AN INTRODUCTION TO EXPERIMENTAL STRESS ANALYSIS

by

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The application of Experimental Stress Analysis to structural design and development has grown significantly in recent years and current trends indicate that Experimental Stress Analysis will have an ever increasing part to play in the future.

To the non-scientific, "stress analysis" has an awesome ring. Actually, the concept is as simple as the two words themselves; the analysis of objects in terms of the stress they undergo in use. For instance, measuring the actual stresses and strains to which such structures as aircraft, bridges, automobiles and lawnmowers are subjected, in fact anything that could break or fail in use, can help to determine their design integrity.

Product failure can be very costly in either financial or human terms – often in both. The purpose of Experimental Stress Analysis is to avert failures in use by providing information to aid the engineer in developing safe, reliable and durable products at economical cost.

Experimental Stress Analysis can help detect product failure in the planning stage, to ensure in advance virtual immunity from basic flaws in design, to pinpoint areas where there is not enough structural strength – or where there is too much. Although modern analytical methods offer the possibility of solving more complex stress analysis design problems, requirements for the experimental verification of boundary conditions and integrity of the final product design will increase as higher structural efficiencies are developed.

The growing concern for the conservation of material and energy sources along with basic economic considerations, make it imperative that every load bearing device, machine or structure undergo a thorough stress analysis in order to arrive at the lighest weight, lowest cost unit, while assuring its functional integrity and safety under the prescribed service conditions throughout a specified life.

Increasingly vigorous safety requirements, product liabilities and extended product warranties, will dictate the need for properly tested and evaluated designs. An ever increasing number of product specifications include testing requirements which involve Experimental Stress Analysis Techniques. More and more manufacturers choose to validate the reliability of their products with reference to Experimental Stress Analysis on their products in sales specifications and literature.

Experimental Stress Analysis techniques in one form or another can be applied at all stages in the life of a product. In new product engineering, from preliminary

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design to production design proving, and proof and overload testing. In service for load monitoring, weighing, batch counting, etc. In failure analysis from design defect detection to re-design proving. In materials and structure research.

Techniques of Experimental Stress Analysis

Experiment Stress Analysis involves primarily:

1. Analysis of the design of a structure or part to determine whether or not it can satisfactorily withstand both the normal and abnormal forces applied to it.

2. Investigation of why structures or parts break and prevention of subsequent failures by satisfactory changes in design.

3. Monitoring of in service stresses, loads, torsions, pressures, etc. These are accomplished by measuring strains resulting from the stresses on the part in question as it is loaded under various conditions. There are, however, a wide range of sizes and shapes of different structures and parts under various loads and environmental conditions in which they operate. This in turn calls for a variety of measuring techniques and those which are most widely used today are: 1) electrical resistance strain gauges; 2) photoelasticity; 3) brittle lacquer; 4) moire.

The techniques are used on existing structures or parts, on models of the structures or parts, as models themselves in the case of photoelasticity, or in conjunction with special model materials, to simulate the actual structure or part.

Electrical Resistance Strain Gauges

Since 1940, the bonded resistance strain gauge has been the most powerful single tool in the field of Experimental Stress Analysis and is the most widely used of all the techniques which are presently available.

Basically, the strain gauge is an extremely thin, small strain sensitive electrical resistor bonded to a flexible backing material, which when adhesively bonded to the structure or part under test, transforms surface strains due to stresses into electrical resistance changes. It has a linear output and these resistance changes can be read out directly as strain, load, pressure, torsion, etc. on the appropriate instrument. Strain gauges are produced with an accuracy for precise calibration equipment and with sensitivity to the limits of readout instrumentation.

They are capable of almost unlimited frequency response and are so light in weight that they do not alter the mass, stiffness, balance or natural frequency of the parts which they are attached to.

The measure of gauge sensitivity to strain is the "gauge factor," the ratio of unit resistance change ($\Delta R/R$) to unit strain ($\Delta L/L$).

Gauge factors for common strain gauge alloys range from about 2 to 4. The user has a choice of foil and backing materials and grid configurations to suit a wide range of performance requirements and operating conditions. The versatility of the photo-etching process by which foil strain gauges are commonly manufactured is such that very complex special purpose gauges can be fabricated with relative ease.

The most widely used alloy is copper-nickel invariable known as Constantan or Advance. Other materials include modifications of nickel chromium alloys, and, for dynamic strain measurements, an isoelastic alloy. Typical backing materials include polyamide, cast epoxy, and glass reinforced epoxy phenolic.

Strain gauges vary in active grid lengths from 0.2mm up to approximately 100mm. Typical strain gauge thickness is 0.03mm. The very short gauges are generally used where space is limited or where the strain gradient is steep since it is desirable to measure strain over as small an area as possible in such a case to avoid strain integration. Long gauges are intended for applications where mean strain over a considerable length is more representative. As an example, 50mm or longer strain gauges are commonly used on concrete to average out the effect of the inhomogeneous structure consisting of aggregates and cement.

In addition to single grid configurations, strain gauges are also available in multi-element "rosettes". In order to determine the principal stresses in a biaxial stress field when the directions of the principal axes are unknown, three independent strain measurements must be made. For this purpose, three-gauge rosettes with a grid oriented at either 45° or 60° increments from one another are available in a range of sizes from 0.4mm to 13mm grid lengths.

When the directions of the principal axes are known, only two independent strain measurements are required to determine the principal stress. In this case, a two-gauge 90° rosette is used and the gauge axes are aligned with the principal stresses.

Whilst in the majority of cases strain gauges are adhesively bonded directly to the structure or part to be tested, an alternative approach – particularly for field applications where structure size or weather conditions will not permit adhesive curing – is the use of weldable strain gauges.

The weldable gauge consists of a precision strain gauge bonded to a thin metal carrier for spot welding to structures and components, and has many applications in such areas as pipelines, bridges, tunnels, heavy machinery, pressure vessels, etc.

An important application of strain gauges is for the measurement of residual stresses which can be introduced into materials and components as a result of manufacturing processes such as casting, heat treatment, welding, etc. Residual stresses are frequently causes of failure when service loads are superimposed on them in critical areas. They can be measured by relieving them locally, with a small hole drilled very carefully and precisely in the centre of a rosette strain gauge. The same technique can be applied to determine existing stresses in structures under load such as bridges, buildings, ships, pipelines, etc.

The progress of bonded resistance strain gauge technology in recent years, together with development of relatively low cost, highly stable and accurate instrumentation, has led to a very considerable growth in the transducer industry. The applications for automatic load and pressure monitoring in process control systems have extended into a diverse range of industry. Precise, accurate, repeatable electronic weighing systems are now available and used in many different industries from steel making to food manufacturing and from the oil industry to the retail food store. Miniature transducers are implanted in living bodies for medical research and very large transducers are used in steel rolling mills.

Typical of the present day reliability, repeatability and accuracy of strain gauges is their use in operational transducers in aircraft, including for example helicopter torquemeters, fighter aircraft flying control systems and on board weighing systems in transport aircraft.

Many straightforward day to day load, torsion or pressure measuring problems can be solved with a reasonable degree of accuracy by means of a relatively simple strain gauge installation. This can apply equally to the manufacture of low cost tranducers on a production basis and to the non-standard and "in-house" device that can be made by any competent strain gauge engineer. Strain gauges bonded to simple columns, rings, tubes, torsion shafts, struts, cantilever beams, spring clips, to name but a few, provide repeatable outputs proportional to the loads applied. Strain gauges bonded to pipes give outputs proportional to the liquid or gas pressures in those pipes.

Special sensors derived from strain gauge technology include cryogenic linear temperature sensors, fatigue sensors, which accumulate resistance changes related to the load life history of the structure, crack propagation gauges, and special sensors for the measurement of blast pressure shock wave propagation and high hydrostatic pressure.

Measuring instruments for the detection and presentation of the output from electrical resistance strain gauges are almost without exception based on the use of Wheatstone bridge circuits, of which the strain gauge forms one or more of the bridge arms.

The stability and repeatability of present day strain gauges and instrumentation enables resolutions of strains of at least one micrometer per metre (i.e. $\Delta L/L = 1 \times 10^{-6}$) to be obtained. This corresponds to a stress in steel for example of approximately 2 Kg/cm^2, and an electrical output from a single active strain gauge, with a gauge factor of 2.0, of approximately 0.5 microvolts/volt applied to the bridge circuit.

Photoelasticity

Photoelasticity is the visual full field technique for measuring stresses in parts and structures as opposed to strain gauges which provide point by point measurement. When a photoelastic material is subjected to forces and viewed under polarised light, the resulting stresses are seen as beautiful coloured fringe patterns. Interpretation of the patterns will reveal overall stress distribution and accurate measurements can be made of the stress direction and magnitude at any point. The basic principle of photoelasticity depends on the fact that when transparent materials (notably plastics) are subjected to forces, changes in optical properties take place proportional to the stresses developed, and the material becomes "bi-refringent" or double refracting.

Photoelasticity embraces three broad categories – photoelastic coating analysis, two-dimensional model analysis, and three-dimensional model analysis. Of these, the most widely used technique is that of photoelastic coatings, which enable stresses in actual parts and structures, of virtually any size, shape or material, to be determined under actual operating conditions.

Photoelastic coatings are used as a design tool to provide design validation as a guide to optimizing structural weight and elimination of stress concentration. An important application is for the investigation of residual and assembly stresses which are introduced into components during manufacture and assembly.

The photoelastic coating material can be applied either in the form of flat prefabricated sheets bonded to the surface on flat specimens, or equally by contouring to complex curved surfaces using liquid photoelastic plastic material. It can be used equally well on most materials such as metals, wood, rubber, plastic bone, etc.

Two and three-dimensional model analysis is also being used routinely in a steadily growing number of applications. Analysis of this type is particularly useful at the design stage, specially to determine areas and magnitude of stress concentrations for components and structures having complex shapes and loading conditions. Equally important, it can be used to study areas of low stresses where the material is not being used to full advantage. Three-dimensional model analysis in particular is being used at an increasing rate as this technique is the only practical method that provides a complete solution inside and outside the part.

The new materials and instrumentation available today make the techniques of analysis by photoelasticity straightforward and simple. Model photoelasticity is being used routinely in establishing design criteria, improving product reliability and reducing weight and cost. Future use of photoelastic techniques will play a significant part in meeting the demands of a rapidly advancing technology for radical design in an increasingly competitive market.

BRITTLE LACQUER

In this technique, a special prepared strain sensitive coating is sprayed onto the surface or part to be examined. After it has dried and the part has been loaded the coating develops a series of cracks normal to the direction of the maximum tensile strain on the surface. Thus it is possible to obtain an overall picture of the strain distribution with an approximate indication of strain magnitude and direction. Brittle lacquers are therefore very useful in giving a quick indication of where principal stresses or stress concentrations are likely to occur. They are not used for accurate measurements, but provide a quick economical way of determining exact locations and orientations of subsequent strain gauge installation.

This approach is particularly suitable for inaccessible areas and, for example, on vehicle testing where the part to be investigated can be coated, assembled in the vehicle and then disassembled for examination on completion of a road test. The resultant crack pattern will help to ensure that any subsequent strain gauge investigation is related to the point of maximum interest and the fact that measurements are known to have been taken in the correct place can lead to a reduction in the extent of a strain gauge investigation.

Moire

Moiré is the name given to the optical effect often observed when two closely spaced arrays or grids of parallel lines are superimposed. If the spacing between lines and the orientation are not everywhere identical in both grids, periodic mechanical interference to the transmission or reflection of light occurs, producing a pattern of alternative light and dark bands.

For the purpose of experimental stress analysis, starting with two identical grids, one grid can be bonded uniformly to the surface of a mechanical part or structural member and be viewed through the second grid with the latter serving as a reference. If the test part is initially unstrained and the grids are precisely aligned, no fringes will be observed. When the part is loaded, the surface strains produce displacement of the lines in the bonded grid causing Moiré fringes to appear when viewed through the reference grid.

This technique is primarily applied to solve problems that cannot be solved easily, accurately or economically by other methods.

Typical examples are for high temperature measurements, large elastic and plastic strains, and absolute measurements of strain to establish material properties etc. While the theoretical basis for the Moiré method is relatively simple, the practical problems associated with obtaining accurate strain measurements, particularly for small strains or steep strain gradients and on curved surfaces, have limited its application. It does however have its part to play in those cases where for one reason or another it is not practical to use other techniques.

Summary

With the use of good equipment, proper facilities and well trained personnel, the contribution which these techniques can make in all aspects of engineering development is undoubtedly tremendous. The intelligent application of Experimental Stress Analysis can lead to significant improvements in design and reliability with associated reductions in weight and cost.

Experimental Stress Analysis techniques today are the quality control tools of the design and development engineer, as much as non-destructive testing techniques are the quality control tools of production.