical tank

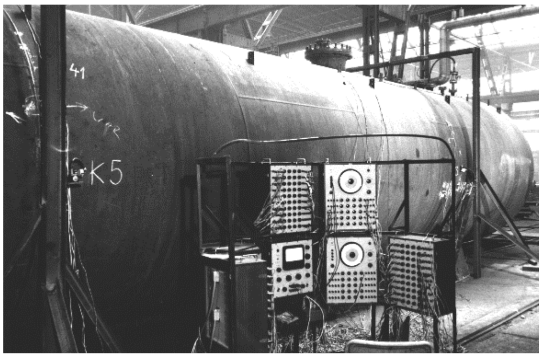

Fig. 12. Testing of static strength of stationary horizontal tank

Fig. 13. Measurement of dynamic stresses of wagon's parabolic leaf spring

The measurement of dynamic stresses of the wagon's parabolic leaf spring is shown in Fig. 13. The measurement of stresses at specific points on rail wheel and box girder are shown in Figs. 14 and 15.

Fig. 14. Measurement of stresses at specific points on rail wheel

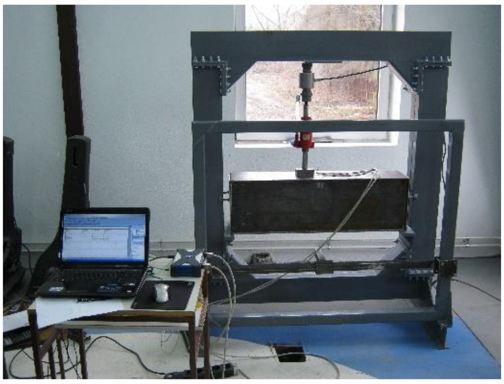

Fig. 15. Measurement of stresses at specific points on box girder

5. CONCLUSION

Strain gauges represent a reliable and effective method for experimental measurement of stresses and strains in steel structures. This paper presented their working principles, measurement techniques using Wheatstone bridge configurations, and practical applications. Through practical examples involving railway vehicles, the versatility of strain gauge systems in testing of steel structures was demonstrated. Their integration with numerical methods like FEM further enhances the accuracy and reliability of structural evaluations. Strain gauges remain essential tools for ensuring safety, durability, and compliance in modern engineering practice.

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