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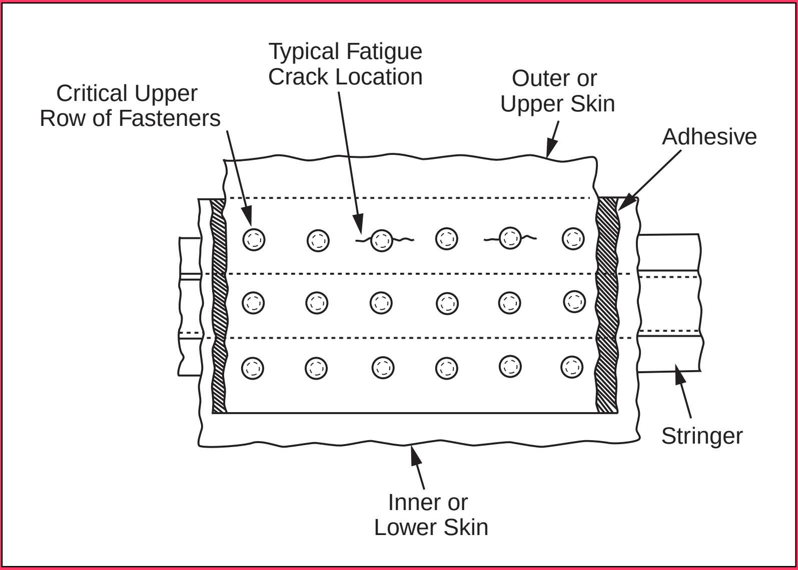
Preventing Fretting Damage Becomes Increasingly Critical as Aircraft Age



FLIGHT SAFETY FOUNDATION
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Aviation Mechanics Bulletin

Dedicated to the aviation mechanic whose knowledge, craftsmanship and integrity form the core of air safety.

Robert A. Feeler, editorial coordinator

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Preventing Fretting Damage Becomes Increasingly Critical as Aircraft Age

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Patrick R. Veillette, Ph.D.

Fretting is a combined form of wear, fatigue and corrosion that can lead to premature mechanical failure at loads well below structural design limits. It is a time-based failure that will require increased attention as the transport-category aircraft fleet continues to age.

The following are examples of how fretting damage can lead to aircraft mishaps:[1]

- A helicopter struck terrain after a connecting rod broke in its piston engine. The primary fracture surface contained a small area of fretting damage. Scanning-electron microscopic examination of the fretting area showed surface damage and the initiation of many small fatigue cracks parallel to the major fracture. Fretting was caused by movement of the bearing shell within the connecting rod big-end bore. The bearing shell had not been installed properly.
- Fretting corrosion occurred in the propeller shaft bearings of a single-engine aircraft operated in a marine environment. Propeller vibratory stresses appear to have been sufficient to cause the fretting. (The report did not say whether the damage was found during routine maintenance or following an accident or incident.)
- After the engine stopped operating in flight, the crew of a military aircraft was unable to restart it because of fretting damage to

> the electrical system. The crew made a successful emergency landing. Investigators found that an electrical connector in the engine-starting system had malfunctioned because of fretting action from vibration-induced motion between the male pin and the female receptacle. The incident-investigation board concluded that the vibration-sensitive connector was not suitable for use in the aircraft; it was replaced with a vibration-resistant connector.

The basic requirements for fretting are relative motions between two surfaces in contact; some mechanical load applied to the surfaces; and a load vector sufficient to cause slip between the surfaces.

Fretting can result in excessive wear, surface fatigue, component fracture, loss of clamping pressure and jamming (by generated debris). Although most reports of fretting damage involve metals, composite materials and ceramic materials also are susceptible to fretting damage.[2,3]

Critical components such as flight controls, powerplant controls and tail surfaces are especially susceptible to fretting damage because they are exposed to the type of vibratory motions that cause fretting. Also highly susceptible are roller bearings, clamped joints, pivots and a variety of other aircraft components.[4,5,6,7]

Whenever a mechanical fastener, such as a rivet, is used to secure two parts, vibratory stresses can cause the fastener to loosen, allowing small cyclic displacements to occur between the two contacting surfaces. This is particularly common in the connections between sheet metal and fuselage frame structural members, and in tail-section connections because of turbulent airflow. Fretting damage also has occurred between mating surfaces in oscillating bearings and flexible couplings.

Small Vibratory Motions Can Cause Fretting

When viewed under magnification, no metal surface appears perfectly smooth. Rather, surface irregularities appear as peaks and valleys. When two metal components are placed in contact under a load, the peaks (called asperities) on one surface will adhere to the asperities on another; simply speaking, the asperities become welded together. When the contacting surfaces are displaced by some vibratory motion, the welded areas rupture. The resulting wear produces debris.[8,9]

Only slight motion is required to cause fretting. Vibratory (back-and-forth) motions as limited as 4×10^{-8} inch (1×10^{-7} millimeter) have been shown to cause fretting.[10,11,12] This limited motion between the surfaces distinguishes fretting from normal wear, which creates debris that typically is removed from the local area. Fretting involves such minute relative movements that the debris remains in the general area of the damage and forms a “third body” between the surfaces. [11]

The motions can be produced by mechanical sources, such as vibrations resonating throughout the adjoining structure. An example is powerplant vibrations that affect flight controls. Vibrations also can be caused by aerodynamic sources.[13] Determining the source of the motion sometimes can lead to a preventive measure. Finding and restricting vibrations from mechanical sources, however, are easier than finding and restricting vibrations from aerodynamic sources.

A significant aerodynamic source of airframe vibration is propeller slipstream (prop wash). Turbulent airflow within the prop wash strikes the fuselage and empennage, flexing skin surfaces and creating vibrations between the structures. Aft fuselage and empennage are especially susceptible to vibrations caused by prop wash.

Wing wake has a large influence on the airflow over the empennage. Turbulent flow from boundary-layer separation begins at fairly low angles-of-attack. As angle-of-attack increases, increasingly turbulent air flows over the rear fuselage and the empennage. Pronounced flexing of skin panels typically occurs at high angles-of-attack.[13]

Debris resulting from the mechanical wear readily oxidizes because of the high temperatures created by friction between the surfaces. Depending on the metals involved, the third body of debris either can act as a lubricant and decrease the coefficient of friction between the two surfaces, or act as an abrasive and exacerbate the wear damage.

Debris often is pressed into the surfaces, causing indentations and furrows. The surface faults create stress risers that accelerate fatigue.[1] (A stress riser, also called a stress *raiser*, is a material discontinuity that induces a local increase in stress.) When fretting occurs between metals of different hardness, the softer metal will deform the greatest amount.

Fretting fatigue cracks are propagated at very low stresses, well below the fatigue limit. The direction in which fatigue cracks grow depends upon the direction of the contact stresses. The cracks grow perpendicular to the maximum principal stress in the fretting area. While the overall applied loads may be small in the region of contact, the localized stresses can be much larger, thus creating subsurface stress zones that will cause accelerated fatigue-crack growth and early component failure.[14]

When the fretting area is exposed to a corrosive environment, failure usually occurs more rapidly and after fewer cycles than in a noncorrosive environment. The severity of corrosion varies, depending on the types of metals involved, the carefulness in their production and storage, the presence of protective surfaces (chemical coatings, films and paint), and the frequency and quality of maintenance.[1]

Corrosion fatigue can decrease significantly the number of cycles achieved before crack nucleation occurs (that is, before a crack begins to form), and corrosion fatigue can accelerate the fatigue-crack growth rate. Studies have shown that fretting damage is more severe in aggressive corrosive environments (for example, warm, moist areas near salt water and/or industrial areas) than in protected environments where oxygen and moisture are excluded. Nevertheless, fretting corrosion cannot be prevented entirely by excluding a corrosive environment.[14]

The most effective method of preventing fretting damage is to use materials that are less susceptible to fretting damage. Because of aircraft-performance factors, materials usually are chosen for their high strength-to-weight qualities, rather than for their corrosion resistance. High-strength, heat-treatable aluminum alloys are very susceptible to various forms of corrosion, including fretting corrosion. Some protection is achieved with chemical surface treatments, but such surfaces require additional maintenance attention.

Machining, Heat-treating Cause Residual Stress

Conventional machining processes and heat treatments used in manufacturing and maintenance of materials can create substantial residual stresses in the surface layer. (Residual stress is stress that remains in the structure after machining or heat treating.) For example, aggressive grinding of a component creates residual tensile stresses that facilitate crack growth. The greater the work performed on the surface of a component, the greater the energy stored as stress, which is an internal force that causes distortion (a change in dimension or shape) and strain (deformation from stretching or compressing).

Crack propagation (growth) is facilitated by the “pulling-apart” action of the tensile stresses, which can reduce fatigue resistance (that is, resistance to progressive failure) by as much as 35 percent.[15]

Residual stresses can be reduced by shot peening, which involves spraying steel shot against the surface of a metal component. Shot peening creates compressive stress (that is, volume-reducing stress) in the surface of the metal; the compressive stress reduces the propagation of fatigue cracks.[16] Nevertheless, the extensive shot peening used in some aircraft applications can produce surface damage that outweighs the positive effect of compressive stress. Shot peening is beneficial in reducing fretting fatigue that typically occurs after relatively few cycles, but has little effect in reducing fatigue that typically occurs after numerous cycles.[17]

Although extensive shot peening can cause crack nucleation, it greatly retards crack propagation. Cracks appear less readily in unpeened surfaces, but they might propagate more rapidly.[18]

There are several methods of determining the residual-stress profile. The two most common methods are X-ray-diffraction analysis and layer-deflection analysis. (The former involves measuring the angle and the intensity at which X-rays are reflected by a component; the latter involves measuring the deflection of very thin layers shaved from the surface of a component.) X-ray-diffraction analysis is especially valuable in measuring residual stresses because much smaller areas can be examined with great accuracy.

Obtaining a stress profile to a depth of a few thousandths of an inch below the surface is essential. Most machine-induced residual stress occurs 0.0005 inch to 0.01 inch (0.0127 millimeter to 0.25 millimeter) below the surface. Residual stress at the surface can be zero, but substantial stresses can be present less than 0.001 inch (0.025 millimeter) below the surface. Key indicators in the profile are surface residual stress, peak tensile stress, the crossover depth (where compressive stress changes to tensile stress, or vice versa), maximum compressive stress and the depth of the residual stress layer.

Corrosive Environment Requires More Frequent Inspections

All aircraft must be examined during scheduled inspections for signs of corrosion and to determine the condition of protective coatings. Such examinations should be conducted more frequently when aircraft operate in corrosive environments.

Certain aircraft components require more attention. Filler materials such as leather, paper, foam rubber and other soundproofing and insulating materials can absorb moisture, and should be inspected carefully. Structures surrounding doors (particularly landing-gear doors), landing-gear wells, wing skins adjacent to countersunk-head fasteners, aluminum-faced honeycomb panels, wing-to-body joints, and structures susceptible to vibration and abrasion should receive particular attention.[19]

Corrosion products (appearing as gray powder or white powder) might be seen visually, along with possible scoring and small indentations in regions of vibratory motion. Bubbling of paint and sheared rivet heads also might indicate fretting corrosion.

Because helicopters create considerable vibratory motion, many of the contacting surfaces must be inspected, particularly those associated with the main-rotor-head assembly, gearboxes, tail-rotor assembly and transmission housing.

Fiber-optic probes, magnifying lenses, mechanical probes, gauges, mirrors and other visual aids can help detect flaws.

Nondestructive-inspection techniques using X-rays, magnetic particles, fluorescent penetrant and ultrasound also can be used to detect fretting fatigue. Scanning-electron microscopy can detect microcracks that signal the early stages of fretting, but this technique is relatively expensive and requires extensive aircraft downtime.

Fretting manifests itself as surface pits surrounded by oxidation debris. The pits usually are shallow and might appear to be fully oxidized. Nevertheless, abrasive action sometimes wears away the top layer of oxidation, thereby exposing the unaffected underlying area. Surrounding debris on ferrous metals normally has a cocoa-like appearance.

A very common form of fretting occurs at the junction of rivets and sheet metal. Debris appears as dark-gray “dust” that flows downstream of the rivet. Because of this, fretting rivets commonly are called “smoking rivets.” (Streaks of oil or dirt that often emanate from rivets are not signs of fretting.) Aluminum alloys and plated-steel surfaces usually exhibit white or red powdery deposits.[19]

Prevention Methods Vary

Materials selection is the most effective means of preventing fretting damage. For example, when a relatively soft metal is in contact with a harder metal, fretting can be minimized by replacing the softer metal with a harder metal. Materials should be carefully selected during design and maintenance to preclude corrosion and fatigue. Materials that are especially susceptible to fretting should be avoided.

Aluminum, a widely used material in aircraft design and maintenance, is susceptible to fretting. Instead of aluminum, titanium alloys and fibrous reinforced thermoset composites are used for some structures.

Fretting fatigue can be reduced by isolating components from corrosive environments. Chemical coatings, films and paint provide protection from corrosive agents. Protective surfaces are most effective when they are kept clean and maintained intact.[19] This becomes difficult when aircraft are operated in environments where foreign-object damage can occur. In arid regions, for example, sand can strike and crack the protective surface, thus allowing corrosive agents to seep under the surface to the underlying metal.

The use of greases or other lubricating compounds also can isolate the surfaces from the environment.

A corrosive attack can be minimized by reducing the amount of time that the corrosive agent remains in contact with the metal. Frequent cleaning can remove corrosive agents. Anodizing (an electrolytic process that forms an airtight oxide film on the surface of aluminum alloys) and chemical treatments can prevent further damage.

Although cleaning is important, some high-pressure, hot-water systems used to wash transport aircraft actually can promote fretting damage. These systems typically generate water pressures of 750–2,000 pounds per square inch (53–141 kilograms per square centimeter). Water temperature is nearly 200 degrees Fahrenheit (93 degrees Celsius).

The high-velocity, heated water rapidly dislodges and dissolves surface dirt, oil, grease and other contaminants. Some systems use cleaning solvents to make the pressurized warm water even more effective.

Nevertheless, these systems can force water, dirt, chemical solvents and other contaminants into areas that should remain free of them, including bearings, bushed joints, actuator seals and electrical connections. The resulting damage to these components leads to increased maintenance costs and aircraft downtime. Furthermore, many cleaning solvents can cause abrasion and corrosion if they are not thoroughly rinsed from the aircraft; operators have reported corrosion and deterioration of roller-bearing elements, bearings and bushings lined with TFE (tetrafluoroethylene), landing gear joints, electrical components and structural elements.[20]

Bearings are very susceptible to fretting damage that begins when direct impingement of pressurized water or solvents forces contaminants into the joints, causing accelerated wear, breakdown of internal surfaces and corrosion of rolling elements.

High-pressure water can penetrate bearing seals and initiate corrosion of bearing surfaces. Water and chemical solvents can be trapped in sealed bearings (that is, bearings that are not designed to be relubricated). Removing water and solvents from sealed bearings is difficult. One suggested method is to purge the bearing with grease; the bearing must be rotated to thoroughly coat the bearing members with grease and force out the water.[20]

One major airplane manufacturer recommends that direct spraying of water and solvents into joints and roller elements be avoided, and that chemical cleaning solvents be applied carefully and be manually scrubbed. Thorough rinsing should be done with generous amounts of unpressurized, warm water. If pressurized washing equipment is used, the manufacturer recommends that the spray nozzle be positioned at least three feet from the aircraft surface, and that the spray nozzle not be used to remove "stubborn" accumulations.[20] Stubborn grease and dirt should be removed by manually scrubbing.

Landing gear and gear doors are susceptible to fretting damage that begins with the collection of moisture, dirt, dust, grime and other contaminants on the tires. In some aircraft, corrosive exhaust gases from the auxiliary power unit also enter the gear well. The contaminants form a corrosive layer of grime that adheres to the surfaces of the gear, doors and wells.

Landing-gear components are made from very high-strength steels that typically are covered with a thick, semipermanent film or with grease. Maintaining the protective covering is essential to prevent corrosion. The protective surface should be reapplied at regular maintenance intervals. Some parts of the landing gear are inaccessible, however, and are protected only by the film or grease that was applied during manufacture.

Therefore, protective grease on landing-gear components should not be removed. Removing the grease will expose the components to corrosive agents. Inadvertent removal of the protective layer may not be discovered until damage has occurred.

Improper storage and shipping can cause small but significant changes to component strength and durability. For example, galvanized sheets (made of steel and covered with zinc by hot dipping or electroplating) can undergo fretting damage if they are not separated during storage to allow free access to the air, or not oiled and clamped during shipment.[15] Bearings that depend on rotation for thorough lubrication can be damaged by vibration during shipping. Damage can be prevented by applying a thin coat of lead on the bearing surfaces before shipping; the lead is worn quickly away in service.[15]

A tracking and inspection process should be used to ensure that storage-and-shipping standards are met.

Fretting-fatigue damage is initiated during the first few fretting cycles.[8] Therefore, such damage can be prevented or reduced by restricting movement (slip) between contacting surfaces and creating and/or maintaining an effective (lubricating) third body between the surfaces before the first loading cycle.

Slip can be reduced in some cases by bringing loose fasteners to their proper torque values. Minimizing or eliminating surface motions in structures such as the empennage, however, is virtually impossible because of the turbulent airflow.

If slip is unavoidable, a solid film lubricant or a soft-metal third body (such as a shim) might prevent or reduce fretting. Hard coatings are a poor choice, because they can induce surface fatigue.

Surface roughness and residual stresses are important factors that influence fretting behavior. Surface roughness decreases a component's resistance to general fatigue and to fretting fatigue.[16] Because many transport-category aircraft are near, or exceeding, their design-service objectives, time-based failures, such as fretting, will become more frequent and more severe as the fleet ages.[21]♦

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About the Author

Patrick R. Veillette earned a bachelor's degree in aeronautical engineering at the U.S. Air Force Academy and a doctorate in civil engineering at the University of Utah. He is a professional pilot with more than 11,000 flight hours and has conducted several research projects on cockpit automation and human error in high-risk environments. Veillette has an airline transport pilot certificate and is a former U.S. Federal Aviation Administration designated pilot examiner.

MAINTENANCE ALERTS

NTSB Wants Improved Containment Capability For General Electric CF6 Engines

Several uncontained failures of General Electric (GE) Aircraft Engines CF6-50 and CF6-80 engines have prompted the U.S. National Transportation Safety Board (NTSB) to call for improved containment capability for the engines.

NTSB cited the following incidents:

- On Dec. 6, 1995, the crew of a Pakistan International Airlines (PIA) Boeing 747-240 shut down the no. 2 engine after hearing unusual noises and seeing indications of loss of oil pressure and oil quantity from the CF6-50E2 engine while departing from New York, New York, U.S. The crew flew the airplane back to the departure airport and landed without further incident. NTSB said that the engine fan midshaft (FMS) had fractured and had caused the low-pressure turbine (LPT) rotor to overspeed and shed blades. Debris punctured the left-wing leading-edge slats and a landing-gear door.

- On Jan. 24, 1996, the no. 1 engine on an American Airlines Airbus A300-600 spooled down on departure from Philadelphia, Pennsylvania, U.S. The crew returned to the departure airport and landed safely. NTSB said that an interturbine-temperature probe in the CF6-80C2A5 engine had separated and had struck one LPT blade. The blade fractured and struck other LPT blades. The damage ruptured the LPT case.

- On Feb. 22, 1996, the crew of a Continental Airlines McDonnell Douglas DC-10 rejected their takeoff from Houston, Texas, U.S. when the no. 3 engine surged. NTSB said that the FMS had fractured and caused an uncontained failure of the CF6-50C2 engine's LPT. Debris penetrated the engine-core cowl but did not damage any other parts of the airplane.

NTSB said that GE data show that 25 uncontained LPT failures have occurred in CF6-50 engines, and that six uncontained LPT failures have occurred in CF6-80C2 engines. NTSB recommended that the U.S. Federal Aviation Administration require GE to "improve the ability of the CF6-50 and the CF6-80 series engines to prevent fractured [LPT] blades from being liberated through the engine cowling."

Evacuation-slide Separations Prompt Call to Mandate System Modifications And Maintenance Training

Citing six incidents in which off-wing emergency-evacuation slides separated from B-757s in flight, NTSB has recommended that aircraft operators be required to modify the systems according to Boeing service bulletins (SBs) and that the FAA ensure that B-757 maintenance technicians receive training on the system modifications.

NTSB said that about half of the B-757 fleet has off-wing emergency-evacuation slides, which are in fuselage compartments just above the trailing edges of the wings. All six incidents occurred soon after maintenance was performed on the slides. Some of the aircraft were damaged when the slide separations occurred, but all were landed safely.

The first incident occurred on June 8, 1993. The United Airlines crew made an emergency landing after the left slide separated at Flight Level 250. Three months later, Boeing informed B-757 operators about the incident, which occurred because a partially engaged door latch allowed the door to flex and then be forced open by the air stream. Boeing also revised the B-757 maintenance manual to clarify door-latching procedures and to incorporate placard instructions on the doors.

In October 1996, Boeing issued SB 757-25-0182, which included information on two incidents that occurred after June 8, 1993, and instructions for modifying the slide system. The incidents involved a Continental Airlines B-757 on Sept. 25, 1995, and a Boeing flight-test airplane on Nov. 15, 1995.

NTSB said that three recent incidents involved airplanes that were not modified according to the SB. The incidents involved:

- An American Airlines airplane from which a slide separated on June 24, 1997. (The NTSB safety-recommendation document provided no further details about this incident, except that the airline subsequently painted red stripes on the slide-compartment door frames to help mechanics determine when the door is properly positioned and latched.);
- A Delta Air Lines airplane that was departing from LaGuardia International Airport in New York, New York, U.S. on June 2, 1998, when the left slide separated. The flight continued to, and landed safely at, the scheduled destination, Covington, Kentucky, U.S. NTSB said that the aft fuselage was substantially damaged; and,
- A United Airlines airplane that was being rotated for takeoff from Seattle, Washington, U.S., when the left slide separated. The flight continued to, and landed safely at, Denver, Colorado, U.S.

NTSB recommended that the FAA issue an airworthiness directive (AD) requiring compliance with SB 757-25-0182 and issue another AD following introduction by Boeing of further modifications to the slide system. (NTSB said that Boeing expected to issue an SB on the new modifications in December 1998.)

NTSB also said that the FAA should “issue a flight standards information bulletin to require that principal maintenance inspectors ensure that all mechanics [who work on these aircraft] are trained on the new off-wing escape slide system enhancements on the B-757.”♦

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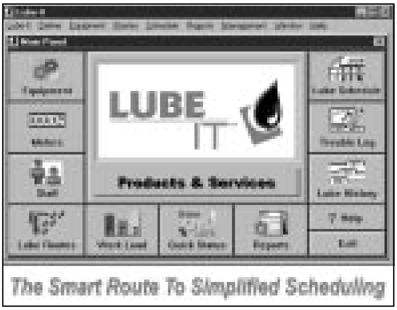

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For more information: Environmental Development Corporation, P.O. Box 854, Findlay, OH 45839-0854 U.S. Telephone +(419) 422-1200.

Kit Indicates Water in Aviation Fuels

The CDF (Clean Dry Fuel) water-indicator-pad kit indicates the presence of undissolved water in mobile or stationary aviation fuel-tank systems, according to the manufacturer. Testing requires a small fuel sample taken in a test cap from the fuel nozzle or the lowest point of a tank sump. A chemically treated pad is dropped into the fuel sample and yields a visual positive or negative result in approximately one minute.

For more information: AVFMATS, P.O. Box 8803, Columbus, GA 31908 U.S. Telephone +(706) 327-0909.♦

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Flight Safety Foundation

11th annual
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"Flight Safety: Management, Measurement and Margins"

March 8–10, 1999

Grand Hotel Krasnapolsky, Amsterdam, Netherlands

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