Reliability of strain gauge measurements to clarify the strength of structures at high temperatures

M V Klymov¹, S V Maslov² and A N Poguliaiko³

¹TESCAN ORSAY Holding a.s., Brno, Czech Republic
²Blagonravov Mechanical Engineering Research Institute, Russian Academy of Sciences, Moscow, Russia
³ZEMIC-TENZO Ltd company, Rostov-on-Don, Russia

maslovsv@inbox.ru

Abstract. The paper considers the problem of ensuring the reliability of experimental data obtained by tensometric studies of existing power plants. A technique that allows taking into account the change in the metrological characteristics of high-temperature strain gauges has been proposed. The design of the installation for determining the sensitivity of strain gages at temperatures up to 700°C has been considered.

Key words: Power plants, strain-stress state, full-scale tensometry, metrological characteristics

1. Introduction

Nowadays, increased demands are placed on ensuring the reliability and safety of operation of equipment of nuclear power plants, thermal power plants and other plants exposed to high mechanical and thermal loads. In a number of cases, the problem of a reasonable extension of the technical lifetime of power plants that have exhausted design service life, arises. To solve these problems, it is necessary to use the maximum possible amount of experimental information obtained at all stages of the commissioning and operation of such plants.

An effective method of obtaining experimental information on the stress-strain state (SSS) of equipment operated at high temperatures (up to 600°C and above), pressures up to 20MPa, variable electromagnetic fields and the effects of aggressive coolants is the method of full-scale tensometry [1,2]. The use of high-temperature strain gauges as primary transducers requires the use of reliable methods for assessing the error of the results of determining the SSS obtained in full-scale studies.

2. Research method

To determine and minimize the error in determining the SSS parameters obtained when using high-temperature strain gauges as sensing devices, it is necessary to take into account possible changes in their metrological characteristics (sensitivity, temperature characteristics, temperature influence function) and the spread of these characteristics that increases due to temperature. A feature of the loading conditions of power plants during start-up and operation is the constant change in their temperature state and the parameters of the mechanical loading of the elements [3], which greatly complicates the estimation of tensometric measurement errors.

Depending on the type of stress state, 3 main options for the location of strain gages in each of the measurement points are used: single-component, 2-component and 3-component sockets.

Accordingly, 3 different formulas for calculating stresses from the measured values of the strain components measured by strain gauges are used. These formulas contain the values of the elastic
coefficient, Poisson's ratio and strain values measured by strain gages in the directions of their longitudinal axes. Each of these quantities contains random errors in their determination; therefore, the stress components obtained as a result of measurements depend on the specific form of their relationship with the measured strains. To assess the strength in hazardous areas of the structure, equivalent stresses are used, which are derived from components obtained from the measured values of deformations, and determined by formulas depending on the strength theory embraced. Thus, the reliability of the strength assessment at hazardous points in a rather complicated way depends on the error in the measurement of strains. In the general case, taking into account the error in determining the elastic coefficient $E$ and Poisson's ratio $\mu$, the formula for the root-mean-square deviation (RMSD) of the experimentally obtained principal stresses $S_{1,2}$ has the following form:

$$S_{1,2} = \left( \frac{E^2}{1-\mu^2} \left( S_{e1,2}^2 + \mu S_{e2,1}^2 \right) + \frac{(\varepsilon_{e1,2} + \mu \varepsilon_{e2,1})^2}{(1-\mu^2)^2} S_{m}^2 + \frac{E^2}{1-\mu^2} \left[ 2\mu \varepsilon_{e1,2} + (1+\mu^2) \varepsilon_{e2,1} \right]^2 S_{m}^2 \right)^{1/2} \tag{1}$$

Where $S_{e1} \cdot S_{m}$ and $S_{e1,2}$ – root-mean-square deviation (RMSD) respectively: determination of the elastic coefficient $E$, the Poisson's ratio $\mu$ and the RMSD of the strain measurement errors by tensometry method.

The problem of minimizing strain measurement errors is associated with the use of special techniques for eliminating uninformative components of the output signal of strain gauges associated with creep, drift, and changes in the temperature characteristics of strain gauges. Additional difficulties arise if the task is to avoid overestimating the error components associated with the formal use of the characteristics of a separate batch of strain gauges instead of their individual values. In field studies of power equipment, a characteristic case is the occurrence of significant temperature drops and their rate of change in each test mode. Figure 1 shows the characteristic graphs of changes in the loading parameters of a power plant (nuclear power plants (NPP) with a VVER-1000 reactor) during the period of tensometric measurements.

As follows from the graphs, during the test periodical temperature changes occur in the amount of 50 - 100°C, the temperature level for various zones of the installation of strain gages is between 100 - 350°C.

As a rule, the largest contribution to the total measurement error is made by the component associated with the accuracy of determining the temperature characteristics of strain gages. The value of the output signal associated with a change in temperature may be higher than the main component associated with the deformation. This occurs if special techniques to minimize the temperature signal are not applied. Therefore, when measuring under such conditions, circuit compensation of the non-informative component of the output signal is used, in which the working and compensation strain gages are included in the adjacent arms of the measuring half bridge. In addition, the working and compensation strain gages are selected in pairs in at least two parameters: a value of temperature characteristic and a value of drift at maximum test temperature.

Using this technique, the measured strain can be represented as follows:

$$\xi = \frac{\xi - \Delta \xi_n}{K F_t} \tag{2}$$

where $\xi$ – a measured value of the output signal of the strain gauge half-bridge, $\xi_n$ – an output value caused by measured strain; $K$ – a sensitivity of a strain gauge, $F_t$ – a temperature influence function, $\Delta \xi_n$ – a difference of non-informative components of the working and compensation strain gages.

In this paper, it is proposed to estimate the error associated with the random error of $\Delta \xi_n$ to use its experimental determination directly in the process of tensometric studies. For this, it is necessary to use a representative sample (at least 20 elements) of mechanically unloaded samples from the material of the full-scale structure with installed control half-bridges of strain gauges. The installation method
of the control half-bridges should correspond to that used for the main measurement points, the signal measurement - as part of the general measurement procedure.

In this case, the determination of the measurement error of the output signals of tensometric half-bridges will be determined by the formula:

\[
S = \left[ \left( \frac{x - \Delta x_n}{K F} \right)^2 + \frac{1}{K^2} S^2_{k} + \frac{1}{F_i^2} S^2_{t} \right]^{1/2} \]  \hspace{1cm} (3)
\]

where \( S^2_{k} \), \( S^2_{t} \), \( S^2_{a} \), \( S^2_{d} \) – are accordingly, random errors in determining the sensitivity and function of the influence of temperature, instrument error and the error in determining the non-informative component of the output signal for a control sample of samples.

Figure 1. Typical changes in the loading parameters of the PGV-1000 steam generator during commissioning tests.

3. Experimental setup

Formulas (1), (2) and (3) do not take into account the error associated with the creep of strain gauges, for an accurate assessment of which it is necessary to conduct an experiment simulating the time variation of the stresses acting at the measurement points.

The function of the influence of temperature \( F_t \) is also not always known, since it is not included in the mandatory list of metrological characteristics indicated in the passport data of a batch of strain gages. For its experimental determination, it is proposed to use a setup with a loaded four-support beam, on the surface of which in the zone of constant bending moment the tested strain gages are installed. The schematic diagram of the developed installation is shown in Figure 2.

The beam is heated by passing an electric current through it, which minimizes the experiment time and minimizes the effect of creep on the measurement results. The main criterion for choosing the material of the beam is a high coefficient of proportionality \( \sigma_{02} \) both at normal and elevated temperatures (up to 700°C). The beam material must also have a sufficiently high electrical resistance for its heating by electric current up to a temperature of 700°C.
Figure 2. Typical changes in the loading parameters of the PGV-1000 steam generator during commissioning tests.

From the point of view of the electrical installation circuit, the beam is sequentially connected to the secondary circuit of the power transformer 5. To ensure a smooth transition in electrical resistance, as well as to ensure uniform heating of the end sections of the beam, the current-carrying tires are soldered onto the beam on one side by high-temperature solder, and, on the other hand, are connected to the current conductors 4 by means of a bolted connection. The width of the power rails is equal to the width of the beam, which eliminates their local overheating in the soldering zone.

Since the allocated power is proportional to the active circuit resistance, the resistance of the section of the circuit of the secondary winding of the transformer (including the secondary winding itself) in addition to the beam should be minimal. To fulfill this condition, the length of the supply busbars and the current density in the transformer windings must also be minimal. At the same time, for maximum heat generation in the beam, its active resistance should be maximum, which is achieved by increasing the length of the beam and reducing its cross section.

According to the classical Joule-Lenz law, the relationship between the geometric parameters, the physical properties of the beam and the amount of heat required to heat it from the initial temperature $t_1$ to the required temperature $t_2$ is expressed by the formula

$$t_2 - t_1 = \frac{I^2 \cdot \rho \cdot \tau}{C \cdot g \cdot S^2},$$

Where $I$ – a current load, A; $\rho$ – an electrical resistivity of the beam material, $\Omega \cdot m$; $\tau$ - a heating time, c; $C$ – specific heat of the material, J*(kg *K-*1); $S$ – a beam cross-sectional area, m$^2$; $g$ – a material density, kg/m$^3$.

As follows from formula (4), a decrease in the beam thickness by 0.01 mm will entail a decrease in temperature by about 1°C when heated from normal temperature to 700°C with the remaining parameters remaining unchanged. A decrease in the width of the section of the beam by 0.01 mm will also lead to an increase in the temperature of the section by 1°C with similar heating. These
considerations determine the tolerance on the overall dimensions of the beam: not more than ± 0.01 mm in the working area. At the same time, by adjusting the width and cross section of the beam, it is possible to adjust its maximum operating temperature for a given value of current load \( I \). It should be noted that the maximum heating temperature is limited by the mechanical characteristics of the material - in particular, the proportionality limit \( \sigma_{02} \), which decreases with increasing temperature.

In the developed installation, the heating temperature is controlled using a temperature sensor installed in the center of the beam. The signal from the temperature sensor is transmitted to the PID controller with an analog output of 4 – 20 mA, where a level of 20 mA corresponds to a temperature of 800°C, and 4 mA to a normal temperature (20°C). An analog signal from the PID controller is fed to the input of a solid-state relay, which, using phase-pulse modulation controls the step-down transformer 5 (Figure 2). The use of a modern element base, in particular the PID controller, allows to achieve the accuracy of maintaining the heating temperature ± 0.1°C.

The loading of the beam to the required deformation is carried out manually with control on the dial scale associated with the mechanism of transferring movements to the movable supports by manually rotating the dial scale. To measure the actual deformation, a special deflection meter is used, resting on the surface of the beam with three supports made of quartz glass. Deformation of the beam through the deflection meter is transmitted to the dial indicator through the rod, also made of quartz glass. To reduce the influence of temperature on the readings of the deflection meter, two metal plates are located between the indicator and the beam, which play the role of thermal screens. The deflection indicator is mounted on a hinge, which allows it to be installed on the beam only at the moment of direct strain measurement. Thus, prior to direct measurement, the deflection meter is removed from the surface of the beam and is not subject to heat. The time required to install the deflection meter on the beam and to carry out the graduation of the dial scale in compliance with the developed methodology is 1-2 minutes. The maximum heating temperature of the deflection meter during measurements does not exceed 75°C, which ensures its operability.

4. Conclusion
The experiments made it possible to establish that the developed methodology and the installation shown in Figure 2 are capable of determining the necessary metrological characteristics of strain gages at temperatures up to 700°C, and when using materials with increased heat resistance - up to 800°C.

References
[1] Mikhalev Y K, Fomin A V and Maslov S V 2008 Full-scale thermal-strain studies of deflected modes of nuclear power plant equipment Journal of Machinery Manufacture and Reliability 5 517-21
[2] Maslov S V 2019 A Computational–Experimental Method for Determination of the Stress–Strain State of Thermally-Loaded Power Equipment according to Full-Scale Strain-Gauging Data Journal of Machinery Manufacture and Reliability 2 141-8
[3] Razumovskii I A, Chernyatin A S and Fomin A V 2014 Experimental-computational methods for determination of the stress-strain state of structural components Inorganic Materials 15 1528-36