Chapter 1
Verifying the Operation and Health of Dynamic Strain Gages on Experimental Structures

Matthew Stefanski and William Boles

Abstract Unlike Accelerometers, microphones, and most other sensors used to measure the mechanical dynamics of structures, dynamic strain gages lack a direct calibration method to a known force input. This paper provides practical guidance for engineers new to structural dynamic experiments on evaluating the integrity and proper response of dynamic strain gages. The techniques will include post-installation inspection, impedance measurements, and signal integrity checks that can be used to identify and mitigate potential sources of error. By implementing these methodologies, engineers can improve the reliability and accuracy of dynamic strain measurements, leading to more trustworthy experimental results.

Keywords Instrumentation · Sensors · Strain · Gage · Structure

The best way to ensure proper function of a thin film strain sensor is to ensure that the gage selection process and gage installation procedures were performed properly. However, the purpose of this paper is to discuss the best practices and procedures to ensure accurate gage functions AFTER the sensor has been installed.

When working with thin film strain gages, the quality control checks of **visual inspection** and process of gaging resistance check involve two primary measurements to ensure a proper installation: **insulation resistance** and the **shift in gage resistance**. These three checks are critical for verifying the quality of the installation and are usually performed with magnifiers and equipment such as a digital multimeter or Vishay Model 1300 Gage Installation Tester / GIT box.

Visual Inspection

The first step to ensure your newly installed strain sensor performs properly is to conduct a thorough **visual inspection**. Preferably under magnification due to the small size particulates voids that may exist, encapsulated under the strain sensor grid.

Trapped voids or foreign particulates within the bond layer of a thin film strain sensor can have significant negative effects on the sensor's performance and accuracy. These defects disrupt the uniform transfer of strain from the test specimen to the sensor's grid, leading to inaccurate and unreliable measurements.

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Adverse Results of Voids and Particulates

The presence of these defects creates a poor mechanical connection between the strain sensor and the article under test, resulting in several adverse outcomes:

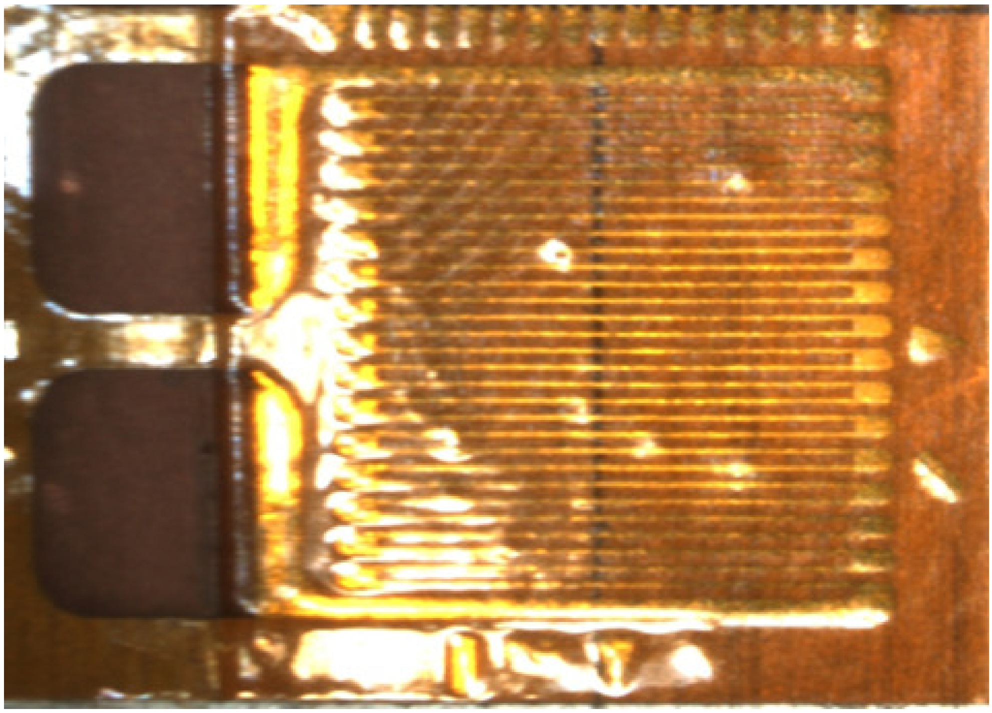

Fig. 1 Particulates in the Adhesive Bond Layer

1. **Reduced Sensitivity and Measurement Error:** The most direct consequence is a reduction in the sensor's sensitivity. Because the strain is not fully transferred, the change in resistance will be less than would be expected for the actual strain. The presence of these defects also introduces non-linearity and hysteresis into the measurements. The sensor may not return to its original zero point after being unloaded, causing a permanent zero shift.
2. **Non-Uniform Strain Transfer:** Voids and particulates prevent the strain sensor's grid from being perfectly bonded to the specimen. This creates localized areas where the strain is not accurately transmitted, leading to a distorted and uneven strain field across the sensor. This is a critical issue because the sensor's function relies on a one-to-one transfer of strain.

Premature Failure: These defects can act as stress concentrators, particularly at the edges of a void or around a particulate. This can lead to premature failure of the bond layer or the sensor itself, especially under cyclic or fatigue loading conditions. The presence of a void also makes the installation more susceptible to environmental factors like moisture and corrosive agents, which can lead to further degradation of the bond.

Cracks in the metallic grid of a thin film strain sensor have severe negative consequences, primarily causing inaccurate readings, signal instability, and eventual sensor failure. These cracks disrupt the intended electrical pathway, altering the fundamental relationship between strain and resistance. Visual inspection should be performed prior to mechanical cycle and periodically thought test cycling, paying close attention to non-repeatable results at identical load point during the cycling.

Adverse Results of Cracks in the Grid

The primary purpose of a strain sensor's metallic grid is to provide a stable, uniform change in resistance with applied stress. When a crack occurs, this relationship is fundamentally broken.

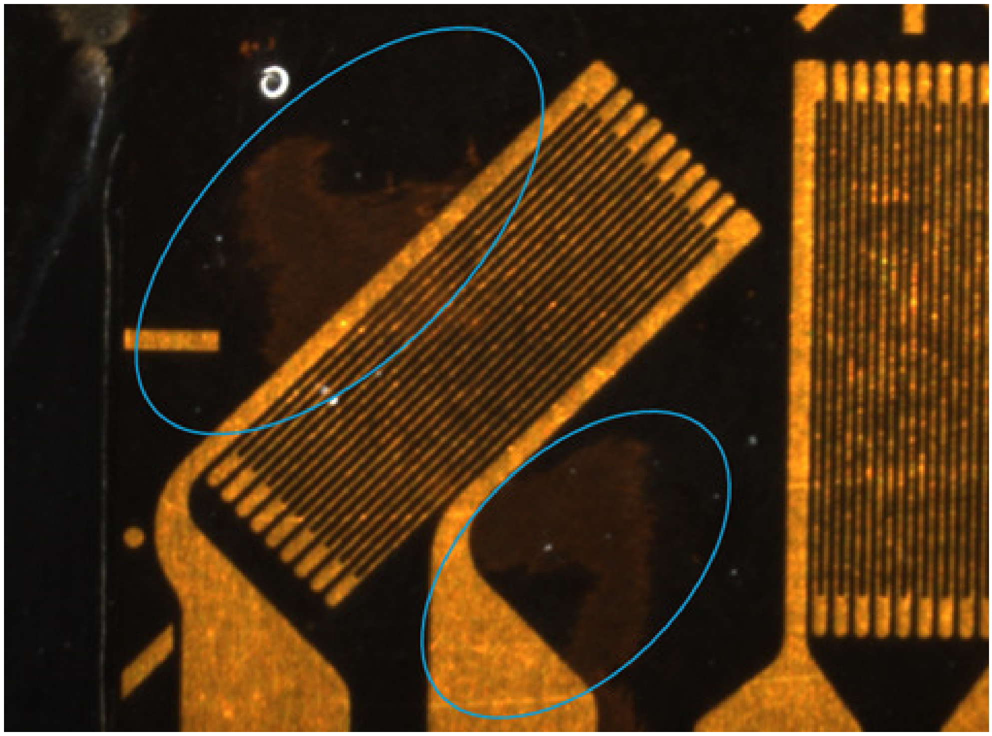

Fig. 2 Voids/Bubbles in Adhesive Bond Layer

- **Non-Linearity and Hysteresis**: Cracks introduce an unpredictable change in the electrical path, making the sensor's output non-linear. The resistance change will no longer be proportional to the applied strain. This also causes hysteresis, where the output for a given strain value is different depending on whether the load is increasing or decreasing.

Electrical Effects and Complete Failure

Cracks can have various electrical effects that degrade the sensor's performance and can ultimately lead to sensor failure.

- **Increased Noise**: A crack acts as a tiny, unstable switch. As the crack opens and closes with minute movements or vibrations, it generates significant electrical noise in the sensor's signal, masking the actual strain measurement.
- **Open Circuit**: If the crack propagates completely through the metallic grid, it will create an **open circuit**. This means the electrical path is broken entirely, and the sensor will cease to provide any output. The resistance will become infinite, rendering the sensor completely useless.
- **Localized Heat Generation**: In cases where a crack significantly reduces the cross-sectional area of the grid, the current density increases at that point. This can cause localized heating, which further alters the resistance and can accelerate the propagation of the crack, leading to a faster failure.

Standard checks for installed thin film strain sensors primarily focus on **installed gage resistance** and **insulation resistance** to verify the quality of the installation before use. These checks are crucial for ensuring accurate and reliable data, as poor installations can lead to significant measurement errors.

Installed Gage Resistance or Shift Resistance: Gage shift in resistance is a crucial measurement for verifying the quality of a strain gage installation. An excessively high gage resistance during the installation of a thin film dynamic strain sensor can lead to several problems, primarily related to inaccurate measurements and poor signal quality. The main symptoms include a **low signal-to-noise ratio (SNR)** and **reduced sensitivity.** This check is taken to ensure the sensor hasn't been damaged during mounting or the installation process. It's important because a significant shift in the gage's resistance from its original, unstrained value can indicate damage from improper handling, excessive clamping force, or other installation issues.

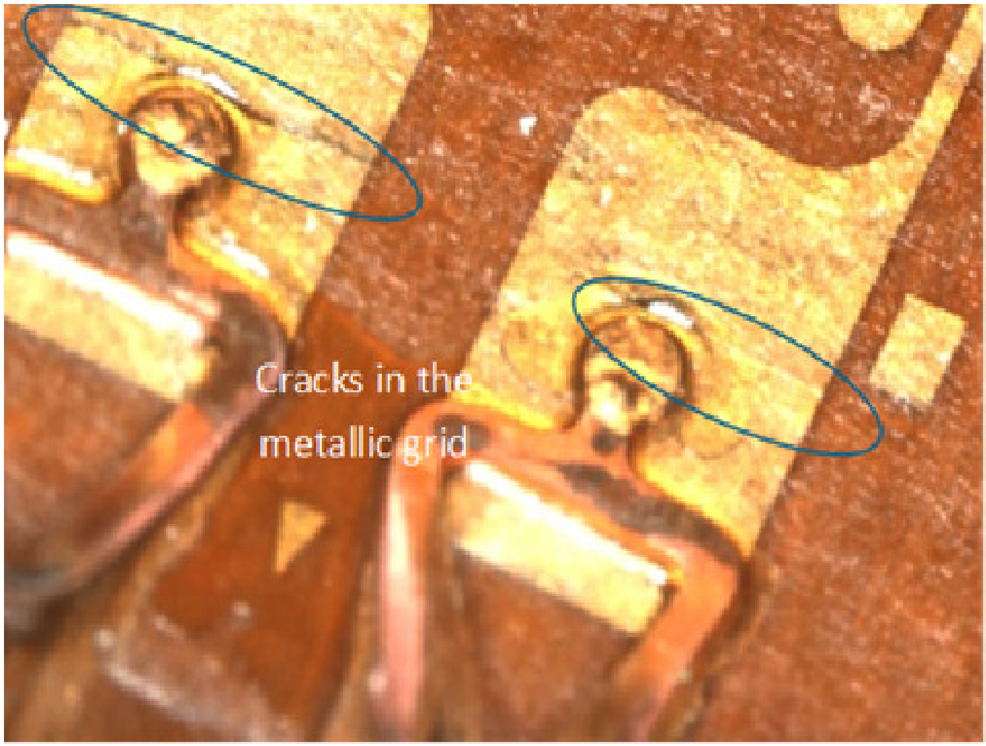

Fig. 3 Cracking of the Sensor Grid

Reduced Sensitivity and Low Signal-to-Noise Ratio (SNR)

The symptoms of excessive gage resistance are directly related to the principles of Wheatstone bridge circuits, which are commonly used to measure strain. The output voltage of a Wheatstone bridge is proportional to the change in resistance of the strain gage. When the nominal resistance (Rg) of the gage is excessively high, it can negatively impact the bridge's performance.

The voltage output of a quarter-bridge circuit is given by the formula:

$$Vout = Vin \cdot \frac{GF \cdot \epsilon}{4}$$

Where:

- Vout is the output voltage
- Vin is the input voltage
- GF is the gage factor
- ϵ is the strain

While this formula doesn't explicitly show resistance, the noise in the circuit does. Thermal noise, which is a key contributor to the noise floor, is proportional to the square root of the resistance. The formula for thermal noise voltage (Vn) is:

$$V_n = \sqrt{4 \cdot k \cdot T \cdot R \cdot \Delta f}$$

Where:

- k is the Boltzmann constant
- T is the temperature in Kelvin
- R is the resistance
- Δf is the bandwidth

As the **gage resistance** (R) increases, the **thermal noise voltage** (Vn) also increases. This leads to a higher noise floor.

A higher noise floor, combined with the relatively small signal generated by the strain, results in a **low signal-to-noise ratio (SNR)**. A low SNR makes it difficult to accurately measure small changes in resistance caused by strain, leading to noisy and unreliable data. The sensor's ability to detect small strains is therefore significantly reduced, effectively making it less sensitive. This can be problematic in applications where precise measurements of low-amplitude vibrations or deformations are required.

Other Symptoms

In addition to the fundamental issues of sensitivity and SNR, excessive gage resistance can also manifest in other symptoms:

- **Difficulties with Data Acquisition:** High resistance can be a challenge for some data acquisition (DAQ) systems, which are optimized for common strain gage resistances (e.g., 120 Ω or 350 Ω). It may require a DAQ system with a higher input impedance to prevent loading effects that would further diminish the signal.
- **Drift and Instability:** High resistance can sometimes be a symptom of a poor connection or a damaged sensor element, which can cause the resistance to drift over time or with changes in temperature. This leads to an unstable zero point and inaccurate long-term measurements.

How to check: To measure the shift in resistance, you compare the **installed resistance** of the strain gage to its **nominal resistance**. This is typically done with a specialized instrument like the Vishay Micro-Measurements Model 1300 Gage Installation Tester, which is designed to measure this deviation with high precision but can be accomplished using a digital multimeter capable of precise resistive measurement.

- **Nominal Resistance**: This is the value specified by the manufacturer, such as 120 Ω or 350 Ω on the sensor packaging.
- **Installed Resistance**: This is the resistance of the gage after it has been bonded to the test specimen and the lead wires have been attached.

The measurement is often displayed as a **percentage deviation** from the nominal value. A resistance shift greater than the recommended limits, found in Vishay Application Note VMM-15, entitled "Quality Control of Strain Gage Installations", indicates a potential problem with the gage installation.

Recommended Values and What They Indicate

Vishay Micro-Measurements documents provide specific guidelines for acceptable resistance shifts, which can vary depending on the type of adhesive used:

1. **Room-Temperature-Curing Adhesives**: For these adhesives, the resistance shift should not normally exceed 0.5% of the nominal gage resistance. A shift greater than this limit usually indicates damage to the gage from improper handling or clamping during the installation process.
2. **Elevated-Temperature-Curing Adhesives**: With these adhesives, a larger shift is expected because of the difference in thermal expansion between the strain gage and the test specimen. This creates thermal stress in the gage as it returns to room temperature after curing. While the magnitude of this shift can vary, it should never exceed 2% and should be uniform among identical installations to within about 0.5%.

By performing this simple test, you can identify installation flaws like a damaged grid, poor solder connections, or lead wire damage before you begin your critical strain measurements.

Insulation Resistance (Leakage to Ground) :

This check measures the electrical resistance between the strain gage's grid and the test specimen. It's a fundamental test to ensure the gage is properly insulated from the surface it's bonded to.

Bad insulation resistance, or leakage to ground, in a thin film dynamic strain sensor creates a stray current path that can significantly interfere with measurements. This short circuit from the sensor's active element to the grounded test structure introduces a variable resistance in parallel with the strain gage, causing several critical symptoms.

Fig. 4 Vishay Model 1300 Gage Installation Tester

A low insulation resistance can cause extraneous signals to be introduced into the measurement, leading to inaccurate reading. It's often caused by trapped foreign matter, moisture, residual soldering flux, or damage to the gage's backing material.

Key Symptoms

- **Drift and Instability:** A primary symptom is a measurement baseline that **drifts** and is **unstable**. The leakage path's resistance isn't constant; it changes with temperature, humidity, and even the applied strain itself. This causes the output signal to fluctuate erratically, making it impossible to establish a reliable zero point for the measurement. You'll see the strain wander without any real load being applied.
- **Reduced Sensitivity and Low Output:** The leakage resistance creates a parallel path for current to bypass the strain gauge. This effectively lowers the overall resistance of the sensor circuit, which in turn reduces the change in resistance (ΔR) for a given strain. As a result, the output voltage from the Wheatstone bridge circuit is lower than expected, making the sensor less sensitive to strain.
- **Increased Noise:** Leakage to ground can introduce noise into the signal. The stray current path acts as an antenna, picking up electrical noise from the surrounding environment. This noise is superimposed on the small strain signal, leading to a poor **signal-to-noise ratio (SNR)**. This symptom is particularly problematic for dynamic measurements, where the signal is already small and easily obscured by noise.
- **Incorrect Strain Readings:** The most direct consequence is a false strain reading. The change in resistance from the leakage current is indistinguishable from the change in resistance caused by actual strain. This can lead to erroneous

tensile or compressive strain values, even if the structure is at rest. The error is unpredictable and can change with environmental conditions, making it impossible to correct in post-processing.

Causes and Troubleshooting

The primary cause of bad insulation resistance is damage to the thin film's dielectric or insulation layer. This can happen during installation due to:

- **Moisture or Contamination:** Trapped moisture, flux residue from soldering, or other contaminants under the sensor can create a conductive path. This is a common issue and is often a reason for the unstable, fluctuating readings.
- **Mechanical Damage:** A scratch, crack, or pinhole in the sensor's protective coating or substrate can expose the active grid to the grounded surface.
- **High Temperatures:** In high-temperature applications, the insulation resistance of the ceramic or polymer substrate naturally decreases, increasing the risk of leakage.

To test for this problem, you can perform an **insulation resistance test** (often called a "megger" test) using a specialized multimeter or insulation tester. You would apply a low DC voltage between the strain gauge circuit and the ground of the test structure and measure the resistance. A healthy installation should have an insulation resistance of **over 20,000 MΩ** (megaohms), although a reading at 10,000 MΩ or greater is generally considered the minimum acceptable value. Unstable readings or values under 10,000 MΩ indicate a problem.