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STRAIN GAGES:
POSTAGE STAMP STRESS ANALYZERS

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STRAIN GAGES: POSTAGE STAMP STRESS ANALYZERS*

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ABSTRACT

Stress cannot be measured directly but strain can. Lord Kelvin, in 1856, discovered that when a wire is subjected to mechanical strain there is a change in its electrical resistance. In 1938, this principle was utilized in the invention of the bonded resistance strain gage.

Strain gages can be used in liquid hydrogen and in 2000° F environments, submerged in sea water on ships' hulls, and subjected to hydrostatic pressures of 50 000 psi. They have been bonded to almost all metals, to concrete, brick, bones (living and dead), wood, rubber and plastics. They have been used in and on operating gas turbines, reciprocating engines, airplanes, rockets, cranes, earth-moving equipment and automobiles -- wherever a stress problem required their use.

As a safety tool, strain gages are used in the development and testing of parts and structures to determine whether they are safe.

*Work done under auspices of the U.S. Atomic Energy Commission.

INTRODUCTION

Resistance strain gages have been used to measure strains as low as fractions of a millionth of an inch per inch, as well as strains up to 23% on rubber and plastics. They have withstood environments from liquid hydrogen to 2000°F combustion exhaust gases. They have operated submerged in sea water on ships' hulls for periods of years, and have been used in hydrostatic environments at pressures greater than 50 000 psi. Resistance strain gages can faithfully follow strains from zero frequency (dc) to more than 50 000 Hertz, and upper frequency limits have not yet been determined. They have been mounted to withstand 600 000-g loading on rotating machinery, and signals have been obtained from them at close to 100 000 rpm rotational speeds. When used to measure quantities other than strain, such as load, pressure, and torque, they have exhibited accuracies of 0.1% for 20 years. Resistance strain gages have been bonded to almost all metals, to concrete, cement, brick, bones (living and dead), wood, rubber and plastics. They have even been woven into fabrics. They have been used in and on operating gas turbines, reciprocating engines, airplanes, rockets, submarine hulls, cranes, drilling rigs, earth-moving equipment, automobiles--wherever a stress problem required their messages. Load cells operating as strain gage transducers are used in process and control industries for chemical batching, automatic mixing, continuous conveyor belt weighing, and totalizing.

GENERAL CONSIDERATIONS

Concepts of Strain and Strain Measurement

The criterion of failure of a material, machine, or structure is usually expressed in terms of the stress, or force per unit area, which must exist in the material before failure will occur. The concept of stress, being somewhat artificial in nature, has always had as its main disadvantage the fact that it is not a quantity which can be measured directly. The unit elongation, or strain, of a material under stress, can be measured, however. Strain is used almost universally, in conjunction with the elastic and plastic constants of the material, to arrive at experimental values of stress. In the simplest case, uniaxial stress, the stress and the strain in the material are directly related by the modulus of elasticity of the material within its elastic range. This relationship is expressed as $S = E\epsilon$, where S = stress, E = modulus of elasticity of the specimen material, and ϵ = strain. The unit of strain is expressed as microinches/inch or more commonly as micro-strain, and is abbreviated $\mu\epsilon$. Other states of stress, such as biaxial or triaxial, involve more complicated relationships between the material constants, stress, and strain; the stresses can still be obtained even though the formulas are somewhat complicated.

As modern designs become more complex, it is more difficult to predict their behavior theoretically, and the experimental verification of a design becomes more important. The experimental measurement and verification of strain is a vital portion of modern technology in all fields of engineering endeavor leading toward safer materials, machines, and structures.

Development of Strain-Measuring Devices

The very definition of strain as a unit or percentage change in length creates the impression that its measurement is no more complex than the measurement of changes in length. Indeed, for many years, calipers and a ruler were standard strain-measuring instruments. These were satisfactory for very large strains, but they would not be suitable nor nearly accurate enough for the typical strain magnitudes frequently encountered in stress-analysis studies today. A stress of 30 000 psi in steel, for instance, is equivalent to 1000 microstrain, or 0.001 in. per in. of gage length. Strains of this magnitude are extremely difficult to measure with calipers and a ruler, even though this represents a relatively high stress in the steel. Calipers and a ruler were succeeded, in later years, by gear trains and optical, acoustic, pneumatic, and mechanical lever systems. The most accurate strain-measuring devices, frequently used as standards, are optical in nature, and include both interferometric means and optical lever-arm techniques.

Subsequent developments occurred in the electrical fields, where capacitance, inductance, reluctance, and resistance were made the bases of numerous extensometer instruments. Today, by far the most popular strain-measuring device is the electric resistance strain gage.

Development of Electric Resistance Strain Gages

The basic principle of operation of the resistance strain gage was discovered by William Thompson (Lord Kelvin) and presented to the Royal Society in 1856. In his research on "The Electrodynamic

Qualities of Metals" he discovered that metallic wire, subjected to mechanical strain, changes electrical resistance, and that this change is not always predictable by considering only geometric changes in the shape of the wire. There is a basic strain dependence of the electrical resistivity of materials. Subsequent investigators found that different materials exhibited different resistance-strain characteristics, varying even as to the sign of the effect. Professor R. W. Carlson of the University of California at Berkeley was the first to utilize this phenomenon to measure strain. In the late 1920's, he wound fine wires between binding posts anchored in different locations on concrete dam structures, and measured the strains within the concrete by measuring the changes in electrical resistance of the wire windings.

The bonded resistance strain gage was invented in 1938, almost simultaneously, by Edward E. Simmons at the California Institute of Technology, and by Arthur C. Ruge at the Massachusetts Institute of Technology. The idea of bonding a length of fine wire directly to the part to be tested, with the cement acting as an electrical insulator, made possible many applications of resistance strain gages.

The wire gage has been all but obsoleted by the foil strain gage developed in the late 1950's. Instead of the 1- to 2-mil-diameter wire strain-sensing element, a 0.1- to 0.5-mil-thick etched foil grid is used. The foil is laminated with a backing material, as with the wire gage--1-mil polyimide and phenolic being the most commonly used backing for the foil gage. The application techniques and the instrumentation for the foil gage are exactly the same as for the wire gage.

Types of Gages

Now, what do these magical devices we call strain gages look like? In Fig. 1 we can see the three basic strain gage configurations that are most commonly used today.

The gage on the right in Fig. 1 is a single-element gage and is used for measuring strains in one direction only. The middle gage is called a two-element or "T" rosette gage, and can be used to measure strains in two directions at once, perpendicular to each other. The gage on the left is called a three-element, stacked rosette--"stacked" because the three gage elements are laminated with the centers of the grids superimposed. It is used when a complicated strain field is encountered. The three strains that are measured simultaneously with this gage, at exactly 45 deg from each other, are needed to calculate the maximum and minimum principal strains in the structure.

STRAIN GAGE CHARACTERISTICS

Transducing Process of the Resistance Strain Gage

The transducing process on which the resistance strain gage is based is actually a dual one. A mechanical strain input results in a change in electrical resistance. This change in electrical resistance is observed as a change either in current or in voltage under the action of an auxiliary source of electrical energy. Thus the strain gage, being a non-self-generating, passive transducer requires two energy inputs--the mechanical energy, in terms of strain over the gage length, and the electrical auxiliary energy, which permits the strain-induced resistance change to be measured.

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Fig. 1. Strain Gages. Right to left: phenolic-backed single-element gage, polyimide-backed two-element gage ("T" rosette), and phenolic-backed three-element gage (stacked rosette).

In practice, one or more of these gages is bonded to the exact spot where strain is to be measured. The gages, being very thin and flexible, cling to the surface as if they were actually a part of it. When the surface to which the gages are bonded is bent, stretched, or twisted, the metallic sensing element of the strain gage is similarly distorted, causing a change in electrical resistance of the element. The resistance change (an increase denotes tension and a decrease indicates compression) is a measure of the amount of strain.

Strain Transmission

It is necessary to transmit the strain from the surface of the specimen to the gage. The mechanism of strain transmission can be broken down into two general areas: strain transmission at a boundary--this occurs at the specimen-cement interface and the cement - gage backing interface--and strain transmission through the adhesive that bonds the gage to the specimen. Unless the strain is faithfully transmitted to the strain-sensitive element of the gage, the results will be in error and the data will be invalid. Bonding a strain gage to a specimen is an art and is the most important step in using strain gages. If the gage is not bonded properly the strain transmission will be erroneous.

Gage Length Considerations

Another possible problem in using strain gages is that the strain we measure is averaged over the gage length. If we install a gage in an area where there is a high strain at a small point under the gage, the resultant gage reading will be too low because of the averaging of the strain under the entire gage. Use of a very short gage, located accurately, lessens this problem.

Gage Factor

Every gage element material has a distinct relationship between a change in strain and the corresponding change in resistance. This relationship is expressed mathematically as $GF = \frac{\Delta R/R}{\Delta \epsilon}$, where GF = gage factor of the gage, ΔR = change in resistance, R = original resistance of the gage, $\Delta \epsilon$ = change in strain.

The gage factor, then, is a measure of the amount of resistance change for a given change in strain, and is an index of the strain sensitivity of the gage. The higher the gage factor, the more sensitive the gage. The gage manufacturers enclose the gage factor with every package of strain gages.

The most common strain gage grid materials and their associated nominal gage factors are: constantan (nickel-copper), 2; Nichrome (nickel-chrome), 2; Karma (nickel-chrome-aluminum-iron), 2; Iso-elastic (nickel-chrome-iron), 3.5; and platinum 4.8. However, the higher the gage factor, the more sensitive the gage is to temperature changes, because of a higher temperature coefficient of resistance of the gage grid material.

"P"-type (positive strain sensitivity) semiconductor gages have a gage factor of about 100 to 150, and "N"-type (negative strain sensitivity) semiconductor gages have a gage factor of about 100. The obvious advantage of a semiconductor gage, with its high gage factor, is its very high strain sensitivity--approximately 50 to 75 times as sensitive as that of a constantan gage. In most cases it is also much more sensitive to temperature changes than a constantan gage.

USE OF STRAIN GAGES

Strain gage instrumentation involves a great deal more than just a good collection of gages and adhesives and a "lick-'em and stick-'em" technique. It requires a thorough knowledge of the behavior of the different kinds of gages, the specialized adhesives, and the many combinations of both. A knowledge of the vast array of protective compounds is also essential in order to adequately shield the gage installation from the many hostile environments frequently encountered.

The surface to which a gage is bonded must be absolutely clean; this requires a painstaking procedure.

Reinforcement of the Specimen

When a strain gage is bonded to a surface, there is a resulting reinforcement or strengthening of the specimen in the area of the gage. The reinforcement is insignificant if the specimen cross section is thick, but it can be appreciable in a thin specimen. The strain gage will measure the net effect of the gage's being bonded to the surface (a locally laminated structure if you will). The result will be a strain reading that is lower than if the specimen were free to respond without the strengthening influence of the gage. This is one of the common problems in the measurement field. We are constantly trying to answer the question, "How can we make a measurement without disturbing the object we are interrogating?" This problem of reinforcement on thin specimens can be minimized by carefully selecting the gage type and size and carefully controlling the adhesive thickness.

Stresscoat

Unless a strain gage is mounted at the point of highest strain and

oriented in the direction of the highest strain, no amount of sophisticated instrumentation will result in a valid reading of the maximum strain in the structure. This property of the strain gage, indicating strain only at a point and in only one direction, has resulted in some bizarre applications. One can find in the literature, examples of strain gages plastered by the hundreds, side by side, so that an entire surface can be analyzed. These multitudes of gages are accompanied by multi-hundred-channel digital data-handling systems and computer data-reduction facilities. Obviously, this method of stress analysis is extremely expensive. There are well-known ways of avoiding this complicated data system and the bonding of many strain gages on a specimen. Sometimes we do have to use many gages, but analyzing the problem carefully beforehand usually leads to a simpler system.

The problem of installing the most economical number of gages at the right locations can be solved by employing the brittle-coating method of stress analysis called Stresscoat. Brittle materials fail at the location of the highest tensile strain, by cracking perpendicular to the direction of the strain. Because of these two properties, Stresscoat is a convenient and reliable indicator for telling us where to bond strain gages for quantitatively determining the strain in the part.

The specimen is sprayed with a coating of brittle lacquer and allowed to cure, the curing process requiring approximately 18 hours. As the load is applied, cracks in the coating will appear first in the areas of highest strain, or the weakest portions of the specimen. Strain gages would then be installed at these locations for quantitative analysis.

The brittle-coating method has been called the one-cycle fatigue test because in one loading cycle it will permit prediction of failure of the structure once subjected to fatigue loading.

In Fig. 2 we can see how the strains are distributed in the pipe-branch connections. Strain gages would be installed at the points where the cracks are closest together, the crack "density" being an indication of strain intensity. The higher the crack density, the higher the strain. These areas would be A, B, C, and D in Fig. 2.

STRAIN GAGE INSTRUMENTATION

The Wheatstone Bridge

Now that we know all about the gages themselves and the care that must be used in installing them, how do we determine what the strains are during a test? First, some basic strain gage electronics. The circuitry used for obtaining data from a gage is basically that of a Wheatstone bridge, as seen in Fig. 3. The active gage (the gage that is subjected to the mechanical strain) is R1. R2 and R3 are bridge-completion resistors and R4 is a variable resistor used to maintain bridge balance. From Fig. 3, we can see that if we start out with a balanced bridge (that is, one in which all four resistances are equal) there will be no current flow through the meter. However, if R1, the strain gage, changes resistance, the bridge will be unbalanced and there will be a current flow through the meter. An adjustment in R4 is necessary to rebalance the bridge. Since we know the relationship between resistance change and change in strain (remember the gage factor equation) we then know the amount of strain the gage experienced as indicated by the amount of resistance change needed to rebalance the

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Fig. 2. Stresscoat stress analysis on pipe assembly.

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Fig. 3. Schematic of Wheatstone bridge circuit.

bridge. Simple, isn't it? There are variations of this circuit that are in common use today for many different applications, but they are all based on this circuit.

Temperature Compensation

When a strain gage is bonded to a specimen and the specimen's temperature is changed, there is a change in the resistance of the gage. The strain gage instruments can't tell the difference between this change in resistance due to temperature and the change in resistance due to strain. We therefore have to modify our circuit slightly to compensate for temperature fluctuations. We simply bond another gage from the same lot, using the same cement and technique, to a sample of the same material as the specimen, but one that does not "see" any strain. The unstrained sample is placed in the same environment as the active gage so that it will experience the same temperature changes as the active gage. This temperature-compensating gage is connected to the bridge in place of R2 and automatically cancels any temperature effects that might occur in the active gage leg of the bridge.

Data-Acquisition Instruments

The instruments used for static strain data acquisition are called strain indicators. Recorders or oscilloscopes are used for dynamic strain analysis. Data can be obtained from gages on rotating or moving machinery by using slip-rings or transmitters. In the last few years, telemetry systems have become quite small and lightweight, and the transmitter can "go along for the ride" quite safely without being torn off by the centrifugal or shock-induced forces developed during machine operation.

There are many different kinds of strain gage instruments on the market, but just as selecting a strain gage that is best for a particular application is critical to successful analysis, so too is selecting the right data-acquisition instrument.

EXAMPLES OF STRAIN GAGE APPLICATIONS

In Fig. 4 we see Surveyor I, the famous spacecraft that successfully soft-landed on the moon June 2, 1966, and sent back photos of the moon's surface. Strain gages went along and provided valuable information on the spacecraft's structural loading at touchdown. Gages were bonded to the three shock absorbers on each of Surveyor's three legs, as shown in the circled areas in Fig. 5. The spacecraft was then "drop" tested, as depicted in Fig. 6, to determine the strain gages' response to impact and to calibrate the system. Figure 7 shows the strain gage data telemetered from the moon. The three landing gear footpads touched down 0.01 sec apart, with number 2 first, number 1 next, and number 3 last. Note from the traces in Fig. 7 that the spacecraft bounced after the initial impact but quickly settled on the moon's surface. The magnitude of the loads on the legs of Surveyor as shown on the graphs in Fig. 7, proved to the engineers that the craft had indeed made a soft landing on the moon as intended.

Craig Breedlove set the world land speed record of 600.6 mph (at Bonneville, Utah in the Fall of 1965) in the racer shown in Fig. 8. Of prime importance was keeping the vehicle from becoming airborne during a run. Its lift at speeds above 500 mph was appreciable and it acted more like an airplane than a car. The racer was equipped with adjustable canard fins, shown in Fig. 9, to compensate for the effects of aerodynamic lift. A method was needed to determine the correct

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Fig. 4. Surveyor I spacecraft (courtesy BLH Electronics).

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Fig. 5. Surveyor I strain gage locations (courtesy BLII Electronics).

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Fig. 6. Surveyor I drop test and system calibration (courtesy BLH Electronics).

Composite graph shows strain gage readings for each of the spacecraft's three legs before, during and after impact. Vertical divisions, representing 0.1-second time intervals, reveal that Surveyor I made an almost simultaneous three-point landing, with only 0.01-second intervals between touchdown of each leg. Following initial impact, about six secondary impacts were recorded before the spacecraft assumed a static relationship with the lunar surface.

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Fig. 7. Surveyor I impact data telemetered from the moon (courtesy BLH Electronics).

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Fig. 8. Craig Breedlove's Spirit of America racer
(courtesy BLH Electronics).

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Fig. 9. Schematic of Breedlove racer (courtesy BLH Electronics).

angle setting of the fins to just keep the car on the ground but not to slow it down unnecessarily. Strain gages were bonded to the car's torsion and antisway (stabilizer) bars to measure the torque on these bars. This, enabled the crew to "weigh" the car both at rest and in motion. The difference in weight was an indication of how much aerodynamic lift was produced at high speed. As the car tended to lift, the bars would unload, thus changing the strain sensed by the strain gages.

After a series of simulation tests, a canard fin setting was theoretically determined followed by a trial run. The actual torsion and stabilizer bar strain changes were recorded during the test run and compared with the theoretical strain changes. Adjustments were made on the fins and verified by further runs. After several trials the correct fin setting was established and the land speed record of over 600 mph was recorded. The safety ramifications in this application are obvious. If the car had become airborne, Mr. Breedlove would have faced disaster.

These two strain gage applications seem to be quite dramatic at first glance. However, they are really basically quite straightforward-- it is the devices to which they are bonded that are exotic. Telemetering signals from the moon is done all the time now, and the strain gage data was just one more batch of information that was transmitted. Reading and recording the output from strain gages on a vehicle traveling at 600 mph was accomplished by mounting an oscillograph in the vehicle for the test runs.

In 1967, we of the Strain Gage Instrumentation Group at LRL - Berkeley were asked to test a pressure vessel that was to be used in an

experiment in the Bevatron. This vessel was to contain propylene, which is a flammable gas and a dangerous fire and explosion hazard. Obviously we had to have a safe and reliable container for this fluid. Safety procedures required that the vessel be able to withstand twice the working pressure for a period of 24 hours. The working pressure was to be 135 psig, thus dictating a test pressure of 270 psig.

Some structural problems led those in charge of the project to believe that the container would have been unsafe if used in its then current condition. It was fabricated from 6061-T6 aluminum alloy. During welding the areas near the welds were annealed to a 6061-T4 condition, which has a yield strength approximately one-half of 6061-T6.

We bonded strain gages to the vessel in the areas of concern and pressurized it hydrostatically. At approximately 160 psig or only 1.2 times the working pressure, the strain gages indicated that the vessel was about to rupture. We halted the test immediately.

After this test, the vessel was heat-treated to try to restore the yield strength to its original value. We again installed strain gages and pressurized the vessel. This time we found that the vessel was strong enough to withstand the required pressure and that the heat-treatment was indeed successful. Figure 10 shows the vessel with the strain gage instrumentation. This illustration depicts a test simulation only. During the actual hydrostatic test, the instruments and operators were positioned behind a protective barricade. In Fig. 11 we see a close-up of three of the strain gages and the welded area that was of prime concern.

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Fig. 10. Simulated hydrostatic test on pressure vessel. (Test instruments and operators were behind a protective barricade during the actual test.)

XBB 681-435

Fig. 11. Strain gages on pressure vessel.

We then performed a creep test to verify that the material would withstand prolonged pressurization. The vessel was pressurized to 270 psig (twice the working pressure) and held for 24 hours. Upon releasing the pressure we found that the strain in all gages returned to zero, thus proving that there was no creep in the metal.

We carried this strain gage application one step further. We found that during the testing the strain gage response to small hydrostatic pressure changes was quite good. At 270 psig the strain was about 6000 microstrain. Our strain sensitivity, then, was about $22 \mu\epsilon / \text{psig}$ pressure, a magnitude that is easily measured. Since the experimenter needed to remotely monitor the propylene pressure during the experiment, we devised an electronic pressure surveillance system that would utilize the strain gages on the vessel. They were already installed, so why not use them? The monitoring system consisted of a strain gage power supply, Wheatstone bridge network, amplifier, and warning light. Once the desired pressure was established in the vessel, the Wheatstone bridge was balanced. If the pressure either increased or decreased by a preset amount, in this case $\pm 0.5 \text{ psig}$, the warning light would switch on. The proper adjustments would then be initiated. The pressure vessel-strain gage combination, then, became a pressure transducer--a strain-gage-based pressure transducer. It was easily calibrated and proved to be a stable and reliable system.

CONCLUSION

When designing and fabricating a part or structure, whether it be a miniature shaft for a spacecraft or a bridge spanning an enormous

canyon, failure is the last thing one wants to encounter. Most of the time we can utilize well-known and established equations in determining safe loading conditions. Many times, however, we cannot calculate the stresses in a complicated structure with an acceptable degree of confidence--we must determine these stresses experimentally. The electric resistance strain gage, which permits such determinations, has proven an invaluable tool in helping engineers design safer structures. As so many inventions and developments do, it came along at just the right time in history, and was a major factor in speeding the development of planes and ships that were so badly needed in World War II. It seems incredible that such a small and simple-looking device could completely revolutionize mechanical design, but that is exactly what it has done. Strain gages have enabled engineers to design much more effectively, producing structures and machines that are safer, lighter, more useful, and less expensive.

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