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FATIGUE FAILURE OF METAL COMPONENTS AS A FACTOR IN CIVIL AIRCRAFT ACCIDENTS

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SUMMARY

A review of records maintained by the National Transportation Safety Board showed that 16 054 civil aviation accidents occurred in the United States during the 3-year period ending December 31, 1969. Material failure was an important factor in the cause of 942 of these accidents. Fatigue was identified as the mode of the material failures associated with the cause of 155 accidents and in many other accidents the records indicated that fatigue failures might have been involved. There were 27 fatal accidents and 157 fatalities in accidents in which fatigue failures of metal components were definitely identified.

Fatigue failures associated with accidents occurred most frequently in landing-gear components, followed in order by powerplant, propeller, and structural components in fixed-wing aircraft and tail-rotor and main-rotor components in rotorcraft.

In a study of 230 laboratory reports on failed components associated with the cause of accidents, fatigue was identified as the mode of failure in more than 60 percent of the failed components. The most frequently identified cause of fatigue, as well as most other types of material failures, was improper maintenance (including inadequate inspection). Fabrication defects, design deficiencies, defective material, and abnormal service damage also caused many fatigue failures.

Four case histories of major accidents are included in the paper as illustrations of some of the factors involved in fatigue failures of aircraft components.

INTRODUCTION

Civil aviation accidents in the United States were investigated by the Civil Aeronautics Board from 1940 until 1967, when the National Transportation Safety Board was established as an independent agency within the Department of Transportation. On April 1, 1967, the safety functions of the Civil Aeronautics Board, including the responsibility for investigating and determining the cause of civil aviation accidents, were transferred to the new Safety Board. Hence, the information on accidents used in the preparation of this paper was taken from records and files accumulated partly by the

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Civil Aeronautics Board (CAB) but now maintained by the National Transportation Safety Board (NTSB).

An aircraft accident is defined in NTSB Regulations as "an occurrence associated with the operation of an aircraft which takes place between the time any persons board the aircraft with the intention of flight until such time as all such persons have disembarked, in which any person suffers death or serious injury as a result of being in or upon the aircraft or by direct contact with the aircraft or anything attached thereto, or the aircraft receives substantial damage." The Board regulations also contain definitions of terms, such as "serious injury" and "substantial damage," that form a part of the definition of an accident. During the last 10 years (1960-1970) the number of civil aircraft accidents per year meeting this definition has ranged from 4709 in 1961 to 6185 in 1967. More than 98 percent of these accidents were in general aviation, which, of course, means that, in general, they involved relatively small aircraft engaged in private flying, business trips, and small commercial operations.

Information on the extent to which fatigue failures in metal components are involved in the cause of accidents was obtained by reviewing accident records and laboratory reports that are available in Safety Board files. The accident records provided considerable data on material failures but did not provide statistically reliable information regarding either the mechanism or cause of failure. Hence, the data presented under the heading of "Accident Records" is included primarily as background information for the results of the study of laboratory reports. Four case histories of major accidents are presented as illustrations of some of the factors that are involved in fatigue failures of aircraft components.

ACCIDENT RECORDS

There were 16 054 civil aviation accidents in the United States during the 3-year period between January 1, 1967, and December 31, 1969. NTSB records show that material failure caused, or was a factor in the cause of, 942 of these accidents. Thus, material failure was involved in the cause of slightly less than 6 percent of the total number of accidents during this period. Only 20 of the 942 material failure accidents occurred in air carrier operations.

Fatigue was identified as the mode of material failure in 155 accidents. There were many other accidents in which fatigue failures might have been involved but the fractures were not identified as fatigue in the record. For example, there were a number of in-flight failures of propeller blades and many cases of connecting rods, connecting rod caps, or connecting rod cap bolts failing in reciprocating engines in which the mode of failure was not identified. It seemed likely that in many cases the investigator may have been unable to recognize evidence of fatigue or that such evidence might have been destroyed by subsequent damage to the fracture surfaces.

Information obtained from the accident records is summarized in tables 1 and 2. The serious nature of fatigue failure accidents is shown by the fact that the 16.4 percent of the material failure accidents in which fatigue failures were identified accounted for 31 percent of the aircraft that were completely destroyed, 46 percent of the fatal accidents, and 63 percent of the fatalities.

There may be some inaccuracies in the classification of components in table 2 because the specific part that failed was not always adequately identified in the record. For example, a few parts listed as landing-gear components might actually be parts of the hydraulic system or some parts listed under powerplants might be more properly identified as electrical system components. However, the general trend of component failures shown in the table indicates that landing gears and powerplants are major problem areas.

The records from which the data in tables 1 and 2 were obtained did not provide any significant amount of information regarding the basic cause of failure except in one category. Definite evidence of improper maintenance or inadequate inspection was found in 130 accidents, whereas there were indications that many other accidents might have been prevented by better inspection and maintenance procedures.

The number of accidents listed in the tables, of course, represent only a small percentage of the total number of material failures in civil aircraft. Most of such failures do not result in accidents and the failed components are replaced or repaired on a more or less routine basis.

LABORATORY REPORTS

Additional information regarding the mechanisms and causes of aircraft material failures was obtained from a study of 230 laboratory reports on the examination of failed components. These were reports on work done in the Safety Board's laboratory, work done for the CAB and the Safety Board at the National Bureau of Standards, and a few reports from industry laboratories. All the reports were on components from aircraft that had been involved in accidents between 1962 and 1970. Reports on failed components that were not pertinent to the cause of an accident were eliminated from the study insofar as possible.

A summary of the results of the study is given in table 3. In classifying the causes of failure, fabrication defects were listed as such only when they appeared to have been caused by a manufacturing operation. When this kind of deficiency occurred during maintenance, the cause of the resulting failure was classified as "improper maintenance."

The "abnormal service damage" category includes only failures caused by service damage that probably would not have been detected by normal inspection procedures. The cause of failure was listed as improper maintenance if it appeared that the service damage could have been found and repaired prior to failure by ordinary good maintenance practice. As anyone who has been involved in the investigation of service failures will realize, the evidence regarding the cause of failure was not always conclusive. In many of the cases studied, some element of judgment entered into the classification. Stress corrosion and hydrogen embrittlement failures were grouped together in the table because, in some cases, reports of studies of the fracture surfaces with an electron microscope identified the fractures as "stress corrosion or hydrogen embrittlement" but did not attempt to distinguish between the two failure mechanisms.

Fatigue failures accounted for more than 60 percent of the failed components on which laboratory reports were available in NTSB accident files. The distribution of fatigue failures among the causes listed in table 3 illustrates one of the major difficulties of preventing such failures in aircraft. So many different kinds of material defects, design errors, mechanical damage, and corrosive attack can contribute to the cause of fatigue failures that it is extremely difficult to guard against all of the possibilities. As in the review of accident records, the results of the study of laboratory reports indicated that improper maintenance is the most frequent cause of fatigue and other types of material failures that contribute to the cause of aircraft accidents.

Specific causes of failure included in each category in table 3 are as follows. (No attempt was made to list these causes in order of frequency of occurrence. The exact number of failures due to each specific cause could not be determined because in many cases the failure could be placed in one of the broad categories but the cause could not be more specifically defined, mainly because of discrepancies in maintenance records, inconclusive results of laboratory work, and more than one factor being involved in the cause of failure.)

Improper maintenance:

- Inadequate inspection
- Failure to replace damaged parts
- Failure to comply with manufacturer's service bulletins or FAA Airworthiness Directives
- Inadequate lubrication
- Failure to service air drying system
- Unsatisfactory welding
- Inadequate shot peening
- Failure to repair damaged protective coating
- Inadequate or excessive torque applied to fasteners
- Failure to install fasteners

Use of unsatisfactory replacement parts
Inadequate cleanup after repairs
Foreign material left in gear housing
Improper alteration of components
Surface damage due to misuse of tools
Inadequate control of plating operations
Grinding cracks
Application of excessive force to press fits not adequately prepared for assembly
Improper adjustment of gear engagement
Insufficient thread engagement
Damage from misuse of inspection equipment

Design deficiencies:

Inaccurate stress analysis (mainly due to insufficient consideration of sources of stress concentration)
Inadequate specification of dimensional tolerances
Failure to allow for fabrication and assembly variables
Selection of unsuitable material or incompatible combinations of material
Insufficient consideration of the effect of possible bending loads on parts designed to resist tension or compression loads
Insufficient consideration of the direction of grain flow in forgings and extrusions
Insufficient consideration of maintenance problems
Failure to specify adequate decarburization limits

Fabrication defects:

Machining errors
Unsatisfactory welding or brazing
Unsatisfactory plating
Improper drilling of rivet holes
Surface damage by defective tools
Damage by careless use of tools
Failure to remove cleaning solution from a closed cavity
Inadequate cleaning after an internal machining operation
Inadequate control of bonding operation

Defective material:

Surface decarburization
Heat treating cracks
Omitting heat treatment or surface hardening operation
Forging flaws
Defective extrusion bonding
Overheating during heat treatment

Casting porosity or cracks
Excessive nonmetallic inclusions
Gas contamination
Failure to use specified material

Abnormal service damage:

Engine overspeed
Excessive vibration
Failure of pilot to follow operating instructions
Inadequate securing of cargo
Unauthorized towing procedures
Excessive maneuvering loads
Deformation from undetermined source
Bird strike
Excessive loads resulting from damage to an associated component

DISCUSSION

The results of the studies summarized in this paper emphasize the importance of fatigue and maintenance problems in the operation of aircraft equipment. By far the most common type of material failure encountered in aircraft accident investigation is in landing-gear and powerplant components of small fixed-wing aircraft. Material failures most frequently cause accidents when they occur while the aircraft is airborne or during landing, although serious accidents may result from failures during any phase of operation.

Opportunities to reduce the number of accidents caused by fatigue failures and other types of material problems exist in almost all phases of aircraft construction, maintenance, and operation. The greatest potential for reduction in the number of accidents is in improving the maintenance of general aviation aircraft. However, numerous accidents in both general aviation and air carrier operations could be prevented by improvements in design; better quality control during material processing, fabrication, and assembly; improved inspection and maintenance programs; and more careful handling of aircraft, particularly on the ground during taxiing and towing operations.

Although the air carriers have had relatively few accidents caused by material failure, in the 3-year period included in the review of accident records, 6 of the 20 air carrier accidents in which material failure contributed to the cause resulted in 138 fatal injuries. Accidents involving fatigue failure accounted for 103 of these air-carrier fatalities. In several failures of landing-gear components and jet engine compressor and turbine disks, major disasters were avoided only by fortunate circumstances. Thus, this study indicates that air carrier, as well as general aviation, aircraft have serious material failure problems.

CASE HISTORIES

Four case histories of accidents due to fatigue failures of components are presented.

I. Los Angeles Airways, Sikorsky S-61L Helicopter; Compton, California; August 14, 1968

This helicopter crashed when a fatigue failure of one of the main rotor blade spindles caused the blade to separate from the rotor hub. The drawing of the failed spindle in figure 1 shows the location of the fracture. A fatigue crack had propagated from a single origin (fig. 2) in the journal-bearing fillet through approximately 70 percent of the cross section of the spindle shank prior to complete failure. The spindle was made of quenched and tempered 4340 steel, with a specified hardness of 34 to 38 Rockwell C and a specified minimum ultimate tensile strength of 150 000 pounds per square inch. This spindle had been reworked in 1966, 2 years before the accident, according to a procedure recommended by the manufacturer. The rework included regrinding, shot peening, and nickel plating the journal bearing surface and fillet where the fatigue crack originated. In June 1968, approximately 2 months before the accident, during a regular periodic inspection, the spindle was inspected for cracks by a fluorescent magnetic particle method. No cracks were detected.

A laboratory study after the accident revealed the following factors that were probably involved in the cause of the spindle failure:

1. The fatigue crack was a high cycle, low stress, slowly propagating crack that probably had been present when the spindle was inspected for cracks 2 months before the accident.

2. The fatigue nucleus was in the steel, under the nickel plating, in an area where very small, shallow pits were found in the surface of the fillet.

3. In the area where the fatigue crack originated the steel had a banded microstructure. The overall hardness in this area was 28 Rockwell C, below the specified minimum of 34 Rockwell C, and the fatigue nucleus was in one of the softer bands where the local hardness was well below 28 Rockwell C.

4. Residual tensile stress in the fillet surface as a result of nickel plating might have contributed to the initiation of the fatigue crack although the plating process specified by the manufacturer was selected to minimize residual stresses.

5. The fillet where the fatigue crack originated had not been properly shot peened. This fact is considered to be an important contributing factor as adequate shot peening would probably have eliminated the effect of the shallow pits and would have reduced the effect of the banded microstructure and low hardness.

II. Lake Central Airlines, Allison Prop-Jet Convair 340; Marseilles, Ohio; March 5, 1967

A fatigue failure of a propeller torque cylinder (fig. 3) precipitated the crash of this two-engine, turboprop aircraft. The fatigue failure, however, was caused by a prior failure in another component of the propeller pitch control system. The initial failure was excessive wear in the splines of the torque piston.

Propeller blade pitch in this aircraft is controlled through torque units (one unit for each of the four propeller blades) operated by hydraulic oil pressure. Through a system of splines, linear movement of the torque piston in the torque cylinder produces changes in propeller pitch. An increase in hydraulic pressure moves the piston outward to increase blade angle and a decrease in pressure permits the normal aerodynamic loads on the propeller to decrease blade angle. The piston has both internal and external splines and after the accident both sets of splines in one piston were found to be severely worn. These splines had not been nitrided as required by the manufacturer's specification for the piston. The excessive wear in the splines allowed the piston to float free in the cylinder without engaging the splines of the mating parts. This condition did not immediately cause any detectable change in the operation of the propeller because of the redundancy built into the pitch control system. However, each time the oil pressure in the system was increased the free piston was forced hard against the cylinder cap. This force resulted in stresses exceeding the fatigue strength of the cylinder wall and eventually caused a complete fatigue failure of the cylinder.

Examination of the fracture (fig. 4) showed that small fatigue cracks had propagated from the inner surface of the cylinder wall and combined to form a continuous crack completely around the inner circumference of the cylinder. This fatigue crack did not penetrate completely through the wall so that hydraulic pressure was maintained until the cylinder failed completely. When the cylinder failed, loss of hydraulic pressure occurred so suddenly that the propeller pitch lock failed and resulted in a severe propeller overspeed. All four propeller blades were thrown off the propeller hub; and one of them went through the fuselage and caused the airplane to break up in the air and crash.

The series of events that led to this accident started with the omission of the nitriding of the torque piston splines. As a result of investigations associated with the accident, changes were made in the quality control system of the propeller manufacturer and several design modifications were made in the propeller pitch control system. These changes appear to be adequate to prevent a similar set of circumstances causing another accident.

III. Wein Consolidated Airlines, Fairchild F-27B; Pedro Bay, Alaska; December 2, 1968

This aircraft encountered severe to extreme clear-air turbulence and crashed during a flight from Anchorage to Iliamna in Alaska. Investigation of the accident showed that an in-flight structural failure of the right wing had occurred through an area where fatigue cracks had weakened the structure on both sides of an access door in the bottom surface of the wing.

The piece of wreckage in which the fatigue fractures were found is shown in figure 5. Fatigue cracks had originated at four fastener holes, two on each side of the access door, that were alined in a chordwise direction. These initial cracks had propagated and joined to form a crack about $3\frac{1}{4}$ inches long on the aft side of the access opening and about $2\frac{1}{2}$ inches long on the forward side. No evidence of fatigue cracking was found in the access door cover. Adjacent to the fastener holes, the fracture surfaces were flat and smooth, as shown in figure 6, but as the cracks progressed away from the holes, they showed an increasing tendency to propagate as slant fractures. Numerous crack jump marks (small regions of ductile rupture) were found in both the flat and slant fracture areas. An example of the appearance of these jump marks is shown in figure 7.

Fatigue and fail-safe tests of an F-27 wing made several years before the accident gave some indication that a load equal to about 77 percent of limit load might have been required to break the wing with cracks about 3 inches long on both sides of the No. 1 access door. However, the numerous indications of high stress intensity found on the fatigue fracture surfaces suggested the possibility that high gust loads might have caused a rapid tearing extension of the cracks shortly before the wing failed completely. Such a rapid crack extension would not have left any visible evidence on the fracture surface. If it included rupture of the access door cover, it would have connected the two fatigue cracks; thus the crack length was increased to more than 17 inches and the load required for final failure was reduced.

A Federal Aviation Administration (FAA) Airworthiness Directive requires U.S. operators to make periodic inspections for cracks at many locations in the F-27 wings. For several years before the accident, X-ray inspections at 1200-hour service time intervals had been made in the area of the No. 1 access door in both wings of the plane that crashed. There was nothing in the aircraft maintenance records to indicate that cracks had been detected. Reexamination of the inspection radiographs after the accident, however, revealed evidence that cracks had been present in the vicinity of the access doors in both wings for more than a year before the accident. Crack indications were found in three sets of radiographs made during this period. If the cracks had been detected and reported, the operator would have been required by the Airworthiness Directive to make an approved modification of the wing structure which would have increased the strength of the access door area where the wing failed.

As soon as the crack indications were found in the radiographs, the FAA was notified and a special inspection was recommended by the Safety Board. The FAA issued a telegraphic Airworthiness Directive requiring an immediate inspection for cracks in the wings of all F-27 aircraft with 5000 hours or more time in service. Sixty-seven aircraft were inspected in compliance with the Airworthiness Directive and 13 cracks were found in eight aircraft.

IV. TAG Airlines DeHavilland Dove; Lake Erie near Cleveland, Ohio; January 28, 1970

A TAG Airlines DeHavilland Dove crashed through the ice into Lake Erie in January 1970, after a fatigue failure of a wing attachment fitting. The appearance of the failed fitting is shown in figure 8 and the surfaces of the fatigue fracture in figure 9. Fatigue cracks had originated at the edge of the hole for the main wing-to-fuselage attachment bolt and had propagated through approximately 75 percent of the cross-sectional area at that point before the fitting failed completely.

The fitting was made of steel that had been heat treated to an ultimate tensile strength of approximately 175 000 pounds per square inch, and the bore of the hole where the failure occurred had been chromium plated. No chromium plating had been used in the original design, but some fittings with chromium plating in the attachment bolt hole were installed prior to 1961. The National Transportation Safety Board report on this accident stated:

> "The manufacturer had long been aware of the problem caused by the chromium plating process and had reduced the 'safe life' of this fitting to 10 000 flying hours in July 1961 (Technical News Sheet 178). At this time, it was recommended that an inspection for the chromium plating of the root-joint attach fitting be carried out at the next convenient opportunity and, in any case, prior to the accumulation of 10 000 flying hours. It was recommended that any fitting found to have the chromium plating be changed at the next removal of the wing or before 10 000 hours, whichever came first. This recommendation had the approval and concurrence of the United Kingdom's Air Registration Board. These requirements became mandatory for aircraft registered in the United Kingdom but not for those registered in the United States.
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> "Based upon this recommendation by the manufacturer, the Federal Aviation Administration issued Airworthiness Directive 61-18-3, effective September 1, 1961. This directive repeated the opening preamble of the Technical News Sheet 178 but adopted only the requirement to inspect the fitting for chromium plating and to

replace it, if so plated, prior to the accumulation of 10 000 flying hours. The recommendation to replace any chromium plated fittings at the next wing removal was not made a part of the requirement by the FAA on the U.S. registered aircraft."

In November 1965 the wings of the aircraft had been removed for certain required modifications. At that time, the fitting that eventually failed had been in service for 4998 hours. It was inspected for cracks, but was not replaced, and failed after 9383 hours of service time. A factor in the failure of the fitting before it reached the 10 000-hour mandatory removal time was the severe operating conditions at TAG Airlines. TAG flights were considerably shorter and were flown at higher speeds and lower altitudes than the standard flight profile for Dove aircraft.

TABLE 1.- U.S. CIVIL AVIATION ACCIDENTS INVOLVING MATERIAL FAILURE AS A CAUSE OR CONTRIBUTING FACTOR

[January 1, 1967 to December 31, 1969]

	Air carrier	General aviation	Total
All material failure accidents:			
Number of accidents	20	922	942
Number of fatal accidents	6	53	59
Number of fatalities	138	110	248
Material failure accidents involving fatigue failure:			
Number of accidents	12	143	155
Number of fatal accidents	4	23	27
Number of fatalities	103	54	157

TABLE 2.- U.S. CIVIL AVIATION ACCIDENTS INVOLVING MATERIAL FAILURE AS A CAUSE OR CONTRIBUTING FACTOR

[January 1, 1967 to December 31, 1969]

	Number of accidents	Number of accidents in which fatigue failures were identified
Type of aircraft:		
Small fixed wing	814	107
Large fixed wing		
Turboprop	16	7
Reciprocating engine	11	5
Turbojet and turbofan	5	2
Helicopters	96	34
Phase of operation:		
In-flight	416	76
Landing	352	45
Take-off	145	28
Taxiing or towing	28	6
Parked	1	---
Extent of damage to aircraft:		
Substantial	818	117
Destroyed	122	38
Minor or none	2	---
Type of component that failed:		
Landing gear	371	58
Powerplant	333	23
Propeller assembly	76	35
Flight controls	25	5
Structural	24	10
Fuel system	24	1
Hydraulic system	17	1
Electrical system	14	---
Tail rotor assembly	25	14
Main rotor assembly	23	8
Instruments	5	---
Auxiliary components	5	---

TABLE 3.- SUMMARY OF DATA FROM 230 LABORATORY REPORTS ON FAILED COMPONENTS

Classification of causes	Number of failures due to –							Totals
	Fatigue	Overload	Stress corrosion or hydrogen embrittlement	Excessive wear or deformation	Corrosion	Stress rupture	High temperature oxidation	
Improper maintenance	52	18	11	15	4		2	102
Fabrication defects	31	6			1		1	39
Design deficiencies	24	5	4	1	1	1	1	37
Defective material	10	3	1	1				15
Abnormal service damage	13	7	1			2		23
Undetermined	11	2	1					14
Totals	141	41	18	17	6	3	4	230

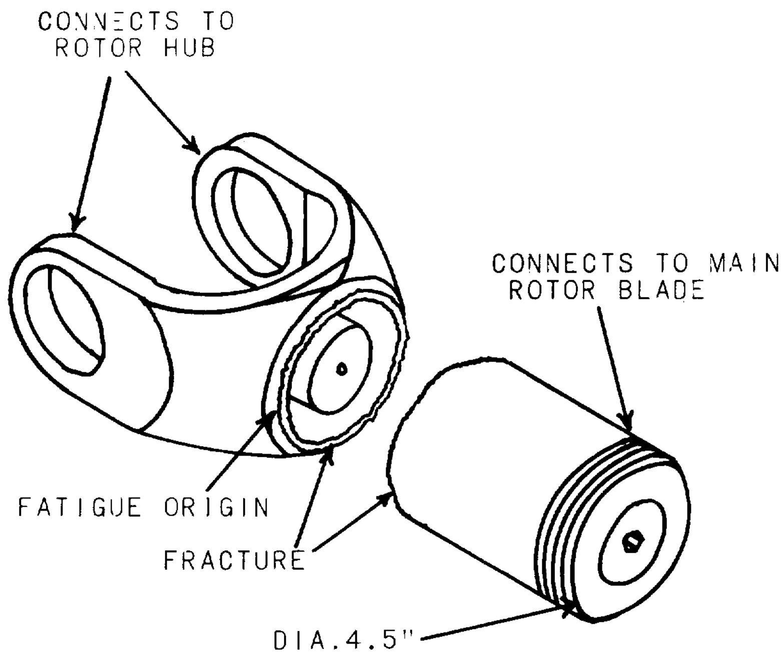

Figure 1.- Drawing of the failed main rotor spindle, showing the location of the fracture.

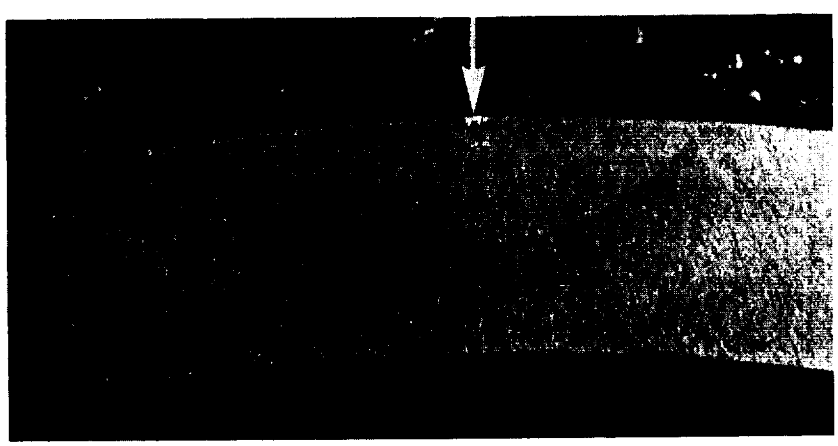

Figure 2.- Appearance of the spindle fracture in the vicinity of the fatigue origin (arrow). X 6.

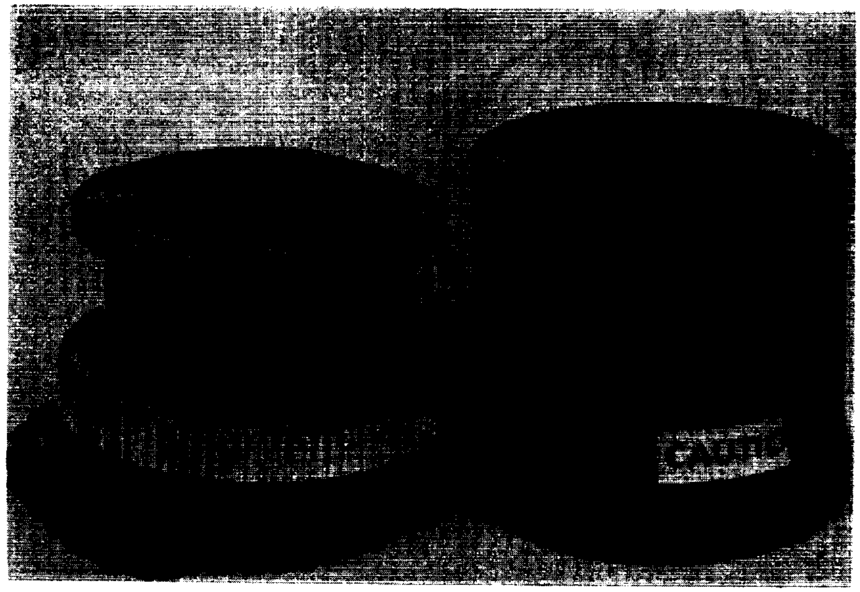

Figure 3.- Failed torque cylinder. Arrows indicate the mating surfaces of the fracture in the two pieces. Approximately X 1/2.

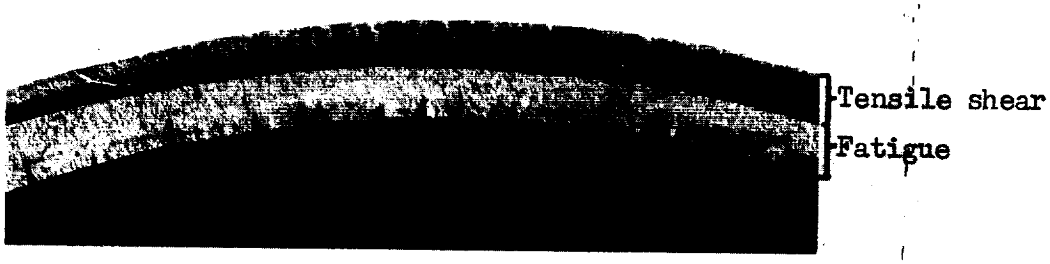

Figure 4.- A portion of the fracture in the torque cylinder shown in figure 3. The remainder of the fracture was similar in appearance. X 3.

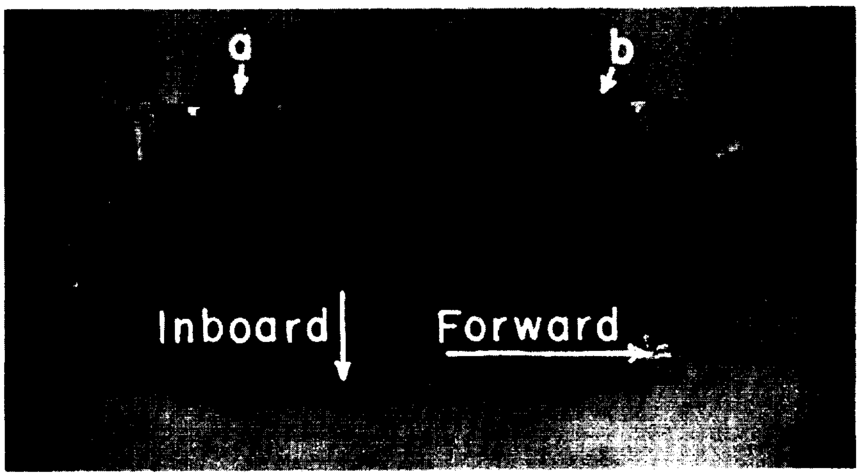

Figure 5.- Piece of the lower surface of the right wing, including the inboard end of the No. 1 access door. Arrows "a" and "b" indicate the location of fatigue fractures. X 1/8.

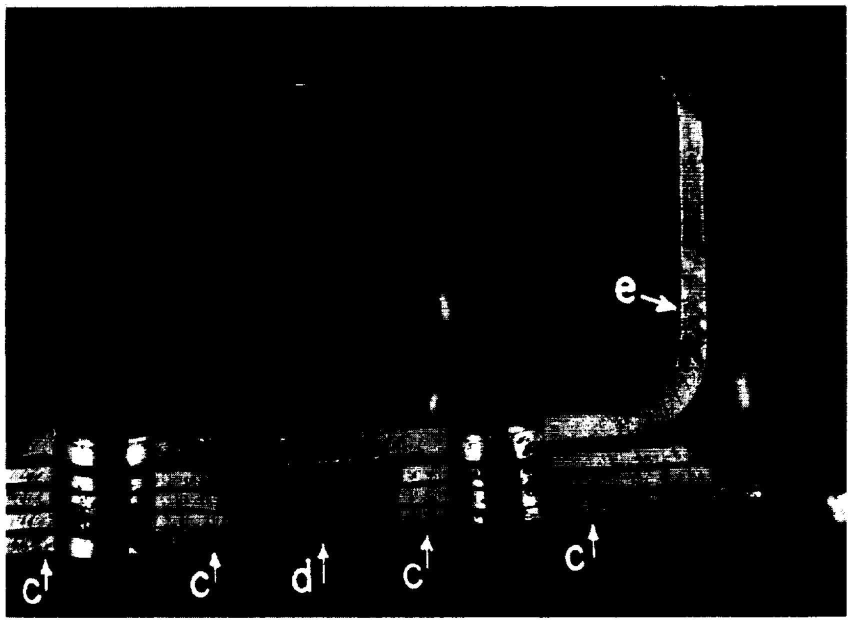

Figure 6.- A portion of the fatigue fracture indicated by arrow "a", figure 5. Arrows "c" indicate flat fracture areas; arrows "d" and "e," slant fractures. X 2.

Figure 7.- Appearance of one of the fatigue fracture areas that showed numerous small regions of ductile rupture between fatigue striations. X 8.

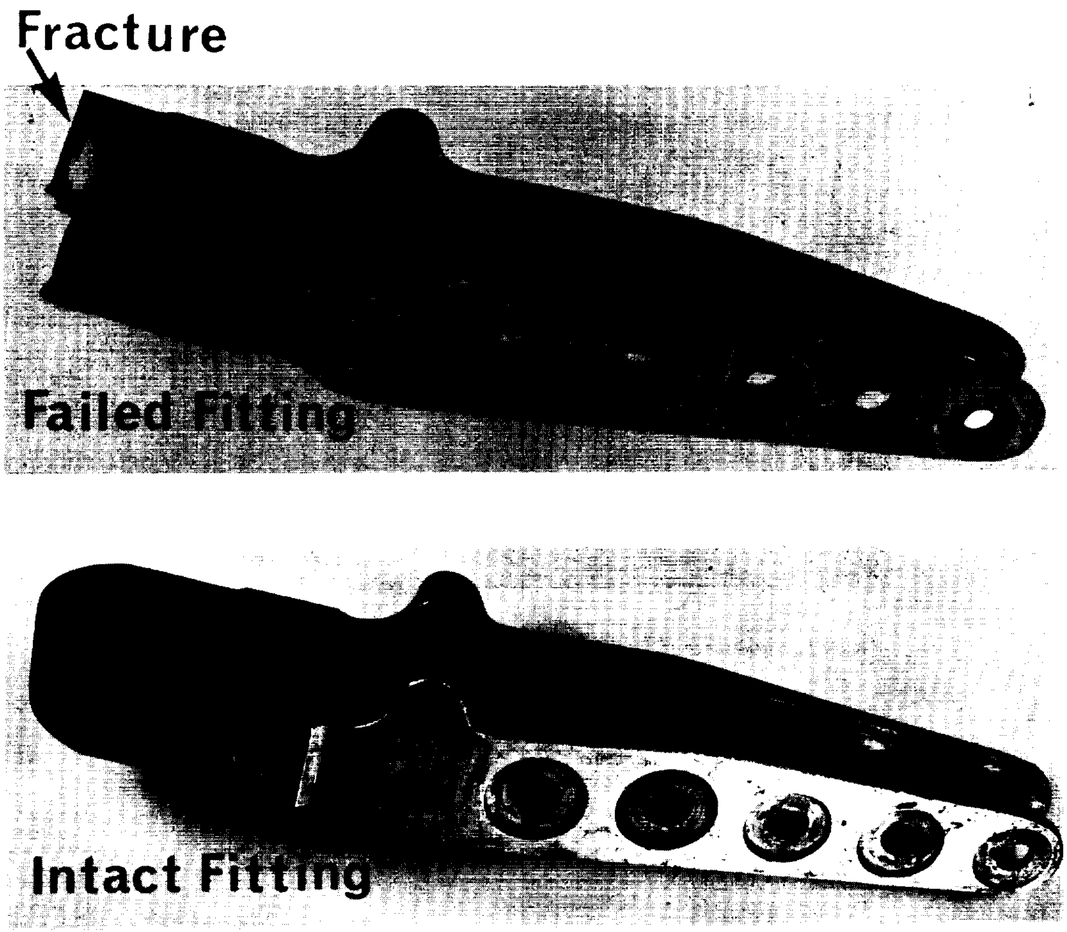

Figure 8.- Failed wing attachment fitting with an intact fitting to show the shape of the end where the fracture occurred. X 2/3.

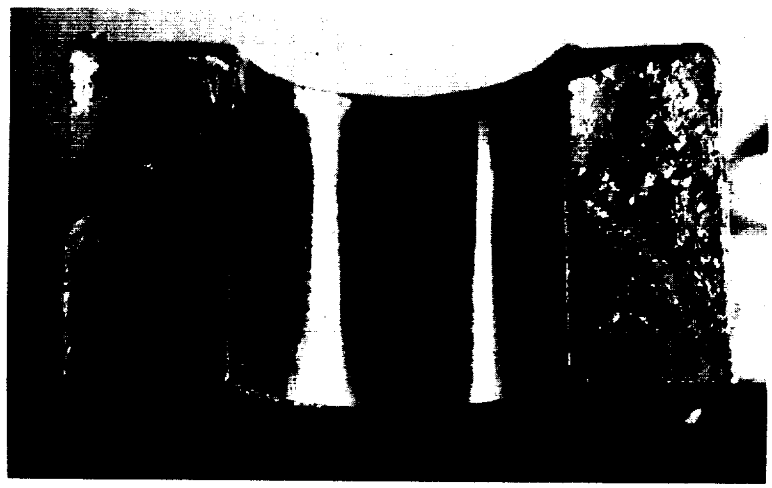

Figure 9.- Appearance of the fracture in the failed fitting shown in figure 8. X 2.