and future needs of the industry be met, the future designs be planned, and the existing design be improved.

As part of this co-operation, we issue from time to time, as they are required, Service Circulars to all operators of the S-51. These Circulars contain information which assists the operator in many ways, either in the form of improvements to a part to give added life, the design of a new tool to improve servicing, or maybe information concerning a fault. These Circulars are often issued as a result of information received from our Associates and much valuable information is circulated in this way.

The operator in return is requested to send to the manufacturer a monthly report sheet on the behaviour of his helicopter, and with this liaison a complete and regular service between operator and manufacturer is maintained.

It is hoped that in listening to this paper you have gleaned a little of the ways and means by which the Westland-Sikorsky S-51 helicopter is maintained in service, although each subject has been treated briefly.

Helicopter maintenance generally will advance automatically with design. Simplicity in design usually means simplicity in maintenance, and in the building of bigger helicopters much attention will have to be given to their maintenance. However, much advance has been made in the past years, and reviewing this advance with reference to the S-51 helicopter we find the following :—

Inspection Schedules have been brought into line with those used in the aircraft industry, component overhaul life is increasing, inspection methods are efficient and special equipment is not excessive, the unit change system ensures more available flying time, skilled engineers are increasing in number, and liaison between manufacturer and operator is established. All these assets are necessary to permit planned operations commercially and in the armed forces, and provide an essential basis for future helicopter operation.

PAPER

By MR. W. E. COOPER (Messrs. Fairey Aviation Co. Ltd.).

THE CHAIRMAN : This is a most important subject, and Mr. COOPER is very well qualified indeed to write the paper. He is a Fellow of the Royal Institute of Chemistry, a Fellow of the Institute of Metallurgists, a Member of the Institution of Mechnical Engineers and a Fellow of the Royal Aeronautical Society. He was trained at Birmingham University and the Central Technical College ; he was Head of the Metallurgical Department of Messrs. Guest, Keen and Nettlefold, Birmingham ; Chief Metallurgist, Messrs. R. A. Lister and Co., Dursley, Glos. ; and is Chief Metallurgist of the Fairey Aviation Co., Ltd., having been there since 1936. He has been Chairman of the S.B.A.C. Materials Committee for more than eight years, and is a member of various B.S.I. committees.

Unfortunately, he is not with us today, and we are grateful to Mr. HODGESS, of the Fairey Aviation Company, who will present the paper.

MATERIALS AND THE FATIGUE ASPECT

By Mr. W. E. Cooper (*Member*).

It will be appreciated that, in this short paper, only brief reference can be made to various aspects of importance to the design and performance of rotary wing aircraft. Nevertheless, it is suggested that these references will serve as a basis for discussion, as well as to emphasise the necessity for more investigational work.

Because of the rapid development in the " science " of rotary wing aircraft, the subject of materials of construction will become increasingly important and most probably difficult as the designers' demands and desires increase. Today, therefore, any discussion on materials can only be based on current design knowledge and requirements, with indications to the materials which may be considered most suitable for future projects.

Bearing in mind such limitations in scope, together with the fact that a certain amount of choice of material is left to the designer, it is proposed to refer to various aspects of materials and their selection which, in the opinion of the author, warrant the attention of those concerned with the responsibility of design development and research.

In general, a rotary wing aircraft can be regarded as consisting of three main units :

(1) Fuselage ;
(2) Power Unit and Transmission ;
(3) Rotor System.

(1) *Fuselage.*

Since construction and materials are the same as for orthodox fixed-wing aircraft, including monocoque stressed skin design, and since sufficient experience and knowledge of the properties and use of these materials exist, no particular new problems seem likely to arise as yet.

(2) *Power Unit and Transmission.*

Here again, the power unit and simple transmission system (including reduction gears) can conform to well-established aero engine practice, and it would appear that only in the rotor head and articulations is special consideration necessary, and designers are well advised to make use of the knowledge gained in aero engine and propeller design. This applies particularly to the selection of suitable materials and correct design use in such dynamically stressed mechanisms.

(3) *The Rotor System.*

This unit, which characterises the rotary wing flying machine, is subjected to a more complex system of forces than is the fixed-wing of an aeroplane and, although good agreement has been reached by aerodynamicists both in this country and abroad on the major fundamentals, it cannot be admitted that everything is known about the forces in a rotor blade under all possible conditions of flight—this ideal state of affairs has not yet been reached even with fixed wings. The fluctuating forces acting on a rotating wing are cyclic in character principally from the dissymmetry of flow in forward flight ; the blades and rotor head are not only subjected to fluctuating torque loads of rotor frequency, but also of engine frequency, unless special precautions have been taken to damp these out ; and finally, harmonics of both these fundamental vibrations are present.

Unfortunately, the resulting varying forces and moments create fatigue stresses in the material of which the blades are constructed, and it is only by extensive strain gauging under actual operating conditions that the designer can satisfy himself that the fatigue strength of the blade is above the minimum safe limits—remembering that the fatigue strength of a composite unit is usually less than that of its component materials.

It is customary to make the blades from a central spar member (which carries all the main loads) and, by means of ribs, to attach a lightweight skin of suitable aerofoil section. The main property requirements for the blades can be generalised as follows :—

(1) *Tensile and Proof Strength* to take the centrifugal load.
(2) *Torsional Rigidity* against pitching moments.
(3) *Stiffness* in the horizontal plane.
(4) *Flexibility.* A certain amount of flexibility is permissible in the vertical plane and is considered advantageous by some designers to relieve bending moments in this plane.
(5) *Weight.* Within reason this should be low and is usually less than 10% of the all-up weight of the aircraft.
(6) *Skin Material.* This must be capable of acquiring a smooth finish in aerofoil section and of convenient attachment to the blade ribs.

Choice of Materials for the Blade and its Attachments.

Wood (natural and impregnated), as well as light alloys and steel, has been used for blade construction. Although wood has certain attractions on account of its lightness and ease of shaping, and allows one to use liberal dimensions, it would appear that this material should be the least favoured when one is faced with conditions of both known and possibly unknown fatigue stresses. Apart from the low fatigue *strength* of both natural and impregnated wood, *e.g.*, mahagony ± 1.45 tons/sq. in., and Jicwood $\pm 4\frac{1}{2}$ tons/sq. in. at 50×10^6 cycles, not only have these materials no definite fatigue limit but, as is well known, they are extremely notch sensitive. As a matter of interest, in timber it is rarely possible to distinguish between the appearance of a static and a fatigue fracture.

Light Alloys. The use of light alloys, with their relative high static strength combined with light weight, would appear to be very suitable, particularly as it could be argued that on tensile strength/weight and fatigue strength/weight characteristics they compete very favourably with alloy steels. However, it must be noted here that light alloys, just like other non-ferrous metals, have no definite fatigue limit and, furthermore, they are relatively much more notch sensitive in fatigue than steels.

Steels. It is true to state that we have considerably greater knowledge and experience of the properties of steel than of any other material used in engineering. In spite of the greater difficulty of producing desired shapes (as compared with wood and light alloys), and in spite of its higher specific gravity, we are dealing with material capable of much higher static and fatigue strength and generally of lower notch sensitivity. Bearing in mind the general requirements for the blade (mentioned previously), as well as the known and possibly unknown fatigue loads which have to be reckoned with, it is considered that high tensile steel is the best choice for a rotor blade spar.

Having decided upon the use of steel as the basic material, it is proposed to refer to several aspects regarding the design, treatment and use of steel in relation to its ultimate service life.

Spars.

From primary consideration, *i.e.*, strength/weight ratio, the hollow steel spar has been developed, circular towards the root end, and gradually transforming to an oval shape, with tapering gauge towards the tip end. The most highly loaded portion being the root end, this is of liberal dimensions, initially produced by drawing the tube with increased diameter and wall thickness, and then grinding off the excess metal to leave a collar. Naturally, the manufacture of such a special tubular section presents difficulties, but the manufacturing technique and plant have been developed which ensures a satisfactory product.

In the earlier days of helicopters in which steel spars were used, failures occurred due to stress concentration at bolt holes or welds, and these resulted in the life of the blades being limited to a fixed number of flying hours. Today, we are in a much better position, and there is no reason why blades cannot be designed to withstand almost indefinite life, providing that fullest use is made of modern testing equipment (including strain gauges), and of existing knowledge of fatigue and corrosion protection.

Inherent Fatigue Strength.

For the type of steels in aircraft use the endurance limit (for infinite life) for reversed bending at zero mean stress varies between .40 and .50 of the Ultimate Tensile Strength of the material, obtained on specimens carefully polished and free from surface stress raisers. A standard type 80-ton tensile Cr-Mo or Ni-Cr-Mo steel, for example, will be found to have an endurance limit of about ±40 tons/sq. in. in the Bar and Forging form and ±33/36 tons/sq. in. in the Sheet and Tube form. These values are, of course, really "academic" ratings, being obtained upon ideal laboratory-prepared test pieces and, while incapable of direct application to engineering parts, they are most valuable in assessing the relative fatigue properties of steel.

In referring to these fatigue values for indefinite cycles of reversed stress, it should be pointed out that there exists no reliable data for the safe fatigue strength (endurance load) for finite life, particularly for cycles of load below 10^6. Considerable scatter of results is experienced at the finite end of the S/N curve, even with the most carefully prepared test pieces, rendering it exceedingly difficult to obtain a true slope of the curve. For instance, such ideal specimens can show variations as great as 30% of the failing load at 10^5 cycles, apparently due to the effect of minute stress raisers in the material. This fact is mentioned to emphasise the extreme difficulty in obtaining safe limiting loads for finite life on even laboratory specimens, and the considerably greater scatter which must exist with engineering parts not so ideally designed and prepared. Any proposal to work to low factors of safety for spars must, therefore, be supported by multiple test evidence —having full regard to scatter.

Evidence tends to show that the steepness of the sloping part of the S/N curve is related to stress raisers (notches), so that a steeply sloping curve can be associated with serious notch conditions and considerable scatter on tests.

As previously mentioned, non-ferrous metals, alloys and wood have no definite endurance limit and, further more, investigators experience greater scatter of test results than in the case of steels. A few typical “ ideal ” endurance limits for common materials are shown below.

Material		*U.T.S. tons/sq. in.*	*Endurance Limit tons/sq. in.*
Mild Steel	S.21	32	± 14 at 20×10^6 cycles
Medium C Steel	S.1	35	± 15 ,, ,,
Ni-Cr-Mo Steel	S.11	60	± 32 ,, ,,
Ni-Cr-Mo Steel	DTD.331	85	± 42 ,, ,,
Ni-Cr-Mo Steel	S.28	100	± 41 ,, ,,
Duralumin Bar	L.1	28	$\pm 9\frac{1}{2}$,, ,,
Duralumin Forging	DTD.150	23	$\pm 5\frac{1}{2}$,, ,,
Light Alloy Bar	L.40	28	$+ 9$,, ,,
Mahogany			± 1.45 at 50×10^6 cycles
Jablo			$\pm 4\frac{1}{2}$,, ,,
Jicwood			$\pm 4\frac{1}{2}$,, ,,
Spruce			± 1.4 at 10×10^6 cycles

In engineering practice it is almost impossible to develop the ideal values of fatigue strength, mainly because of the size, shape, surface finish and other variable factors inevitable to structural parts ; consequently, the actual available fatigue strength is much lower. Most of the factors affecting the available fatigue strength are generally referred to under the broad heading of “ notch effect,” and the response of materials to notch effect (which varies with different materials), as “ notch sensitivity.” Some of the main factors constituting notch effect will be mentioned later, but it should be emphasized at this stage that we have not yet arrived at any agreed formulae concerning notch effect and notch sensitivity in fatigue which can be directly applied to design. Apart from known notch effects, evidence of other factors come to light from time to time, thus complicating the whole subject.

Although it is possible to derive approximately the actual fatigue strength of a part of simple shape (which is somewhat rare), it is found that combinations of even simple parts to form a unit fitting develops a fatigue strength lower than its integral parts, when the strength is assessed on its constituent materials. Generally, it would appear that our knowledge of the influence of geometry of design and combination fittings upon the available fatigue strength is very limited, and much investigation requires to be done to determine the effect of such factors.

Notch Sensitivity in Fatigue.

Notch sensitivity in fatigue is a phenomenon associated with stress concentrations, which may be classified as follows :—

(*a*) *Geometric Notches.* Holes, grooves, pits and non-uniform stiffness in a member giving rise to high stresses at the more rigid locations.

(*b*) *Material "Defects."* Inclusions, decarburisation, porosity, coarse segregation and local variations in surface hardness, local welds, *e.g.*, locally reducing, say, a uniform 80 ton member to, say, 55 tons Ultimate Tensile Strength.

(*c*) *Residual Stresses* resulting from heat treatment, cold work, grinding, drilling, punching.

(*d*) *Method of Loading.* Local high stresses resulting from non-uniform distribution of applied loads, *e.g.*, rivets and areas of contact of gear teeth, clamping stresses.

Although the static stress concentration factor of certain notches can readily be determined photo-elastically and mathematically, it should be noted that these refer to static loading below the elastic limit. Further, the same given notch produces a different percentage reduction of the fatigue strength in different materials. No relationship between the Stress Concentration Factor of a notch (where it can be determined) and the reduction in fatigue strength caused by the notch has yet been found, as it appears that there are other features besides S.C.F. influencing the fatigue strength under notch conditions. However, it has become usual to refer to the general subject of notch sensitivity in fatigue in terms of Strength Reduction Factor and Notch Sensitivity Index, and these are related as follows :—

$$\text{Notch Sensitivity Index : } Q = \frac{K_f - 1}{K - 1}$$

when K_f = Strength Reduction Factor,

K = Stress Concentration Factor.

Either the Strength Reduction Factor K_f itself, or the percentage decrease in fatigue strength due to the notch, $\left(1 - \frac{1}{K_f}\right) \times 100$, is used to denote the Notch Sensitivity of a material, K_f being determined by tests.

Neither the Strength Reduction Factor K_f, nor the percentage decrease in fatigue strength due to the notch, can be used as a measure of notch sensitivity except for comparing cases where the stress system is the same. It takes no account of the magnitude of the stress concentration factor and other features which have a vital influence on the Strength Reduction Factor K_f.

The value Q varies from 0 for a metal insensitive to notches to 1 where the notch has its full theoretical effect.

Austenitic steels (*e.g.*, stainless) can give negative values for Q, *i.e.*, higher fatigue results when notched than unnotched ; this appears to result from cold working of the notch during its preparation. Note that the fatigue strength of such stainless steel is higher than the yield point.

Cast metals are often less notch sensitive then wrought material, and most light alloys show considerable notch sensitivity, which increases as the strength increases. It has been suggested that material having a value of Q greater than 0.6 be excluded from engineering use.

Obviously, where an inevitable notch exists in a part which is sensitive to fatigue failure, there would be no advantage in changing to a higher tensile material having greater notch sensitivity.

Notches.

Examples of notches commonly experienced have been quoted above, and others can be identified upon investigation. Surface finish of the material is a common factor in determining the fatigue strength of a part, reductions of up to 40% in strength being caused by rough finishes producing sharp indentations.

Nevertheless, it should never be taken for granted that because a fatigue failure began at an identifiable notch that the notch itself was solely the cause. It is probable that the part as a whole was designed too weak (against fatigue) and the notch merely accelerated failure.

Clamping Stresses, resulting from tightly fitting collars and sleeves, have been shown to reduce the fatigue strength.

Fretting is a type of notch effect which, although common and serious, is liable to be overlooked. This occurs between closely fitting metal surfaces where repeated slight movement (chafing) can occur. Frequently, the movements are only microscopic, but are sufficient to initiate fatigue cracks in parts subjected to fluctuating stresses. Reduction in fatigue strength of the order of 20% and over is known to occur from this cause. Fretting can be overcome by separating the mating surfaces with a lubricant, plastic material or an electrodeposit of Cadmium, Tin or Copper.

Residual Stresses. Since most fatigue failures commence as tension failures on the surface, any process which gives the material an initial residual tensile stress in the surface layer will reduce the effective fatigue strength of the material. Examples of this are Chromium and Nickel plating and Grinding, which can effect reductions of up to 40% in the fatigue strength. On the other hand, Nitriding and Surface Cold Working, which result in a residual compressive stress in the material, increase the fatigue strength, particularly where notch effect exists.

Grinding operations induce such high surface tensile stresses that frequently surface cracks develop.

Reducing Notch Effects.

Obviously, the geometry of design in detail should receive prior attention to eliminate, where possible, abrupt changes of section, however small, in locations subject to fatigue conditions. The ideal surface finish (smoothly polished) should be attained and any likelihood of residual tension stresses obviated. The use of stress relieving grooves adjacent to existing stress raisers should also be considered.

The creation of residual compressive stresses in the surface by Shot-peening, Cold Rolling or the use of a nitrided layer are recommended methods of improving the fatigue strength under notch conditions. However, with respect to cold working of the surface layers, it is essential that this be carried out under carefully controlled conditions, otherwise damage can ensue.

It is considered that greater use could be made of nitrided steels than is being done at present, especially as it has been shown that the endurance limit can be raised 36% for notch-free specimens, and 300% for notched specimens. Nitrided surfaces are also much less corrosive than the plain steel surfaces, and consequently the corrosion-fatigue resistance of nitrided steel is superior.

Corrosion-Fatigue.

The fatigue strength of metal already corroded is naturally reduced because the corrosion pits and surface inequalities become stress raisers. When corrosion occurs simultaneously with fatigue stressing, the position is, therefore, most serious. Under such conditions it is found that even steels have no definite endurance limit, *i.e.*, the S/N curve continues to fall away with cycles of stress. Under corrosion-fatigue conditions time becomes a further factor in addition to the number of cycles of stress, and consequently, no ordinary laboratory corrosion-fatigue testing can exactly simulate service conditions. Laboratory investigations are therefore useful only to obtain the relative corrosion-fatigue resistance of different alloys. The avoidance or corrosion, either be effecting surface treatments or by the use of non-corrosive metal, simplifies this problem.

The use of stainless steel for spars deserves serious consideration. Unfortunately, the best (austenitic) types have very low Limit of Proportionality and Proof Stress values, and these seriously offset their use. The heat treatable, high tensile stainless, such as the DTD.203 type, deserve consideration, because this class of stainless steel usually develops an endurance limit of about 0.4 of the Ultimate Tensile Strength to which it is commonly heat treated. Although not so corrosion-resistant as the austenitic variety, it should be very useful for rotor spars.

Low Temperatures.

For operational service of aircraft at sub-zero temperatures, much investigation has been going on recently with regard to the properties of standard materials under such conditions. It is found that materials behave differently, and attempts are being made to classify grades of materials according to their ductility, etc., at low temperatures. At this stage, however, it can be stated that, with regard to steels in general, Hardness, Ultimate Tensile Strength, Proof Stress and Fatigue Strength tend to increase with decreasing temperatures. Ductility and Impact values decrease with temperature, austenitic steels showing a gradual change.

The properties of light alloys appear to be less affected than steels by low temperatures.

In the foregoing remarks, brief reference has been made to a selected number of factors associated with materials, and which determine the intrinsic properties and service life of the finished part. Consideration of these problems, bearing in mind our limited knowledge, particularly on a quantitative basis, is ample justification for much further research work and, in the meantime, application of adequate factors of safety.

THE CHAIRMAN: Thank you, Mr. HODGESS, for a most excellent rendering of the paper. I would ask you to convey to Mr. COOPER our deep appreciation of his important contribution.

A paper on " Inspection of Components and Assemblies " was to have been presented by Mr. D. SMITH (of Messrs. Cierva Autogiro Co., Ltd.), but Mr. Smith was unable to attend the meeting.