Fatigue and the Comet Disasters

By TOM BISHOP*

The British inquiry into the cause of disasters to jet-propelled air liners will doubtless remain a classic for all investigators of structural failures. It appears probable that, at a high altitude, a tiny fatigue crack initiated catastrophic failure of the cabin wall and the pressurized cabin literally exploded.

After the crashes of the British de Havilland jet-liners near Elba on Jan. 10, 1954 and near Naples on April 8, 1954, the fleet of these passenger aircraft nicknamed the Comets was grounded. These accidents triggered off what is probably the most exhaustive and costly series of tests ever undertaken to investigate a failure. A public inquiry was started in London in October 1954 which lasted 22 days, evidence being heard from 68 witnesses, and 145 exhibits shown. Excluding the report on the investigations at the Royal Aircraft Establishment at Farnborough, England, directed by Sir Arnold Hall, the evidence to the Court covered 1600 pages of transcript, representing over 800,000 words. In addition, Sir Arnold Hall's report from the Royal Aircraft Establishment, presented at the opening of the inquiry, contained over 120,000 words and 285 illustrations; it was 4 in. thick and weighed 10 lb. An attempt is made here to summarize briefly this massive documentation, the engineering and metallurgical tests carried out to determine the cause of the accidents, and the findings of the marathon investigation, which were released in February of this year. Prior to that time publicists in England were prevented from analyzing the case or reporting in anything but general terms, it being inadvisable to discuss cases under judicial inquiry, as this one was.

When the last crash occurred just off shore near Naples, the wreckage retrieved of the previous accident from shallow water near Elba was only just beginning to accumulate, having been spotted by underwater television. No deductions could yet be drawn from it. Early attempts were therefore made to assess the probable causes in the light of general evidence. In particular, it was noted that both accidents had occurred during initial climb and at heights of 30,000 to 35,000 ft. It was precisely under these conditions (where maximum stresses would exist in the


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walls of the pressure cabin) that fatigue failure would be expected to occur if the structure had been underdesigned or if unprovided for and localized stress raisers existed. Fatigue failure of the pressurized cabin structure was therefore tentatively listed as a possibility.

Other factors were also taken into consideration by the investigators at Farnborough. Comets had been operating with pressures in the cabin greater than had hitherto been in general use for civil aircraft. Furthermore, owing to its size, the pressure cabin had not been tested as a complete unit, although the designers and builders had done much testing in sections. Finally, there might be some unpredictable interaction within the cabin structure between gust loads and pressure loads which could only be discovered by tests with apparatus of a kind that was not yet in existence.

The Farnborough Test

A new type of test was therefore devised and special apparatus built wherein the fuselage was filled with water and also entirely submerged in a large tank of water (Fig. 1). A pumping system was arranged so that internal cabin pressure rose and fell realistically. For these tests a complete airplane was used, the wings remaining in position. Only their roots were submerged with the fuselage; the most of the wings projected through the sides of the water tank. A flexible seal held back the water and allowed the necessary freedom for articulation. The equivalents of up-and-down gust loads were also applied to the wings outside the tank by hydraulic rams.

The test rig is believed to be the first of its kind to apply and cycle the air loads on the wing simultaneously with the pressure loads on the cabin. As remarked above, the rig comprised a 200,000-gal. water tank 112 ft. long by 20 ft. wide by 16 ft. high. The complete aircraft G-ALYU (or "Yoke Uncle") was wheeled into the rig when the latter was about half built. Working

Fig. 2 — Long Tear in Front Fuselage of Yoke Uncle Starting From Fatigue Failure at Rivet Hole Attaching Reinforcement Around the Forward Escape Hatch
night and day, the rig was designed and constructed in about six weeks. The fuselage was appropriately ballasted to give the correct loading conditions.

This Comet G-ALYU had already flown for 3500 hr. — about the same length of time as the ill-fated one which crashed into the Mediterranean off Elba. After pulsating tests giving a total life equivalent to about 2½ times the former life in flying, a crack suddenly opened and a large piece of the pressure cabin wall was pushed out (Fig. 2). The corresponding damage to a cabin filled with compressed air would, in all probability, have amounted to widespread destruction due to the expansibility of the gas.

The first conclusion to be drawn from this experiment was that "Yoke Uncle" (G-ALYU) would, had it continued to fly, have met with disaster after about 9000 hr. of flying, through weakness of the pressure cabin wall. Corresponding deductions concerning the two Comets which went down near Elba and Naples were less positive, for such fundamental reasons as that the fatigue lives of nominally identical structures vary considerably. However, experience regarding such variation in life of rather simple mechanisms subjected to alternating or pulsating loads indicated that fatigue failure of both these ill-fated aircraft was definitely possible.

The water-tank test was also applicable to wing fatigue since, so far as was known, the special arrangements for loading the pressure cabin did not invalidate the test for the wings. A serious crack developed at the wheel-well at about 5500 hr. total, and it was considered that if the test had continued without repairs, the crack would have become catastrophic. Structural failure in this region, however, did not appear in the Elba wreckage recovered.

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**Chemical Composition**

2.1 The chemical composition of the alloy comprising the core of the sheets and coils shall be: copper, not less than 3.5 nor more than 4.8%; iron, not more than 1.0%; silicon, not more than 1.5%; magnesium, not more than 0.6%; manganese, not more than 1.2%; titanium, not more than 0.3%, and aluminium, the remainder.

2.2 The composition of the coating shall be aluminium, not less than 99.7%.

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**Mechanical Tests**

The mechanical properties of the test pieces machined from the samples selected and prepared as specified in Clause 7 must comply with the following tests:

Tensile Test — 0.1% proof stress (applicable only to sheets and coils thicker than 25 standard wire gage (0.020 in.)] not less than 21 tons per sq. in. (47,000 psi.); ultimate tensile stress, not less than 27 tons per sq. in. (60,500 psi.); for sheets and coils thicker than 12 S.W.G. (0.104 in.), elongation not less than 8%.

Single Bend Test (applicable only to sheets and coils 12 S.W.G. and thinner) — The test pieces must withstand without cracking being bent as specified in Clause 6.4 over a radius equal to five times the nominal thickness of the sheet or coil.

[Editor’s Addition: The corresponding American alloy is 24 S-T 4, nominal composition 4.5% Cu, 0.6% Mn, 1.5% Mg. In Alclad 1/16-in. sheet the tensile strength is 58,000 psi. min., the yield strength is 57,000 psi. min., and elongation in 2 in. is 11% min. Endurance strength for 500 million cycles in reverse bending of bare 24 S-T 4 is 20,000 psi. — see Metal Progress Data Sheet No. 521.]

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**Test Loadings**

The main loads imposed during the tests at Farnborough were (a) cabin pressure, (b) steady loads in level flight and (c) up-and-down gust loads on the wings. The cabin pressure was simply a cycle of differential pressure rising from zero to 8.25 psi. and falling again to zero, such as occurs in a climb to 40,000 ft. and return to ground level. Superimposed gust loads on the wings corresponded to alternate up-and-down gusts of 10 ft. per sec.

In this life-sized test under alternating loads the first damage occurred when a portion of the cabin wall, about 8 x 3 ft. in size, was forced outwards. This portion included the forward escape hatch, with its window insert, on the port side. On later examination a small fatigue crack in the skin was discovered at a rivet hole in the lower rear corner of the escape hatch frame. It was considered that this was the start of the failure which progressed rapidly. Even later examination revealed another crack about 1½ in. long in the cabin skin at the upper rear corner of the first window forward of the wing rear spar on the port side.

**Metallurgical Examination**

The fractures in the fuselage of the test Comet G-ALYU after a total of 3057 pressurized "flight cycles" in the water tank were examined most carefully at Farnborough. A piece of the skin from the port side fuselage, containing one side of the longitudinal fracture produced in the fatigue test was examined for evidence of fatigue. This portion of 20-gage (0.036 in.) D.T.D. 546 clad aluminum sheet* was about 7 ft. 6 in. long and had an average width of about 8 in. The important region was the inner surface at the lower
part of the escape hatch. As shown in Fig. 3, fracture had occurred through two countersunk rivet holes at the rear edge of the hatch, and another at the forward edge. The fracture at the rear side of the hole was consistent with fairly rapid fatigue and similar in form and texture to other fractures produced in the laboratory with fresh D.T.D. 546 sheet in test specimens, containing a drilled hole, when loaded axially in cycles from zero to a load sufficient to break them after 800 to 4000 loadings.

On the forward side of the rivet hole, the angle of fracture was off normal and gradually changed to that consistent with tensile failure, approximately 45° to the direction of maximum stress. This again indicated rapid failure that most probably commenced after the start of a fatigue crack on the rear side of the hole. Under the microscope, small specks of green algae were present in the fracture along a hollow portion 0.07 in. long, suggesting that this was probably the length of the fatigue crack before the very rapid tensile tearing commenced. The surface of the countersink on the rear side was rough and blackened due, most probably, to a combination of attrition and corrosion. Such roughening would also lower the endurance of the metal appreciably.

Of the other two rivet holes, the fractures at the rear and forward edges of one were more consistent with tensile failure, but in the other, a tiny area of fatigue fracture was present at rear and forward edges, leading into a coarser, fractured surface more typical of tensile failure.

The total equivalent life, including actual flying of the aircraft tested, was 3057 pressurized flights; 439 unpressurized flights; six proving tests to 11 psi. and 9000 hr. total flying.

The pressure cabin of "Yoke Uncle" was repaired at this stage, a complete new piece of structure being fitted into place at the region shown in Fig. 2. Strain gages were then attached all around the window corners. The results for the worst situations, given for the component loadings separately, were as follows:

<table>
<thead>
<tr>
<th>Loading</th>
<th>Stress</th>
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<tbody>
<tr>
<td>8.25 psi. pressure (by strain gage)</td>
<td>35,100 psi.</td>
</tr>
<tr>
<td>Plus extrapolation to edge</td>
<td>8,000</td>
</tr>
<tr>
<td>Difference between steady loads in level flight and aircraft on ground</td>
<td>650</td>
</tr>
<tr>
<td>Gust of 10 ft. per sec.</td>
<td>1,950</td>
</tr>
<tr>
<td>Total, maximum</td>
<td>45,700 psi.</td>
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</tbody>
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Thus a peak stress of 45,700 psi. was deduced, a stress which, in practice, is reached two or three times per flight. For the actual material (D.T.D. 546) the estimated static strength is about 65,000 psi., so that the peak working stress was 70% of the ultimate! Furthermore, rivet holes in the stress field cause localized increases in this measured stress over regions too small for measurement by strain gages.

While these tests were being made on the ground two other Comets had been converted into flying laboratories. One, G-ALAV or "Able Victor" was plastered inside and out with strain gages, loaded with recording instruments attended by a score of observers, and flown daily to compare actual and computed stresses for various flight conditions. A third, G-ALYS or "Yoke Sugar" was used for fueling tests to determine the possibility that the disasters might have been caused by gasoline explosions, a hypothesis noted below.

Fatigue Tests on D.T.D. 546 Material

Fatigue tests were made on D.T.D. 546 material in a Haigh fatigue machine, and on cylinders loaded cyclically with internal pressure.

The Haigh machine varied the stress in a drilled specimen from zero to a maximum. The specimen was 0.5 in. wide, 0.035 in. thick and the hole 0.012 in. in diameter. The theoretical stress concentration factor was 2.42. The results

Fig. 3 — Close-Up of Fuselage Skin at Bottom Rear Corner of Escape Hatch, After Failure Shown in Fig. 2, Viewed From Outside

Origin of Failure

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obtained are shown as the full line in the accompanying graph, Fig. 4, plotted by the author.

Tests on large hollow cylinders, 44 in. in diameter, were carried out by an outside firm. The cylinder walls were 0.036 in. thick; they had a riveted lap joint along one side and a riveted butt along the other. Rivets were $\frac{3}{8}$ in. diameter with countersunk heads. The cylinders were loaded cyclically with internal pressure which varied from zero to a maximum. Results of these tests are given in the dashed curve.

Opinions From the Farnborough Report

The Farnborough Report (portions of which formed part of the evidence before the court) contains an outline of the investigation and states the opinion which the Royal Aircraft Establishment's staff had formed as to the cause of the accident:

"We have formed the opinion that the accident at Elba was caused by structural failure of the pressure cabin, brought about by fatigue. We reach this opinion for the following reasons:

"1. The low fatigue resistance of the cabin has been demonstrated by the test described and the test result is interpretable as meaning that there was, at the age of the Elba airplane, a definite risk of fatigue failure occurring.

"2. The cabin was the first part of the airplane to fail in the Elba accident.

"3. The wreckage [assembled as in Fig. 5] indicates that the failure in the cabin was of the same basic type as that produced in the fatigue test. [See Fig. 6]

"4. This explanation seems to us to be consistent with all the circumstantial evidence.

"5. The only other defects found in the airplane were not concerned at Elba, as demonstrated by the wreckage.

"Owing to the absence of wreckage, we are unable to form a definite opinion on the cause of the accident near Naples, but we draw attention to the fact that the explanation offered above for the accident at Elba appears to be applicable to that at Naples."

(It might be added that the medical evidence as to the state of the bodies recovered was consistent with the conclusion thus reached.)

Other defects mentioned in 5 above were (a) the relatively low resistance of the wing to fatigue; (b) the possibility of gas from the fuel tank venting system entering the trailing edge area of the wing near the jet pipe shrouds; and (c) risk of internal damage during refueling to the outer wing tanks under conditions which, though abnormal, may sometimes have occurred in practice. (As noted above, this possibility had been exhaustively studied during flights with G-ALYS, "Yoke Sugar").

Lord Cohen, in charge of the inquiry, subsequently accepted the main conclusion of the Farnborough Report, that the cause of the accident to the Elba Comet was the structural failure of the pressure cabin brought about by fatigue. Owing to the absence of wreckage at Naples, Lord Cohen could but agree with the opinion suggested in the Farnborough Report.

Metal Fatigue

The assessors gave general information on metal fatigue, stating that the fatigue of metals has been studied for upwards of 100 years, and
there is a world-wide literature about it. The name correctly suggests that metals (and indeed other materials) suffer from a type of weakness not unknown to human beings. They will break after loads which are repeatedly applied and removed, even though they can support a much larger steady load without distress.

There is one generalization which applies to all failures due to fatigue. The higher the intensity of the stress (unit load) caused by the external load, relative to that which would just cause failure when applied once, the lower is the number of applications of that load under which failure by fatigue will occur. The higher or more intense the repetitive load, the shorter the life will be.

A second generalization applies to certain materials (in particular steel—though not, in general, to alloys of aluminum): There is a sizable fraction of the ultimate strength below which fatigue is borne indefinitely. This is usually termed the endurance limit.

Enough is now known about the fundamental physics of metallic fracture for engineers to be aware that there is still much to be learned about fatigue. Research is continuous. But this relates more to discovering how to improve the resistance of materials to fatigue than to removing any doubts about the principles which should govern the design of engineering structures which must have long life under fluctuating loads. This is true both of mechanisms such as rotating machinery where the number of cycles of loading in an economic life runs into millions or billions, and the computed loads of service must then be below the endurance limit, and of relatively static structures, such as bridges, or the wings or pressure cabins of aircraft, where the alterations which must be carried safely are numbered in thousands, and hence the unit stress computed for the principal members can be somewhat higher.

Designs to take advantage of a higher level of stress than the one just mentioned are comparatively rare. Virtually no engineering components are designed to have a short life under alternating loads. Nor would it be easy so to design them with any confidence since the scatter of experimental points defining the upper leg of the so-called S-N curve is very high. There-
fore the symptoms of failure after relatively few cycles are quite unfamiliar; they are also less specific. The process has not gone on very long, and most of the obscure symptoms of a disease which spreads gradually are absent. This is not to say that fatigue failures in machinery are rare—quite the opposite. But these result from unanticipated variants either in the fabrication shops or in service which introduces “stress raisers” into the part which fails—usually notches, scratches, or corrosion roughening. The uninitiated and the mechanic have a pat (but completely erroneous) name for such failures: “recrystallization”.

In the evidence given by Alfred J. Murphy, professor of industrial metallurgy at the University of Birmingham, are two remarks which summarize the situation as seen by an experienced metallurgist. He said:

“I am strongly impressed by the high general level of stress around the corners of the cabin windows, and I do not feel it necessary or even relevant to try to pursue the last final speck, as it were, which set off the fatigue failure. I think in various places there was a readiness for fatigue failure, and it required only a mild stress raiser (such as a rivet or bolt hole) to initiate failure... The prime consideration is, I think, to get the general stress level down so that you are not in jeopardy in this way. If you can get the general stress level down, you can tolerate the variations which are very liable to happen in practical manufacture. If you have a high stress level, you are setting yourself the task of guarding against most minute variations from the ideal.”

The Comet investigation and other research have resulted in a wealth of new knowledge and will benefit aviation throughout the world where it is heeded. This knowledge will be built into new British aircraft coming along. The makers of the Comets, de Havillands, have stated that, among other future measures, they propose to use thicker-gage materials in the pressure cabin area and to strengthen and redesign windows and cut-outs, and thus lower the general stress to a level at which local stress concentrations—either at rivets and bolt holes, or such as may occur by reason of cracks caused accidentally during manufacture or subsequently—will not constitute a danger. In addition, de Havillands are already engaged on an extensive program of detailed testing to establish a design technique which will minimize the effect of such local stress raisers as are necessarily inherent in the design.

The Minister of Transport recently announced that the decision has been made to go ahead with the employment of the redesigned Comets II and III on a large scale.