Failure Analysis of Materials Systems in Aircraft Structures

I. Roman and D. Rittel
Materials Science Division
School of Applied Science and Technology
The Hebrew University of Jerusalem, Israel

I. INTRODUCTION

I.1. General

The main purpose of failure analysis is to increase the safety and reliability of materials systems, by avoiding the occurrence of what had already happened once. Failure modes of mechanical/metallurgical components of aircraft structures are similar to those occurring in any other mechanical/metallurgical system, so that the failure analysis of the failed aircraft components can be conducted according to the general guidelines of failure analysis as described in this paper.[1]

Nevertheless, failure of aircraft components may result in very severe consequences; i.e. loss of human lives, and/or enormous economical damages. Fortunately those catastrophic failures rarely happen, due to engineering safety precautions and procedures. The purpose of this paper is to outline and demonstrate the procedure exercized in conducting a structural failure analysis in the case of aircraft accidents.

I.2. Materials reliability, design rules and failure definition[2]

Most engineering structural materials can be characterized by their intrinsic mechanical properties, for instance:

δ_{ys}	Yield strength
δ_{uts}	Ultimate tensile strength
K_{1C}	Plane strain fracture toughness

Until lately, the materials property utilized in design was the materials yield strength (δ_{ys}), the criterion for a safe design being:

$$\delta_w < \delta_{ys} \qquad (1)$$

were δ_w are the operating stresses.

In other words:

$$\frac{\delta_{ys}}{\delta_w} = \text{S.F. (safety factor)} \qquad (2)$$

Such criterion assumed discrete values for materials properties and duty stresses, however in reality, these parameters are statistically distributed around an average value. The overlapping area of these distributions, as demonstrated in Figure 1, is the failure probability of the materials system.

Failure of a materials system is defined as the lack of ability of this system to perform satisfactorily under the design conditions. This definition is not restricted to mechanical failures (fracture, deformation, blow-up) but includes also environmental failure (corrosion), electrical failures and others.

I.3. Non-destructive testing and fracture mechanics[3,4]

A more realistic approach to design is the following one:

— It is assumed that every structure contains discontinuities such as inclusions, cracks, porosity, so that:

a) These discontinuities can be detected and their size estimated within the confidence limits characteristic of the inspection system employed.

b) A failure criterion is employed which takes into account three distributions, namely: Material's properties, working stresses, geometry of discontinuities.

A variety of Non Destructive tests has been developed which can characterize the discontinuities contained in the material. Those techniques are based on different physical principles and most of them require highly skilled personnel.

Listed below are the most widely used N.D.T. techniques:

visual inspections
magnetic particles, liquid penetrants
ultrasonic testing

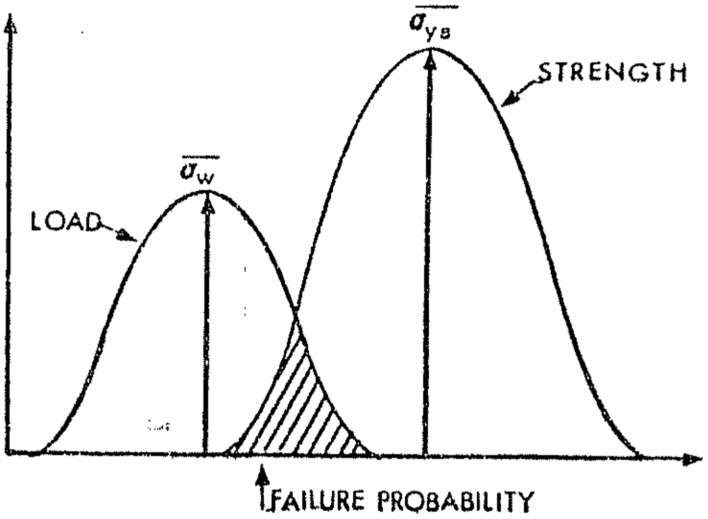

Figure 1
Distribution of working stresses and yield strengths in a real-life system.

acoustic emission
X-ray, ray radiography

The failure criterion (b) is based on fracture mechanics. Let's assume that a structure under a δ_W stress contains a flaw of length "a" (Figure 2), then the stress intensity factor K is defined as follows:

$$K = Const.\ \delta_W \sqrt{a}$$

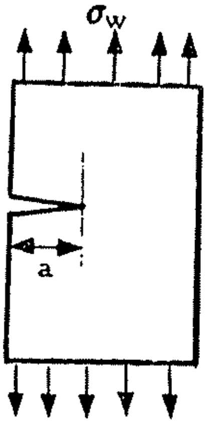

Figure 2
Stressed body containing a flaw of length "a".

The stress intensity factor combines the geometry of (a) with the working stresses (δ_W). Its magnitude is increased either when the flaw grows and/or when the applied stresses increase. When the stress intensity, K, increases so that it exceeds the value of the fracture toughness, K_{IC}, which is a material's intrinsic property, failure will occur. This failure criterion can be written as:

$$K = Const.\delta_W \sqrt{a} > K_{IC} \quad \text{(fract. toughness)} \quad (4)$$

It must be emphasized that K_{IC}, like the other material intrinsic properties, is statistically distributed.

II. AIRCRAFT ACCIDENT INVESTIGATION[4]

When an aircraft accident occurs, the following sequence of actions normally takes place:

a) Procedures on the site of the accident
  1) Rescue and guarding
  2) Survey of wreckage
  3) Preservation of evidence

b) Wreckage investigation

c) Operations investigation

d) Flight records

e) Systems investigation

f) Maintenance, human factors

The failure analyst is mainly concerned with the wreckage and structure investigations, in order to answer the following questions:

WHY did it happen?
HOW did it happen?
HOW to prevent it in the future?

III. STRUCTURAL FAILURE ANALYSIS[4,5,1]

In order to determine the causes and circumstances of a structural failure, the analysis starts on the site of the accident, by preserving the evidence; i.e., cautious visual inspection and complete photographic recordings. The next step is the collection of physical evidence, mainly broken parts of the failed system. The success of the operation is determined by the know-how and the experience of the investigator.

Additional useful information can be collected by means of an objective interrogation of witnesses if there are any. The next steps of the investigation are generally performed in the laboratory:

General visual inspection and photographic documentation of failed parts.

Visual inspection of the fracture surfaces, at low magnification, may indicate possible origin(s) and mechanism of crack propagation.

Next, a metallographic inspection is performed in order to acquire information on the microstructure of the material; i.e., its thermomechanical history. Magnifications ranging from *50 to *800 will generally reveal microstructural abnormalities, such as inclusions, depleted zones, corrosion cracks, unwanted phases and so on. Metallographic studies at higher magnifications can be performed by means of a scanning electron microscope (SEM). Additional information concerning micro-chemistry of the material is obtained, using various attachments such as Energy Dispersive X-ray analysis.

Fracture mechanisms are characterized by examining the fractured surfaces in the scanning electron microscope. Those surfaces, if carefully preserved and cleaned, can be utilized as the fingerprint of the rupture mechanism; e.g., brittle fracture is characterized by cleaved grains, while dimpled surfaces are indicative of a ductile repture. Striations and arrest marks are typical of a fatigue mechanism. Usual magnifications used here range from *40 to *40K.

Next, the mechanical properties and chemical composition of the failed materials are examined, to verify compliance with the design requirements.

In many instances, the analyst may need information additional to that obtained from the failed parts. This is done by an attempt to reproduce, in the laboratory, the system and service conditions. Controlled failure is induced and analyzed under these conditions to produce the desired information. This step is often referred to as "Exemplar testing".

The fracture mechanics concepts discussed in the introduction are utilized to compute, among other parameters, the exerted loads and crack propagation rate.

Finally, when all the evidence and data have been recorded and discussed, the analyst is in a position where he may reach conclusions as to the cause(s) and course of the structural failure which is of utmost importance to the accident investigation.

As an illustration of the principles introduced in the former paragraphs, the failure analysis of an actual case will be described next.

IV. FAILURE ANALYSIS OF AILERON TO WING FASTENING PLATES

The plates shown in Figure 3 fasten the ailerons to the wings of a commercial jet airplane. The four plates failed in flight, resulting in the loss of the left aileron. Four half-plates were lost with it and the remnant complementary broken pieces were brought to the laboratory for investigation.

Visual Inspection

Visual inspection of the failed parts revealed severe smearing and deformation of 2 out of 4 plates, while the two others were undeformed. Visual inspection of the fracture surfaces revealed the following:

> Fracture surfaces of plates 1, 2 include a flat region adjacent to the rivet hole (H in Figure 3), followed by a slant region (45° type inclination). The flat regions contain beach marks, characteristic of a fatigue mechanism. Plates 3, 4 reveal a high degree of deformation and the fracture is essentially of the 45° type.

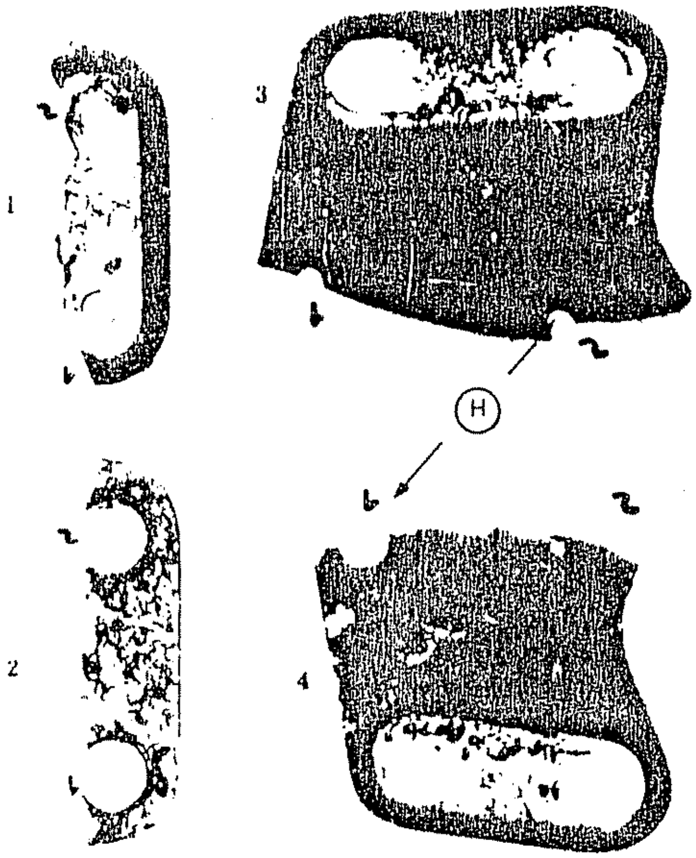

Figure 3
The failed plates.

Metallography

Longitudinal and transverse sections were mounted and prepared for metallographic inspection. Figure 4 shows a typical microstructure which is characteristic of a wrought aluminum alloy, containing an abnormal intergranular crack.

Figure 4
Typical micrograph of the plates material.
Keller's Etch *100

Chemical Analysis

Chemical analysis indicated that the plates material is a 7075 aluminum alloy.

Hardness

The plates' hardness on the Rockwell B scale was found to be in the 86–90 range. This range is typical of a 7075 aluminum alloy in the T6 condition.

Figure 5
Typical fractograph of the flat fatigue region.
SEM *1200

Fractography

The fracture surfaces were examined utilizing a scanning electron microscope (SEM). The presence of striations in the flat portions of the fracture surface confirmed the usual observations as to the initial crack growth mechanism; i.e., fatigure (Figure 5). The topography of the slant regions of the fracture is typical of a brittle rupture mechanism and consists of cleaved grains and some dimples (Figure 6).

Fracture mechanics computations

Rewriting the failure criterion equation (4) as:

$$\delta_W = \frac{K_{IC}}{\text{Const.}\sqrt{a_C}}$$

it is evident that in order to calculate the stresses responsible for the failure, one must know the critical crack size, the fracture toughness, and the equation's constant. A schematic configuration of plate 1 is shown in Figure 7. The critical crack size (a_C) is estimated as the length of the flat portion of the fracture surface; i.e., 18mm. The plate thickness (2mm) insures a plane stress configuration, so that plane stress fracture toughness K_C, is used rather than K_{IC} (plane stress fracture toughness, K_C is not an intrinsic property of the material but it depends on its thickness). K_C and the geometry constant for this particular material and configuration are equal to 98.9 MPa√m (90 Ksi√ inch) and 1.5 respectively[4]. Consequently, it was found that:

$$\delta_W = 275.8 \text{ Mpa } (40 \text{ Ksi})$$

This computed level of stresses corresponds to a fatigue life of about 10^4 cycles[7].

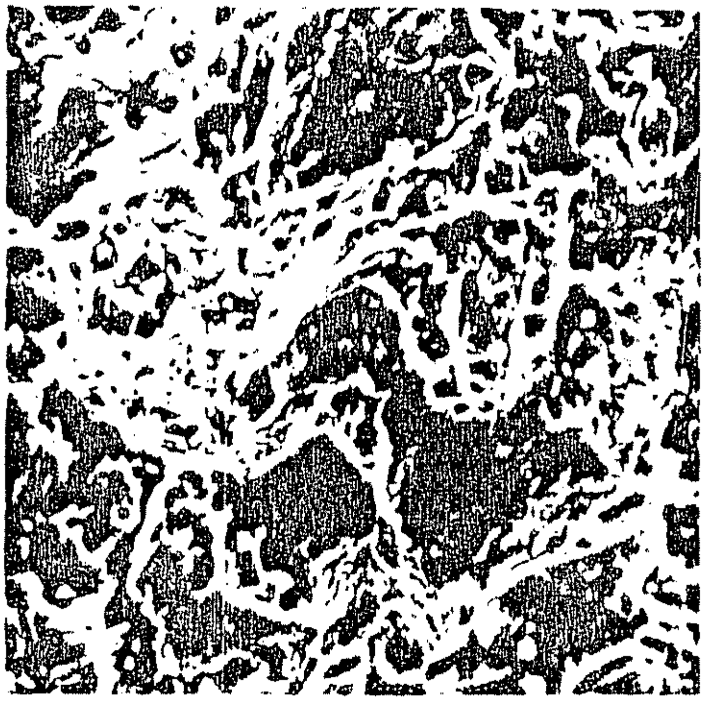

Figure 6
Final overload brittle fracture.
SEM ×400

CONCLUSIONS

1. The stable growth of a fatigue crack, emanating from rivet holes in plates 1 and 2, to a critical size, followed by overload, was found to be responsible for the failure of the system.

2. Plates 3 and 4 failed subsequently by an overload mechanism.

3. The failure stress (corresponding to critical crack length of 18mm) was found to be equal to 275.8 MPa (40 Ksi). At this stress level the fatigue life of the component is 10^4 cycles.

4. The metallographic study revealed the presence of intergranular cracks which may indicate either an environmental assisted initiation mechanism or more likely a manufacturing deficiency.

RECOMMENDATIONS

It was recommended to aircraft users to check the following with the manufacturer:

1. Can the presence of such cracks be avoided in these aircraft quality parts?

2. Are the parts designed to withstand relatively high stresses (275.8 MPa) on the account of a limited fatigue life or did the user overload the aircraft?

In addition it was recommended:

3. To specify inspection intervals and procedures to detect such fatigue cracks before they grow to a critical size.

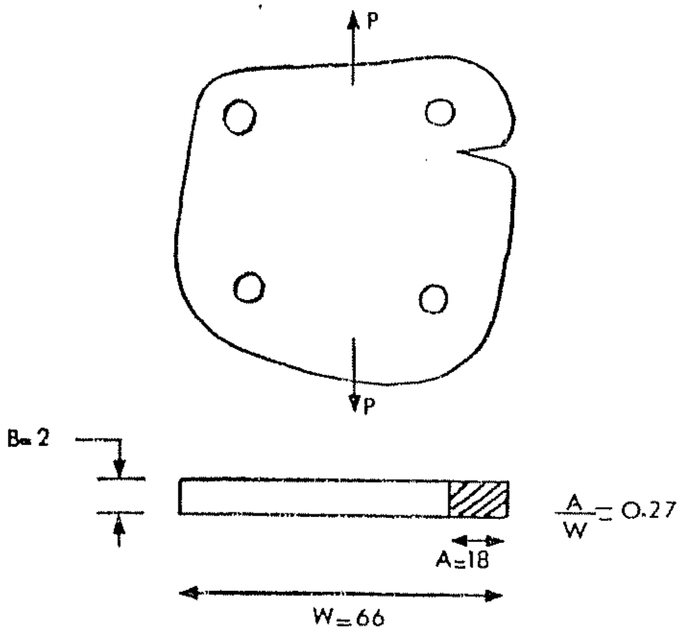

Figure 7
Schematic configuration of Plate 1.

V. SUMMARY

The conclusions and recommendations of such failure analysis should be incorporated to the engineering safety procedure (such as N.D.T.), thus increasing the reliability and safety of materials systems in aircraft structures.

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The Laws of Naval Aviation

By LCDR Carroll R. Beeler, USN
VF-151 ASO

Did you ever have one of thos days when absolutely [illegible]ing went right? Searching for the reasons, you could never really figure out why. Some of us come up with various excuses such as, "They told me to do it this way." Some call it "fate" or "the breaks of naval air." Some say "That's life" or "When the tough get going, the going gets tough," etc. Of course, the cliches go on and on.

I think a personal review of the rules and laws presented will be entertaining and useful, in an obtuse manner. Safety officers or anyone else can take these laws and place locally derived names in front of them. It doesn't have to be Murphy, O'Toole, or the CO. Place one of your own names in front of the law. This list is designed to be cut out and reproduced at will (there is no copyright charge!). By all means, feel free to add or subtract from the rules and tailor them to fit your area.

We've all heard of Murphy. No one remembers Murphy personally, nor does anyone really care, but everyone knows the ramifications of Murphy's law: that is, if an aircraft part can be improperly installed, someone will install it that way. A few of the following rules and laws govern a lot of the activities in naval aviation. Some are general; some are specific.

Murphy's Law: If an aircraft part can be improperly installed, someone will install it that way.

O'Toole's commentary on Murphy's Law: Murphy was an optimist.

The Unspeakable Law: As soon as you mention something, if it's good, it goes away; if it's bad, it happen.

Nonreciprocal Laws of Expectations: Negative expectations yield negative results. Positive expectations yield negative results.

The Skipper's Law: Every man has a scheme that will not work.

The Supply Dept's First Law of Evolving Systems Dynamics: Once you open a can of worms, the only way to recan them is to buy a larger can. Be advised—the larger can is N.I.S. *(not in stock)*

Sailor's Observation: The other line always moves faster.

The Executive Officer's Constant (formerly Flannagan's Finagling Factor): That quantity which when multiplied by, divided by, added to, or subtracted from the answer you get, gives you the answer you should have had to begin with (think about this one).

The Law of Selective Gravity: An object will fall so as to do the most damage or cause the most embarrassment.

Jenning's Corollary: The chance of the bread falling with the buttered side down is directly proportional to the cost of the carpet. (Insert comment regarding uniforms if desired.)

The Maintenance Officer's First Law: If a research project is not worth doing, it is not worth doing well. ("Give me a memo on it.")

NATOPS First Law: If the facts do not conform to the theory, they must be disposed of.

Hoare's Law of Larger Problems: Inside every large problem is a small problem struggling to get out. (This has nothing to do with liberty in a foreign port.)

Water's First Law: When in doubt, mumble.

The P-K Distinction: There are two types of people: those who divide people into two types, and those who don't.

Giles Law: A man with one watch knows what time it is. A man with two watches is never sure.

Ninety Percent Rule of Maintenance Repair Schedules: The first 90 percent of the repair takes 90 percent of the time, and the last 10 percent takes the other 90 percent.

Operations Fourth Law: Necessity and the schedule is the mother of strange wingmen. (Safety can be added here as well!)

—*approach*, august 1979