INVESTIGATION OF FAILURES IN AERONAUTICAL ENGINEERING

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The result of structural failures of air frame, aero engines or propellors can be so serious that Aircraft and Aero Engine manufacturer take every precaution to minimise their possibility. Careful design and rigorous testing of all materials and parts is undertaken with this object in view. However, the rate of development in Aeronautical Engineering is so rapid that a new design may become obsolete even before it has passed the development stage and been put into production. Thus in many cases the final testing stage designs is still during its service and a certain number of failures show up in service life which could not be anticipated in the design or development stage. Fortunately the number of such failures is very small as is shown by the very high degree of reliability obtained from modern Aircraft and aero engines.

In these days of multi engined Aircraft minor failures do not result in crashes but every Aircraft manufacturer of repute investigates these failures very thoroughly from a design and metallurgical point of view to avoid their repetition. There is something to be learnt from the investigation of every single failure and the Aircraft manufacturer is eager to seize this opportunity even though in case of serious deficiencies major modifications may be required and sometimes whole fleets of Aircraft may be grounded until these are carried out.

Engineering failures in Aircraft may be roughly divided in the following Categories :—

(1) Failures which occur during the testing or development stage of either individual components or the complete machine.

(2) Failures which show up during normal service life of the Aircraft.

(3) Failures which occur due to abnormal service conditions, such as heavy landings, aerobatics, going through the sound barrier etc.

When a failure is investigated properly from both the design and metallurgical point of view by impartial investigators it may be possible to further subdivide the cause of the failure in.

(a) Metallurgical causes e.g. material not being up to specification, faulty material, inclusions etc.

(b) Design faults.

Metallurgical Examination: As a rule metallurgical examination is conducted thoroughly to determine whether or not the material from which the part is made conforms to the strength and other physical properties required by the designer and whether or not the part has been given all the process treatments (including proper heat treatment during manufacture). It is also necessary to establish whether or not the material conforms to the standard of cleanliness prescribed for it and if the initial failure started from some defect such as a large non metallic inclusion in the material. A careful micrographical examination supplemented by a chemical analysis and physical tests as far as the size and condition of the broken part would permit are usually undertaken.

Design Faulty: If the metallurgical examination gives a clean bill of health to the part it is usnally assumed that the fault lies in design or selection of the material. As design changes are expensive and difficult to carry out as they may affect other mating parts very often a change over to a better and stronger material may be the easiest way out and in many cases would meet the needs of the situation. But this remedy must not be applied indiscriminately as a part which has been badly designed may continue to suffer failure even when made in a stronger material. And in such case improving the design is the only proper course however inconvenient it may appear to be.

It is well known that Aeronautical Engineering development with its quest for getting the utmost strength out of the lightest structures in the airframe engines and propellors poses a far more difficult task before the designer than other branches of mechanical engineering. In these, the designer has much more latitude to increase sizes of highly stressed parts to provide an additional safety factor. It is with extreme care and the best possible knowledge of stress conditions as determined theoretically and by extensive development testing has it been possible to reach the present stage in the design of air frame and aero engines. The science of stress calculation has advanced a great deal and although its basis is mathematical and purely theoretical most of its results are capable of practical verification under actual test. Not withstanding the contribution of stress analysis service life still provides the best testing ground for any machine as the effect of certain condition like corrosion cannot be anticipated with accuracy in any theoretical stress analysis at the design stage. Therefore it is only natural that a certain number of failures show up in the three stages mentioned above.

Testing of components during design and development: In addition to the trials of the complete aeroplane each important part is subjected to a thorough testing before the design is finalized and incorporated in the Aircraft. The thoroughness with which this work is done is shown in the following examples which are only given as a representative sample of several hundred of such tests which may be carried out on the components of a new design of Aircraft before it is finalized.

Structural Tests: Fig. 1 shows the outer interplane strut of the De Havilland Dragon Rapide Biplane under compression test. The test rig is designed to reproduce the effect of the twisting moment of the lower wing in addition to the compression load on the strut. The test was undertaken to compare the strength of a strut spot welded along the leading and trailing edges as compared with riveting. Failure occured due to the Buckling of the trailing edge both riveting and spot welding were satisfactory. Spot welding was adopted as a quicker production process.

Test on Engine Components: Development tests on engine or propeller parts as a rule are far more difficult to carry out as their working conditions cannot be reproduced accurately with static loading tests. In a majority of cases failures only show up during endurance test run or in some cases during the service life of an engine. Even so as far as possible thorough testing is carried out on any component which may be under suspicion. Figures 2,3,4, show an arrangement for static tensile testing of Gipsy major engine valves. Fig. 2. shows a pair of valves before and after testing in this case the valve pulled through the opening in the testing rig which represented the valve seat. The valve stem did not fail in tension. This was the old type valve. Fig. 3 shows the test rig used showing the dial indicators used to measure deflection of the valve head at various points under different loads. Fig. 4 shows a pair of new type (modified) valves before and after test. Notice in this case the mushroom valve head has not distorted and a tensile failure of the stem has occurred under the valve head.

Fig. 5: The results of the deflection tests on the valve head are summarized and it will be clearly seen that the new type valve head is much stiffer than the old type. These tests were undertaken to compare the strength of the new design with the old one which was subject to occasional failure. The trouble was due to corrosion fatigue and failures occurred under the valve head due to the formation of fatigue creaks across the valve stem. The new design of valve completely cured the trouble.

Fatigue Failures: A majority of failures which show up during the service life of Aircraft Aeroengines are due to fatigue. It has been estimated that over 95% of the failures of

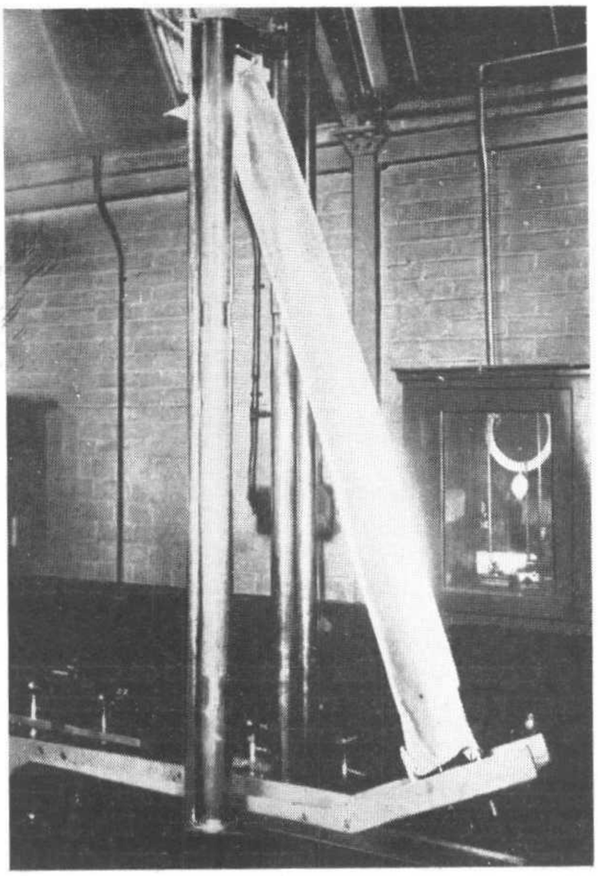

FIG. 1

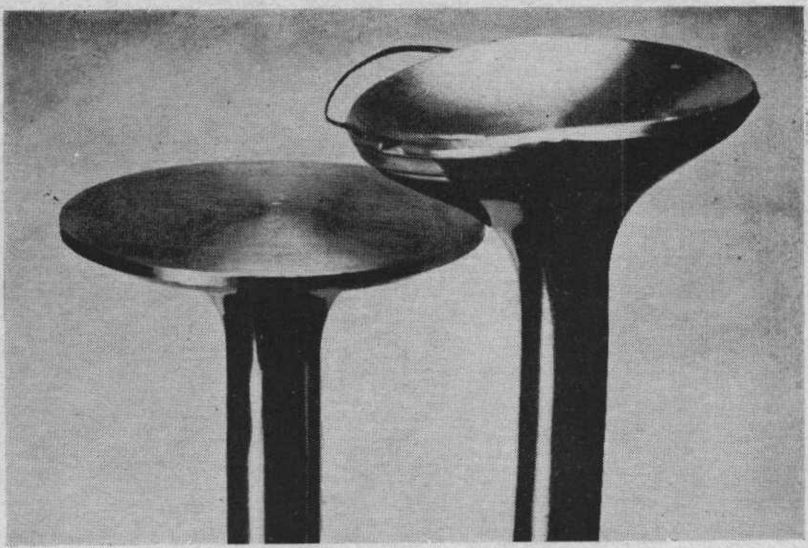

Fig. 2

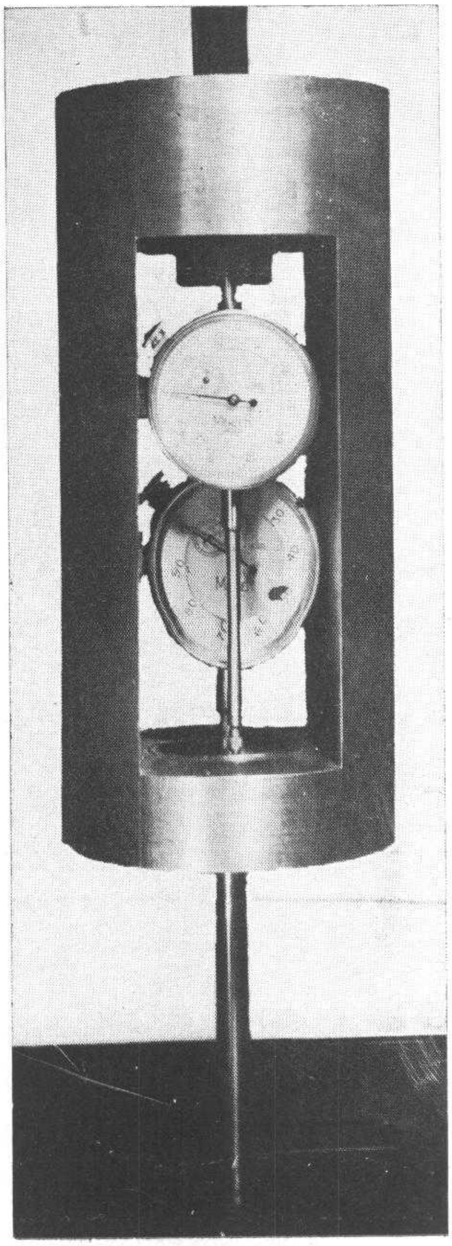

Fig. 3

Fig. 4

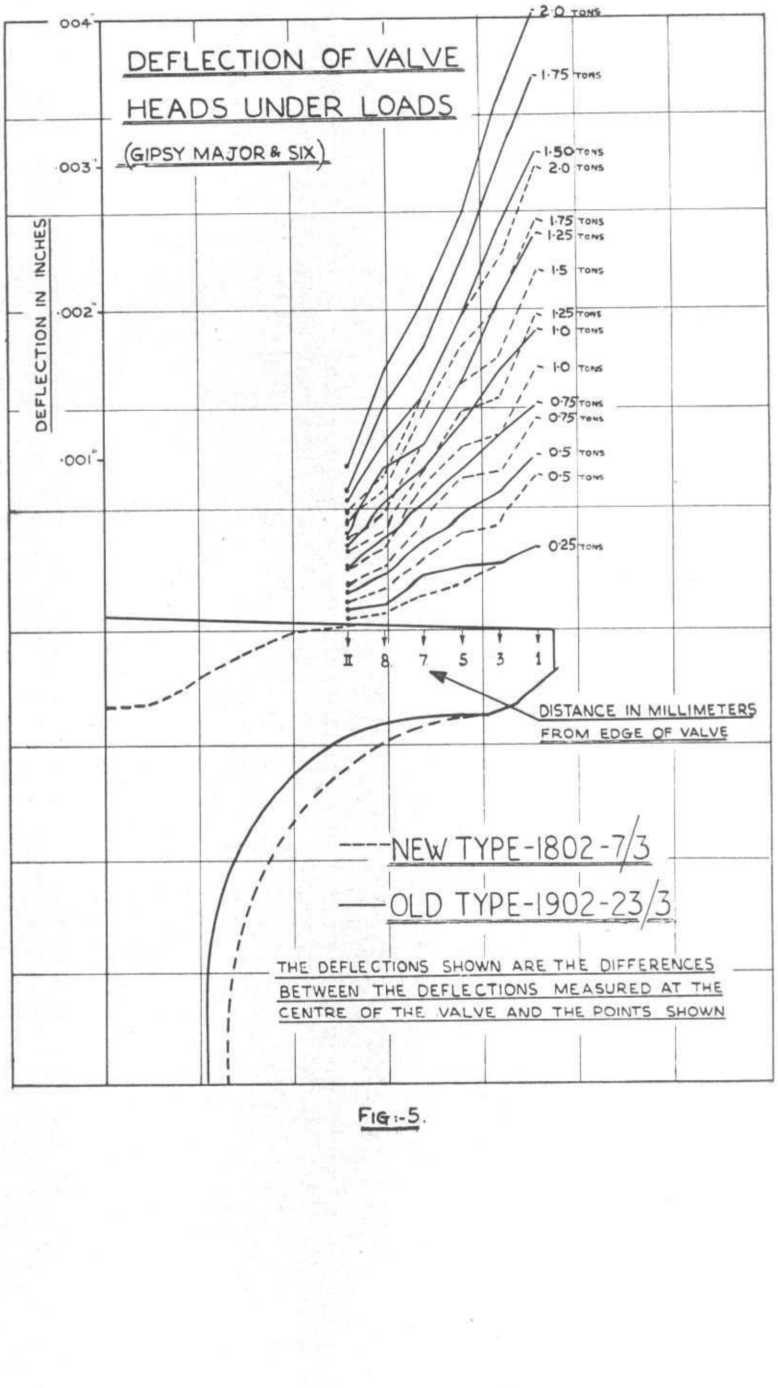
DEFLECTION OF VALVE HEADS UNDER LOADS
(GIPSY MAJOR & SIX)
·004"
·003"
·002"
·001"
DEFLECTION IN INCHES
2·0 TONS
1·75 TONS
1·50 TONS
2·0 TONS
1·75 TONS
1·25 TONS
1·5 TONS
1·25 TONS
1·0 TONS
1·0 TONS
0·75 TONS
0·75 TONS
0·5 TONS
0·5 TONS
0·25 TONS
II 8 7 5 3 1
DISTANCE IN MILLIMETERS FROM EDGE OF VALVE
NEW TYPE-1802-7/3
OLD TYPE-1902-23/3
THE DEFLECTIONS SHOWN ARE THE DIFFERENCES BETWEEN THE DEFLECTIONS MEASURED AT THE CENTRE OF THE VALVE AND THE POINTS SHOWN

FIG:-5.

moving parts or other components which are subject to changing stresses are due to this cause. In some cases careful examination of dismantled engine components may show up a fatigue crack during its stage of development but such lucky finds are rare indeed. If the mating faces of the broken part are not damaged beyond recognition the typical fatigue failure shows the propagation of the fatigue crack as a series of contour lines with their origin showing clearly. In most cases these extend only a part of the way and their surface becomes polished due to the rubbing action of the two parts which are still held together by some sound metal. When the area of the metal holding the part together becomes too small ultimate failure takes place but the appearance of this portion is quite distinct and the tell tale contours lines of the typical fatigue creeping cracks are absent.

How to avoid fatigue failures : There is no simple solution to this problem otherwise good design would be simply reduced to a rule of thumb procedure which it certainly is not. The following rules if followed with an intelligent appreciation of the duties performed by the part designed would undoubtedly be of some help in reducing failures.

(1) A generally smooth streamlined design prevents stress concentration which is the primary cause of fatigue failures.

(2) When changes in section are unavoidable each section should be blended into the next with generous fillets of as large radius as possible. In one aero engine design office they had a slogan written in large letters for all draftmen to sel "make all your fillets with large radii", they add a little weight but a lot more strength.

(3) The designer should always obtain information on the fatigue strength of the materials he selects and only use those which have a value high enough to suit his purpose.

(4) The designer should utilize improvement in fatigue strength produced by such process as shot blasting of the surface and case hardening or other suitable heat treatment.

(5) The design should be studied from a fatigue point of view during stress analysis of the component. A procedure very seldom adopted except in very specialised designs.

Vibration Analysis : The difficulty of analysing the changing stresses produced in a component due to vibrations has been practically overcome by the development of vibration analysis technique. The Aircraft industry is mainly responsible for the development of this technique in which carbon strip elements are cemented to components under test be they wings of the Airframe, rotating blades of a propeller or the impellor of a jet engine. As the material is subjected to changing stresses the stress measuring element changes its electrical conductivity and by using an oscillograph and a high speed film recording Camera it is possible to accurately measure stresses at various points on a propellor blade revolving at 2000 R.P.M.

This technique of stress measurement can be used for measuring stresses in bridge girders, concrete blocks for dams, to stresses in a cylinder holding down stud. The method is of particular usefulness where the stresses to be measured are changing rapidly or where the component is not stationary. In such cases this is the only known method.

Shot Blasting or Shot Peening: The surface fatigue strength of most metals and alloys can be increased by shot blasting or shot peening. The hammering effect of the steel balls on the surface produces beneficial compressive stresses which increases the fatigue strength of components. The method has been used successfully with such parts as Aero Engine valve springs.

Effect of heat treatment on fatigue strength: Heat treatment undoubtedly has a marked influence on the fatigue strength of a material but the precise nature of this effect depends on the type of heat treatment carried out and depends on the nature of stresses left in surface layers of the metal. Fatigue strength is markedly affected specially in steel by any decarburization which may result due to heat treatment. The following results obtained on D.T.D. 331 with standard Wholer test pieces using 10 million reversals are shown below:—

"EFFECT OF HEAT TREATMENT ON THE FATIGUE PROPERTIES OF D.T.D. 331

Material D.T.D. 331. 3/4"Dia bar. Specification analysis.

C.	Si	Mn	S-P	Ni	Cr	Va	Mo	W
.25/·4	.3mx	.7mx	.05mx	3/4.5	.075/1.5	.25mx	.65mx	1mx

The test pieces were heat treated to give a tensile range 82.7 to 87.3 tons/sq."

FATIGUE LIMITS:

	FINISH		% of U. T.S.	% of 1
1.	Heat treated and smooth machined.	plus and minus	44.0	100
2.	Smooth machined and heat treated normally in an electric furnace		19.6	46.8
3.	Smooth machined and heat treated in a controlled atmosphere muffle furnace		21.4	48.8
4.	Smooth machined and heat treated in salt bath Brayshaws Pyromelt		27.8	63.2

It is considered that this drop in the fatigue strength of the steel is due to the effect of surface decarburization caused by the heat treatment processes. Any process which will either prevent this decarburization from occuring or its removal by shot blasting will show an improvement in fatigue stress. The beneficial effect of shot blasting is not due to the removal of decarburized skin only but is in addition to this effect due to the generation of beneficial compressive stresses in the surface skin of the material".

Beneficial effects of case hardening on fatigue strength are well known and in most cases the fatigue strength can be improved over 100%. Nitriding too has the same improving effect and the developent of such outstanding aero engines of the last war as the Rolls Royce merlin round the original crankshaft which was designed for an engine developing under 1000 H.P. to a figure exceeding 2000 B.H.P. was only possible due to the improved fatigue strength obtained by nitriding the crankshaft.

Quenching stresses left in a part during heat treatment as a result of unequal sections can be dangerous specially if they happen to be tensile stresses. The stress concentration caused by deep part numbering can also provide points of failure during heat treatment. Fig 6 shows a steel component which failed during heat treatment due to quenching stresses caused by unequal sections and stress concentration by deep part numbering at the thinest section.

What is not generally realized is that whereas considerable improvement in fatigue strength of a highly stressed component like an aero engine crankshaft is possible by such conventional case hardening methods like box carburizing and nitriding. The same improvement is not obtained by surface hardening by the induction process even though an equally hard surface may be obtained. This is due to the fact that the conventional case hardening methods leave the surface with compressive stresses whereas the induction hardened surfaces are in tension.

One fruitful source of fatigue failures is due to the stress concentrations caused by the discontinuities in the case hardened skin where the hard and soft areas join. In case of one well-known areo engine failure of the main reduction gear teeth occurred because only the flanks of the teeth were case hardened and the troughs were left soft. From a fatigue point of view it is much better to have a part case hardened all over and only very special considerations should be allowed to alter this practice even then care should be taken that the change between case and soft aero takes place in areas of low stress and no stress concentration is possible.

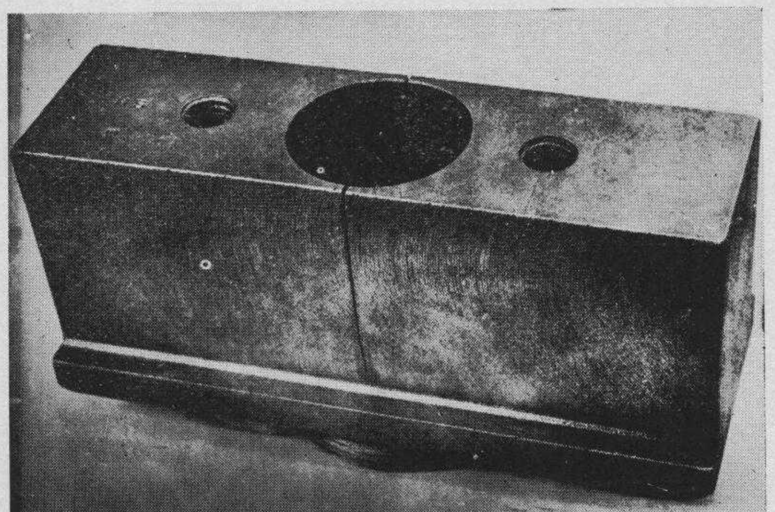

Fig. 6

Failures due to over loading: These as a rule are not so puzzling as fatigue failures as their cause is usally well-known. If an aircraft makes a crash landing it is not unusual for some of the under carriage bolts to shear and a thorough examination is necessary. If the crash is followed or proceeded by complete disintegration of the Aircraft as happened in the case of John Derrey flying the latest D.H. super sonic machine or when Geoffery De Havilland was killed in the experimental D.H. 108, it is often difficult to fit all the bits and pieces together and decide where failure started.

Tensile failures produced during overload conditions are easily recognized as they are very similar to failures which can be reproduced during loading tests in a laboratory. Shear failures present a clean smooth appearance and when a shaft fails in torsional shear it is often difficult to distinguish it from a shaft which has been parted off with a tool on a lathe. The fracture is often smoother.

The subject of failure investigation is a facinating one and the writer was fortunate in having an opportunity of working on this subject for many years in the laboratory of one of the foremost aircraft and engine builders in the United Kingdom. For a proper investigation of failures it goes without saying that a proper unbiased scientific outlook is neceessary but in most cases a merely theoretical or academic approach is unsuccessful and the investigator must possess a sound knowledge of Engineering and operating conditions to reach conclusions which will effectively help in elimitating failures.

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