AC 2008-122: EDUCATIONAL USES OF AIRPLANE ACCIDENT REPORTS

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Abstract

Airplane crash reports from the National Transportation Safety Board and the general media were reviewed to enhance student learning and interests. The science behind the following topics was developed for classroom use: pressure, hoop stress, fatigue testing, inertial loading, motion, crash testing.

Additionally a series of “desktop” experiments were developed to enhance the learning experience. For example much ground can be covered by popping balloons and bending paper clips.

Introduction

In my opinion traditional science and engineering textbooks are very weak at explaining the significance of the material. Most authors are motivated by a belief they have found a better way to explain the science. Few bother to ferret out and develop interesting real life adventures and applications. One source of information is the National Transportation Safety Board (NTSB) crash reports. It can be challenging to reduce these complex aerospace systems to fundamental concepts for educational use.

This material presented here was developed for a new disaster course for engineering students and a disaster based science course for non-technical students. The material is also suitable to supplement more traditional engineering courses such as: strength of materials, material science, finite element analysis, and machine design. Many ABET so called "soft skills" can also be illustrated with related issues such as ethics, cost/benefit analysis of safety improvements, role of government regulation, lawsuits, etc.

Student response and interest were excellent. See limited assessment results at the end of the paper.

In general the stories are fascinating and serve as a great starting point for numerous engineering discussions. The following are example crash stories and associated concepts of engineering science.

Pressure

The de Havilland explosive decompressions of the 1950’s are well known. Also well known is Aloha Airlines Flight 243 on April 28, 1988 in which an 18’ by 14’ section of a Boeing 737 fuselage blew out (see Figure 1). Amazingly all the passengers had their seatbelts on and survived. Only one attendant standing nearby was lost.

Although mechanical engineers study design for metal fatigue, rarely are actual cycles to failure examples available for analysis. Nobody wants to brag about their failures. The NTSB provides hard numbers.

Aloha Airlines was flying short hops between the Hawaiian Islands, some as short as 20 minutes. These planes accumulated more take-off/landing fuselage pressurization cycles than all other 737's. The inspection schedules were based on time; they should have been based on cycles. Flight 243 had 89,680 take-off/landing pressure cycles on the fuselage, the third highest in the world's fleet of 737's. After the explosive decompression, Aloha Airlines inspected two other 737's with 90,051 and 85,409. These two planes were immediately scrapped on the spot.

Although the Aloha problem could have been prevented with more frequent inspections and Boeing already had an improved lap joint design in place, this near disaster triggered a national research effort. Improvements in inspection techniques and fatigue design were developed. New methods to reflect the weakening effect of small fatigue cracks in lined up rivet holes were developed through testing and analysis.

Incidentally the Aloha blast damage demonstrates how well a modern damage tolerant designed airplane hangs together. A surprising number of aircraft have safely landed after a bombing.

Less well known is the more recent China Airlines Flight 611. On May 25, 2002 a Boeing 747 broke up into four distinct pieces at 35,000 feet. The investigation revealed the airplane had a bad landing and tail strike in 1980. Apparently without Boeing's approval a 120" X 22" repair patch covered a scratch that propagated a fatigue crack for the next 22 years. The recovered wreckage had scratches as deep as 0.009"

The dangerous energy contained in compressed gas can be demonstrated with a cylindrical balloon. The balloon filled with air pops and fragments into multiple pieces with some flying up to 8 feet. An identical balloon filled to the same dimensions with water collapses in place; no pop, no fragmentation and no flying pieces.

A slow decompression (highly desirable for the passengers and crew) vs. an explosive decompression can also be demonstrated with cylindrical balloons. If the balloon is taped circumferentially and longitudinally, and the tape strips are close enough (in my case the spacing was less than a half inch), a pin prick will produce a slow hiss and not fragment.

A more interesting application of air pressure is two instances of people being sucked out of a window. On November 3, 1973 National Airlines Flight 27 had an uncontained engine failure on a DC-10. The engine fragments knocked out a window. A passenger was slowly sucked out in spite of having his seatbelt on. Later it was determined his seatbelt was slack 8 inches.

An even more bizarre example of the force of air pressure occurred on June 10, 1990 when British Airlines Flight 5390 had a windscreen blow out at 17,300 feet. The pilot was blown out the window but caught his feet in the control column forcing the airplane into a dive. This worked out reasonably well since the procedure for a decompression calls for diving to a breathable altitude. However the flight attendants had to wrestle the pilot's feet out of the control column and hang on for 20 minutes till the airplane safely landed. The pilot survived the experience. Later it was determined the windscreen had been replaced the night before with undersized bolts.

Hoop Stress

In spite of the extensive network of circumferential and longitudinal ribbing on a modern airplane, most of the fuselage structure is controlled by the hoop stress or pressure X radius divided by skin thickness. Interestingly enough the hoop stress in a pop can (16,250 psi with 50 psig, 1.3" radius, and 0.004" thickness) is about the same as a Boeing 747 (18,300 psi with 9 psig, 128" radius and 0.063" thickness).

The reinforcing ribs are fundamentally there for maneuvering loads. For example, with one of the two engines out on a Boeing 737, there is a tremendous bending moment on the thin skin fuselage. The fuselage will buckle on the compression side, a fact easily demonstrated with a rolled up sheet of paper. (Students expect everything to fail in tension.)

After the de Havilland mid-air breakups in the early 50's caused by metal fatigue and explosive decompression, the ribbing design was "tweaked" for resistance to fatigue cracks. Later designs reflected the development of fracture mechanics and "damage tolerant" designs. Although no airplane is permitted to fly with a fatigue crack (except perhaps un-pressurized to a repair shop), they are designed to be damage tolerant or safe with a 40" tear either from metal fatigue or an uncontained fragment. In fact on March 4, 1996 a 39" fatigue crack was found in a DC-9 during normal inspections. The aircraft had 82,325 cycles. Surprisingly the airplane did not have trouble maintaining pressure in the cabin during its last flight.

Periodically planes are stripped down to the bare metal by removing all interior furnishing and exterior paint for fatigue crack inspection. Although airlines adjust these inspection schedules to their own operations, a typical schedule for partial bare metal inspection of a 737 is every 2,500 hours of flight with a total inspection occurring every 15,000 hours.

Hoop stress and the fatigue cracking in Aloha Flight 243 can be illustrated with the tear pattern of a cylindrical balloon confronted by pin (see Figure 3). The tear pattern in the balloon can be altered by loading the balloon with a torque or axial pull.

Fatigue Testing

The FAA now requires fatigue testing of the entire airplane to twice the design service life for certification. Complete airplanes are fatigue tested with simulated flight cycles. Hydraulic actuators transfer the loads from the fuselage to the wings while simultaneously pressurizing the fuselage. The loading is reversed for landing to complete one cycle. (Random wind gusts have been studied separately.)

Example design service objectives and fatigue test cycles performed are listed in Table 1.

Table 1
Design Service Objects vs. Test Cycles for Selected Planes

	Design Service Objects	Test Cycles
Boeing 737	75,000	150,000
Boeing 777	44,000	120,000
DC-10	42,000	84,000

Manufacturers do not like to use the term "design life" because it implies something that can be used up. It is generally accepted that planes will last almost forever with increased (and costly) inspection and maintenance.

The paper clip "test rig" and paper clip fatigue test data is shown in Figure 2 and is analogous to cyclic testing of a complete airplane. The paper clip long wire is swung +/- any desired rotation. The reduced bending resistance demonstrates fatigue crack initiation and propagation. Rotation vs. cycles to failure is shown in the plot. One paper clip, rotated +/- 11 degrees, is still going strong after 8200 cycles. The paper clip data can be processed with Weibull analysis allowing reliability predictions similar to many aerospace components.

Additional fatigue and fracture concepts can be illustrated with a one inch wide, 0.007" thick strip of aluminum cut from a mini-blind slat. Tensile testing revealed a tensile braking load of 300 lbs.

A crack starter, just a few hundreds of an inch long, must be cut with tin snips in the mini-blind; otherwise the fatigue crack will not easily initiate. With repeated bending the students can watch the fatigue crack grow. Once the fatigue crack has grown about half way across, the expected strength of the remaining ligament would be half of 300 lbs or 150 lbs. The fatigued aluminum slat easily tears apart with perhaps a few pounds of force illustrating the instability of a fatigue crack.

Inertial Loads

Metal fatigue has not caused any wings to fall off in the modern jet era. The wings are designed to pull out of an emergency dive that creates inertial loads of 2.5 g with a safety factor of 1.5. This means the wings should not break with inertial loading of 3.75 g. (This compares to 7 or 8 g's for a dive bomber.) The FAA requires verification of this load by bending the wings during certification. For example, the Boeing 777 wings were bent 24 feet. Although the FAA does not require a destructive test of the wings, Boeing traditionally does deflect the wings till fracture. This approach allows them to take advantage of the last ounce of strength in any future stretched version of the airplane without recertifying the wing loading.

Because the wings are over designed for an emergency dive that rarely if ever happens, they are in fact structurally over designed for normal take-off/landing cycles and minor turbulence. As a result wings do not have metal fatigue problems.

This differs from the fuselage. Most of the fuselage design is controlled by the pressure stress which happens every flight cycle. For that reason minor fuselage fatigue cracks are quite common. Explosive decompression of a fuselage is essentially a solved design problem. If it happens today it is most likely an inspection failure associated with human error or a faulty repair as in the case of China Airlines Flight 611.

Inertial loading also appears within the high rpm engine parts. To provide adequate margin against burst during normal service, engine certification requires the engine to operate at 120% of design rpm for at least 2 minutes. Depending on the design, the engine may spin itself apart shortly after meeting this requirement. This means that the engine normally operates near 1/1.20 = 83% of its burst speed. As expected, aerospace components normally operate near the ragged edge.

United Airlines Flight 232 crashed landed on July 19, 1989. The 38 ten lb fan blades attached to the titanium fan disk rotating at 3,490 rpm create about 3.5 million pounds of inertial loading or centrifugal force distributed circumferentially on the rotating disk every take-off/landing cycle.

The engine designers estimated an average fatigue life of 54,000 cycles. The FAA certified the engine for 54,000/3 = 18,000 take-offs. Additional safety is provided by fatigue crack inspection every time the engine is disassembled. This fan disk in the tail engine was in fact inspected 7 times including one just 760 take-offs before the accident that occurred after 15,503 cycles.

The investigators concluded a manufacturing defect created a 0.055” X 0.015” cavity. (Because molten titanium is so reactive with air it is processed in a vacuum. A leak led to a very brittle titanium nitride ceramic particle.) This cavity grew to a 0.476” X 0.180” fatigue crack at the time of the last inspection and should have been detected. The fatigue crack continued to grow to a size of 1.24” X 0.56” at which time the fan disk flew apart and ruptured all 3 redundant hydraulic lines in the tail.

Hydraulic fluid drained from all three lines and the crew lost control of all flight surfaces. The airplane, just barely maneuverable, was steered by altering thrust to the remaining two engines under each wing. Upon crash landing the airplane broke into three sections and erupted into a fire ball. Amazingly 185 of 296 occupants lived including a baby placed on the floor as instructed.

Airplane crashes are surprisingly survivable. Of the 446 DC-10’s produced, 27 were destroyed in crashes. Only 4 crashes had total loss of life (bombing, flight into a mountain, and two mechanical failures). Of the remaining 23 accidents, almost 90% of the passengers lived.

Displacement, Velocity and Acceleration

Aborted take-offs and botched landings are interesting lessons in motion. Often many of the details of velocity, lengths and forces (drag, braking and thrust reversers) are tabulated in the accident investigation. Because the forces do not remain constant, exact calculations can be tedious, but simplistic approximations can be fun.

Once the pilot reaches V1 speed he or she must take off even if an engine fails because there is not enough runway left to safely stop. If an engine compressor surge occurs with a frightful pop at the very instance that V1 is reached, the pilot has must quickly make the correct decision. A DC-10 had this type of accident on October 19, 1995.

If the airplane tries to land too high, too fast or too far down the runway; a landing overrun accident can occur. A DC-10 on January 23, 1982 experienced a landing overrun accident.

Crash Testing

There have been relatively few crash tests of large planes. The most famous occurred on December 1, 1984 in the Mohave Desert. A remotely piloted Boeing 720 crash landed and erupted into a fire ball. Dramatic pictures and movie clips exist at NASA Dryden. (Search Controlled Impact Demonstration (CID))

Although everyone worries about falling from 40,000 feet, far more common is a botched landing. For this reason numerous drop tests of fuselage sections have occurred. The sections were dropped from 6.2 feet to impact at 20 feet per second and dropped like a rock. The impact velocity predicted by equating the gravity potential energy to the kinetic energy at impact was a perfect match. Other drop tests were done from 14 feet with an impact speed of 30 feet per second.

This compares to FAA regulations requiring landing gear designed to absorb drops from 6.7 inches at the maximum permitted take-off weight and 18.7 inches for the lower maximum permitted landing weight (the difference being the weight of spent fuel). These drop distances correspond to sink rates of 10 ft/sec and 6 ft/sec. Additionally the landing gear is required to withstand a one time drop of 12 ft/sec with out damaging the airplane.

A Boeing survey indicates pilots will report a hard landing (triggering landing gear inspection) at around 4 ft/sec.

On December 18, 2003 an MD-10 had a hard landing accident. Because of a cross wind the airplane landed rolling. The left landing gear touched at 12.5 ft/sec, the right touched at 14.5 ft/sec. Boeing stated the design one time landing maximum absorbed energy to be 843,750 ft lbs of energy, equivalent to a 27 inch drop. Boeing analysis estimated 473,478 ft lbs on the left gear and 563,478 on the right. The right landing gear collapsed and a post crash fire destroyed the airplane. The crew evacuated safely.

Fuselage section drop tests have been done for a variety of reasons: to design and test instrumentation for the Controlled Impact Demonstration, to test new auxiliary fuel tank and other equipment and to provide data for computer simulation.

Being easier to conduct, crash testing and computer modeling of passenger seats is highly developed. This was done as the new FAA rules were phased in requiring 16 g crash tested passenger seats instead of the older 9 g statically loaded seats. In fact computer modeling can be substituted for actual certification seat crash testing for limited circumstances.

A simple pencil drop test illustrates a very common crash pattern of a tail strike (or a nose strike). If the airplane strikes on the tail, the impact force will rotate the aircraft about its center of gravity resulting in a second strike further up the fuselage. A pencil dropped on an angle will have two distinct impact sounds demonstrating this rotation.

Ethics

In an engineering ethics course much ground was covered in the tuck of war between the FBI and the NTSB during the TWA Flight 800 investigation. Also covered were the cost/ benefit/ studies available on inerting fuel tanks and upgrading from 9 g statically tested seats to 16 g dynamically tested seats. The early seat studies estimate future accidents and define the cost of a human life as part of the benefit. The more recent fuel tank studies do not directly state this.

The investigation of American Airlines Flight 191, a DC-10 that crash on May 25, 1979, involved the destruction of a report documenting faulty maintenance procedures. Subsequently all U. S. DC-10's were grounded for 37 days. Some airlines suffered severe economic loss and even sued to have the grounding lifted.

The FAA wears a duel hat. They regulate and promote commercial aviation. The NTSB only investigates accidents and recommends safety improvements. The FAA decides if they will accept any safety improvements. This often creates conflict between the two. Airline crash investigation directly addresses how safe is safe enough, and what are the appropriate limits on the cost of safety improvements.

Limited Assessment Results

A new course titled "Ethics of Engineering Disaster was assessed with a series of questions on a 10 point scale with 10 being strongly agreed. This course was approved for "general education" credits in social science. Perhaps half of the course was based on airplane accidents. Although strongly influenced by engineering issues, the course had a wider mandate. The following two questions are considered representative of student responses.

The goal of critical and creative thinking was obtained by evaluating: evidence, evaluation and analysis of fact and opinion, comparison of different reasons, and the interactions of ethical, legal, technical and regulatory issues. 88% answered 8, 9 or 10

Knowledge was acquired over a broad spectrum of subject areas including ethical, technical, legal, and regulatory issues. 88% answered 8, 9 or 10

In my traditional engineering courses, the question: "Encouraged connection to real world situations" is among my highest ratings and always receives an average above 4 on a 5 point scale.

Summary of Experiments

A popped air balloon illustrates explosive decompression. The longitudinal tear in a cylindrical balloon demonstrates hoop stresses. The longitudinal tear can be altered by pulling or twisting on the balloon. The flimsy fuselage will buckle under flight loads (i. e. the torque from an engine out scenario) similar to bending a paper tube.

The trajectory of the air balloon fragments (6-8) feet demonstrates the energy in compressed air compared to a similar balloon filled with water that collapses in place. The explosive decompression of a pin pricked balloon can be converted into a slow decompression with sufficient closely spaced tape depicting circumferential and longitudinal ribs.

Metal fatigue is illustrated by bending a paper clip or aluminum mini-blind. Fatigue crack growth can be visually observed with the mini-blind. The partially torn mini-blind also illustrates reduced fracture resistance of a fatigue cracked component. The paper clip data shows the statistical nature of fatigue. The data can be processed with Weibull analysis leading to reliability predictions similar to aerospace components.

A tail strike, followed by rotation about the center-of-gravity and subsequent second fuselage strike can be shown with a pencil drop test.

References

1. George Bibel, *Beyond the Black Box: The Forensics of Airplane Crashes*. Johns Hopkins University Press, Baltimore, Maryland. 2008.

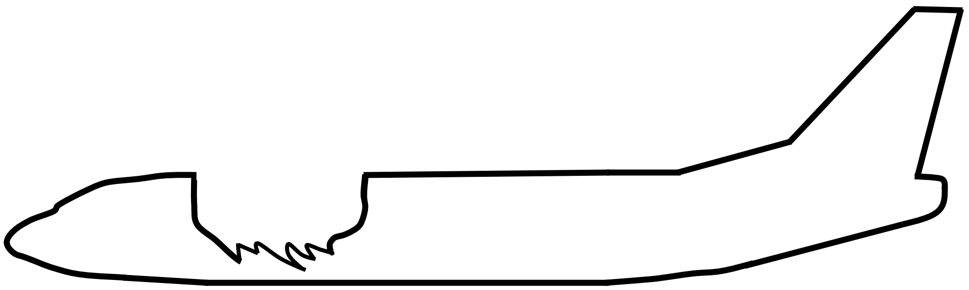

Figure 1: Blast damage for explosive decompression of Aloha Flight 243.

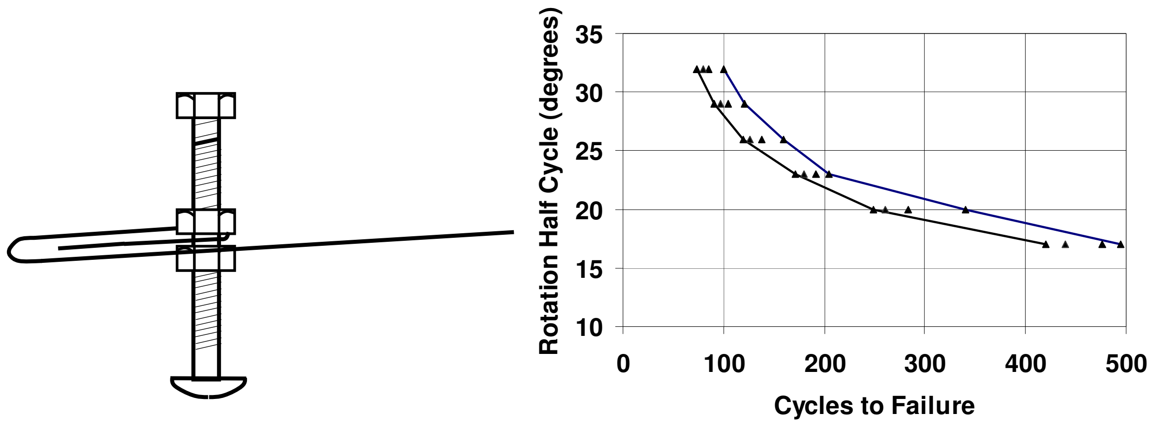

Figure 2: Paper clip test rig and resulting plot of fatigue data.

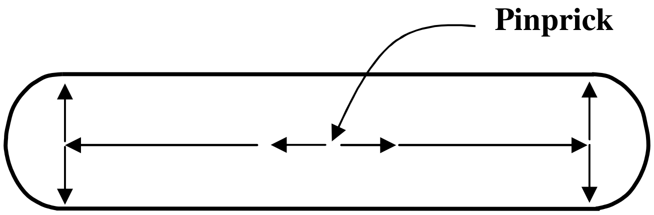

Figure 3: Tear pattern in cylindrical balloon demonstrates hoop stresses in a cylinder and a fuselage.