METHODS FOR MEASURING STRESS AND STRAIN IN SOLIDS

IN present-day engineering design, a stage has been reached when, not content with vastly improved materials and design procedure, the engineer must know the actual stresses throughout the machine or structure, when under test, in order that weaknesses can be corrected in production models and avoided in future designs. Thus the designer, by a method of 'successive approximation', progresses towards the ideal of equal life for every part exemplified by Longfellow's famous "One Horse Shay", every part of which collapsed simultaneously after long service.

In aircraft, every pound of unnecessary weight in the engine or airframe means a pound less payload. Consequently, in aeronautical design more than any other branch of engineering, weight must be pared to the very minimum compatible with safety; while, on the other hand, the probability of a fatal accident if some part or other is of insufficient strength is far higher than in other forms of transport. It is axiomatic, too, that greater speed calls for greater precision in design. That safety has not, in fact, been sacrificed for lightness is shown by the fact that not more than 1 per cent of the accidents to civil aircraft are attributable to structural failure.

It is an official requirement that, before a particular aircraft design is approved, the test structure—in particular the wings—must withstand 1.2 times the design load without failure. For this purpose, a prototype is tested in a large straining frame. During the test, as much information as possible is collected about the distribution of stress, so that any possible weakness can be eliminated with the least delay.

Until quite recently, the only apparatus available for measuring strain during test was some form of visual-reading extensometer. The number of stations at which readings could be taken was extremely limited under these conditions, and the process of taking readings very tedious. A desperate need was felt for some type of strain gauge which would enable a very large number of readings to be made in a short time at each stage of loading. This need has at last been met, by the invention of the electrical resistance strain gauge and of the acoustic strain gauge.

The electrical resistance strain gauge has the following great merits: (1) it is very light and compact; (2) it can be placed in almost any position, for example, inside a wing, on thin sheet and curved surfaces; (3) once stuck on, it requires no further attention; (4) no mechanical adjustment is required; (5) electrical recording lends itself to making a very large number of readings in a short time; (6) all readings can be taken at a central control point; (7) it lends itself to autographic recording, and can be used with automatic switching devices; (8) it can be left in position ready for a repeat test at any time; (9) it can be used for recording rapidly fluctuating stress, and is practically free from inertia effects; (10) if three such gauges are combined, owing to the short gauge-length the principal stresses can be computed without previously knowing their directions; (11) if a sufficient number of gauges are used, analysis of the stresses in every part of the structure can be made.

The rapid progress in recent years in the invention of accurate and convenient apparatus for measuring strains played no small part in the improvements in aircraft and other design during the War, and the

Manchester Branch of the Institute of Physics arranged a conference on the subject during July 11–13. Technicians in widely different industries have not been slow in following the lead of the aircraft industry in applying the electrical resistance strain gauge to their special problems, and the first session of the conference was devoted to the characteristics and applications of this type of gauge.

It had been the intention to cover not only the gauge itself, but also a full discussion of the electrical systems employed in different circumstances; unfortunately, due to the unavoidable absence of Dr. E. P. George, of the G.E.C. Research Laboratories, and of Mr. A. Cogman, of the Havilland Aircraft Co., Ltd., comparatively little discussion was heard of the electrical technique*. However, Mr. E. Jones's paper on "The Physical Characteristics of Electrical Resistance Strain Gauges" aroused lively discussion.

Mr. Jones, after mentioning that the change in resistance when a fine wire is strained is only partly due to the changes in dimensions, but also depends on the change of resistivity of the material from which it is made, gave reasons for preferring cupro-nickel to nichrome wire. The latter is not easy to solder, and, due to the greater temperature coefficient of resistance, the temperature matching of nichrome gauges must be fifty times as good as that with eureka. Seventy per cent of the gauges made of eureka wire are found to give linear response up to 5 per cent strain. After describing various methods used for manufacturing these gauges, Mr. Jones discussed the technique required to minimize errors. The gauges are stuck in the prepared positions using cellulose acetate cement. For each measuring gauge, there is a dummy gauge for temperature compensation, mounted on unstressed metal in thermal contact with the test piece. Each pair is selected by matching, so that, by arranging the measuring gauge and the dummy in adjacent arms of a Wheatstone bridge, and applying a suitable voltage, the gauge resistance is compensated for temperature changes. To prevent serious zero drift, the gauge current should not exceed 35 milliamp. in static tests, but for dynamic tests larger currents are permissible. For high-precision measurements, as for observing wind-tunnel forces, the current is limited to 5 milliamp. It is always necessary to allow sufficient time (say half an hour) after switching on the current for a steady condition to be established. In practice, an extension of 1 per cent in metals is seldom measured. The upper limit of frequency for accurate response is estimated at about 10^5 cycles per second in the case of rapidly varying strains. There is a gradual zero shift with repetition of dynamic strain.

A serious problem frequently encountered is that of protecting the gauge from moisture, since, due to the high gauge resistance, very good insulation is essential for avoiding error due to leakage. Nevertheless, by covering the gauge with a special wax, it can be made to function successfully even under water. In this connexion, Mr. H. Bull, of S.R.E. Admiralty, mentioned instances of gauges applied to ships' hulls for the study of stresses in the neighbourhood of welds. The plate on which the gauge is already fixed is heated to 125° C., using infra-red lamps and, immediately on removing these, a protective wax is

* A good description of the principles of this gauge was given by Dr. A. C. Redshaw before the Royal Aeronautical Society on March 28, 1946. Many papers on methods of application have been published in the *Proceedings of the Society for Experimental Stress Analysis*, U.S.A.

poured over the gauge, thus excluding all moisture. Gauges so prepared have worked well in sea-water over a long period. Other speakers discussed the effect of thickness of adhesive on the steady temperature difference between gauge and test piece. Dr. A. C. Redshaw reported favourably on a new type of woven gauge in which the wires are interrupted and carry end connexions at regular intervals for ensuring uniformity. These gauges, in which the wire is interwoven with artificial silk, he had found to give remarkable consistency.

Mr. E. Jones, questioned as to the adaptability of the normal type gauge to curved surfaces, said that they can be used on curvatures down to $\frac{1}{2}$ -in. radius. The usual gauge-length for aircraft structures is $\frac{1}{2}$ -in. or larger, but gauges no longer than $\frac{1}{16}$ in. have been successfully employed for special jobs.

Strain gauges are conveniently adapted for many different types of measuring instrument. The exhibits shown by the Royal Aircraft Establishment, Farnborough, included dynamometers, manometers, micrometers, and accelerometers which record by this means. It was pointed out that the ring type of dynamometer affords perfect temperature compensation, as the compression gauges mounted opposite those in tension eliminate the necessity for dummy gauges. Dr. E. Orowan (Cavendish Laboratory) gave a brief description of a cylindrical steel pin, about 2 in. in diameter, forming part of a rolling mill bearing, which had been machined away in four places for longitudinal gauges, the compensating gauges being in a circumferential groove. This device is being used for measuring the forces and torques during rolling operations. As the economics of steel mill operation demand that the rate of rolling should be as high as possible without overstressing the mill, an accurate knowledge of these forces is of great importance.

Technicians concerned with the measurement of rapidly changing stress have not been slow in exploiting the great possibilities of the strain-gauge, with its ease of installation, lightness, freedom from inertia effect and robustness as compared with mechanical tensometers. By transforming strain directly to change of electrical resistance, all mechanical parts can be eliminated, and the gauge signal is readily recorded, either by a high-frequency galvanometer or, after suitable amplification, on a cathode-ray oscillograph.

Equipment of this kind is already in use for studying the fluctuations of strain in aircraft propeller blades, strains due to gusts, manoeuvres, and landing in aircraft, for industrial machinery of widely varying types, the performance of fatigue testing machines, and so on. The choice of amplifier depends on the particular application, and frequency modulation is often employed. The L.M.S. Research Laboratories reported at the conference that, using a high-frequency carrier, they can record at 100 yd. from the gauge.

Another interesting form of strain gauge, namely, the acoustic strain gauge, was discussed by Mr. Bull, of S.R.E. Admiralty. These gauges were first tried in Germany. In Great Britain, the Steel Structures Research Committee was the first to use them. The present form of gauge, due to the Building Research Station, has given excellent results in the hands of the Admiralty (S.R.E.) Shipwelding Party and on steel bridges. Mr. Bull said that with acoustic gauges the return to zero is much better than with resistance gauges. The gauge consists of a stretched wire, the

natural frequency of which varies with the strain. The latter is measured by the pitch of the note given out when the wire is excited. This is obtained by the beat method, using a master gauge having a micrometer tensioning head. Alternatively, a cathode-ray tube may be used, in which the two oscillations are connected on the x - and y -axes and brought into step. Aural matching, though quite feasible, is rather trying to the nerves. Owing to the necessity for long-distance recording, an elaborate system of post-office type selection with satellite points and master control was adopted. Six hundred of these gauges could then be recorded in the space of two hours. Though not nearly as fast as some resistance-gauge systems, this rate of recording is certainly a great feat. In the application of this method to welding investigations in ships' plates, one of the practical drawbacks is the magnitude of the temperature stresses which occur in day-time. Most of the work, therefore, must be done in early morning or late evening.

Mr. R. S. Jarratt, of the Building Research Station, described the application of acoustic strain gauges to the measurement of strains in bridge girders. He suggested that the gauge signal, being of audible frequency, could, if required, be transmitted by radio, so reducing very much the amount of screened cable required for distant recording. Using screened cable, the Building Research Station has recorded at a distance of 600 ft.

The morning session on July 12 was devoted to photo-elasticity. The present writer contributed a paper entitled "A Review of some Recent Developments in Photo-elasticity", a summary of which follows:

Advances in equipment and materials have been mainly due to the replacement of Nicol prisms by 'Polaroid' and to the use of synthetic resins having high stress-optical coefficients. The glyptal 'bakelite', known as BT 61-893, has excellent properties, but is in very short supply. Glass-clear phenol-formaldehyde resin can be more readily obtained and has a high stress-optical sensitivity.

Improvements in the technique of preparing models, due mainly to Frocht, have made possible the accurate observation of boundary stresses in plane models.

Three separate methods have been employed for solving 3-dimensional problems—the 'freezing', the 'scattered light', and the 'composite model' methods. The most adaptable of these is the 'freezing' method, for which either 'Bakelite' BT 61-893 or phenol-formaldehyde resin (for example, 'Catalin' 800 glass clear) can be used. When heated the material reaches a softened condition in which Hooke's Law is accurately obeyed, but the Young's modulus is of a much lower order than at room temperature. The stress-optic law has been shown to hold accurately in this condition. A three-dimensional model is heated to the softened condition (to about 110° C. in the case of BT 61-893 and about 80° C. in the case of p -f resin) and the load applied. After maintaining the temperature for some 15-30 minutes to allow the strain to reach a steady condition, the model is cooled to room temperature. The model thus 'sets' or 'freezes' in the strained condition, and on removal of the load, loses only a small proportion of its strain and birefringence. If a plane slice is cut out of the model (using fine cuts and a cooling fluid), it will show the fringe pattern corresponding to the stresses existing in the complete model.

As shown by Hiltcher (1938) the 'frozen' birefringence can be measured by examining a slice (3 mm.

thickness) in convergent light, using a polarizing microscope in exactly the same manner as for crystals. This method will give, for any point, in a slice taken in any direction in the model, the orientation of the three principal stresses, their order of magnitude, and the value of the three principal shear stresses. The chief drawback of the 'freezing' method generally is the production of edge stress in heating, and research is needed into methods for preventing its occurrence.

In the 'scattered light' method, due to Weller, a narrow collimated beam of polarized light is passed through the model, and fringes in the interior of the model can be seen by viewing at an angle to the direction of the beam, owing to the effect of scattering.

The 'composite model' method, originally suggested by Favre, as its name implies, uses a model built up of two materials (having the same elastic modulus). An inner, birefringent section is encased in an outer part which has no stress-birefringence, so that the stresses in the middle part only of the 'sandwich' are shown.

For separation of the principal stresses at interior points on a plane model it is necessary, by some means or other, to determine $P + Q$, the sum of the principal stresses. The isochromatic order, shown by the fringe pattern, gives $P - Q$ only. The classical method for finding $P + Q$ is that of the lateral extensometer as designed by Coker. Three alternative methods were reviewed by the present writer, namely the 'Four Point Influence Method'—a process of relaxation—the 'Method of Oblique Incidence' (as used by Drucker), and the individual measurement of the principal stresses by means of an interferometer.

Some instances of the application of photo-elasticity to special problems were discussed by the author. Perhaps the most valuable photo-elastic work of all has been the determination of stress concentration factors at holes, notches, and fillets, of great importance where components are subjected to repeated or reversed loading.

Mr. H. M. Ross (Kodak, Ltd.) followed with a colour film illustrating stress in a rail and chair under fluctuating loads, and a remarkable slide showing, in colour, the stress waves resulting from the impact of a hammer on a nail embedded in a block. He also described techniques for photographing fringes.

Next, Dr. E. Orowan described briefly an ingenious combination of photo-elastic and photo-electric technique for showing the fluctuations in load in a rolling mill. The skill with which Dr. Orowan applies scientific technique in such unpromising surroundings deserves great admiration.

The discussion on photo-elasticity centred mainly around the behaviour of materials during the 'freezing' process. Photo-elastic observations represent purely elastic conditions of stress, and, for singly connected bodies, the stress distribution is then exactly as in the prototype, being independent of the elastic constants.

On the important question of how exact the collimation should be, Mr. Heywood stated that the fringe patterns shown in an exhibit of pieces of mechanism in 'Bakelite' prepared by Rolls Royce had been made without a collimating lens. There was not the least blurring of the fringes in these photographs. As the interest in any given model usually centres around a small portion of the boundary, indistinctness due to imperfect collimation can be avoided by bringing this portion into the centre of the field.

Several speakers emphasized the need for a full exploration of the possibilities for improving the materials at present available, and directed attention to the difficulty in obtaining photo-elastic glyptal resin in Great Britain. The need for closer contact between those especially interested in photo-elasticity was recognized, and the possibility of forming a photo-elastic group, or society, in the near future, to create an opportunity for workers in this field to meet and exchange views on questions of materials and technique was discussed [see *Nature*, October 5, p. 478].

The afternoon session on July 12 must be passed over very briefly. Mr. D. E. Thomas (Armament Research Dept.) and other speakers described the application of X-ray technique to the measurement of strain in metals. To avoid surface stress due to machining, it is necessary to remove the surface layer by etching to a depth of 0.01 in. Members of the Admiralty Staff further described portable X-ray apparatus for taking strain measurements on welded ships' plates, etc. It was pointed out that the X-ray method is the only non-destructive way of determining surface residual stresses.

Mr. C. E. Phillips (National Physical Laboratory) described different mechanical-optical extensometers, the variety of which appears to be almost infinite. He said that each different type of problem calls for a special design. He also made the point that *stress* is not a measurable quantity. We strain a material, and this induces a stress in it; but it is *strain* which must always be measured. Even in applied photo-elasticity, one feels, with all due respect to Coker and Filon, that it would be more correct to speak of a 'strain-optical' than of a 'stress-optical' effect. Nevertheless, in many materials, when they are stressed beyond the limit of proportionality, the birefringence follows the *stress* more closely than the *strain*. In such a question, the microscopic heterogeneity of the material no doubt plays an important part.

Remembering Griffith's remarkable results on the strength of glass fibres, one is forced to the conclusion that the *strength* of a material in the mass is entirely a statistical effect. Similarly, examination of single crystals of ferrite shows widely different maximum and minimum values of Young's modulus, and these values differ from that for an aggregate of crystals.

It is clear that those quantities which form the entire basis of the engineer's calculations—strength, elastic modulus and stress—are, after all, statistical quantities applicable only to material in the mass. It is indeed fortunate for the engineer that, in respect of these quantities, his materials exhibit such high homogeneity and isotropy.

There are still many questions to be resolved regarding the transition from X-ray results to engineering quantities. In the application of these methods (as in that of many others) to industrial problems, one must guard against the tendency—all too common—to regard them as a machine which must automatically give the right answer. It is not the tool itself, but its intelligent and skilful application, which produces reliable results.

The exchange of experiences and information afforded by a conference such as that held at Manchester is one of the best ways of acquiring mastery in the application of modern methods. The Manchester Branch of the Institute of Physics and, in particular, Dr. F. A. Vick, are to be congratulated on the success which attended their efforts.

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